U.S. Drinking Water Challenges in the Twenty-First Century

Ronnie B. Levin,[1] Paul R. Epstein,[1,2] Tim E. Ford,[1] Winston Harrington,[3] Erik Olson,[4] and Eric G. Reichard[5]

[1]Water and Health Program, Harvard School of Public Health, Boston, Massachusetts, USA; [2]Center for Health and the Global Environment, Harvard Medical School, Boston, Massachusetts, USA; [3]Resources for the Future, Washington, DC, USA; [4]Natural Resources Defense Council, Washington, DC, USA; [5]U.S. Geological Survey, San Diego, California, USA

The access of almost all 270 million U.S. residents to reliable, safe drinking water distinguishes the United States in the twentieth century from that of the nineteenth century. The United States is a relatively water-abundant country with moderate population growth; nonetheless, current trends are sufficient to strain water resources over time, especially on a regional basis. We have examined the areas of public water infrastructure, global climate effects, waterborne disease (including emerging and resurging pathogens), land use, groundwater, surface water, and the U.S. regulatory history and its horizon. These issues are integrally interrelated and cross all levels of public and private jurisdictions. We conclude that U.S. public drinking water supplies will face challenges in these areas in the next century and that solutions to at least some of them will require institutional changes. *Key words:* drinking water, federal regulations, global warming, groundwater, public infrastructure, surface water, waterborne disease. *Environ Health Perspect* 110(suppl 1):43–52 (2002).
http://ehpnet1.niehs.nih.gov/docs/2002/suppl-1/43-52levin/abstract.html

The access of almost all 270 million U.S. residents to reliable safe drinking water distinguishes the United States in the twentieth century from that of the nineteenth century, and the United States from much of the rest of the world even for this century (*1*). Circa 1900, annual typhoid rates in large U.S. cities were about 40/100,000; by 1920, they averaged about 2/100,000 per year, reflecting new water intakes, filtration, and chemical treatment (*2*). By 2000, there were no typhoid cases in the United States attributable to public drinking water.

In this article we address the state of U.S. public drinking water systems at the turn of the millennium. Enormous improvements have occurred during the past century. About 54,000 public water systems now serve over 250 million people (Table 1). [Under the Safe Drinking Water Act (SDWA) (*3*), "public water systems" are defined as those regularly serving at least 25 people or 15 service connections.] More than 80 specific contaminants are regulated, and hundreds of water quality parameters are monitored. Total annual expenditures for public drinking water in the United States are about $36 billion (*4*). Furthermore, the United States is a relatively water-abundant country with moderate population growth (*5*).

Nonetheless, the availability of fresh water is finite, and current trends are sufficient to strain water resources over time, especially on a regional basis (*6*). Thus, many challenges face public water suppliers in the United States at the opening of the twenty-first century. Some are systemic, such as deteriorating infrastructure, whereas others are quite local and specific. Some represent newly emerging circumstances; others

have dogged us for decades. Prudent water professionals are addressing many of them already (*7–10*).

These challenges cross all levels of public and private jurisdictions, from local to international. Some are generally tractable; some are intractably political; a few components present purely technological barriers; most are a combination. Most are also shared by other industrialized nations, and attention by developing countries may enable them to avoid some of the pitfalls we have encountered.

Finally, these challenges are integrally interrelated. An integrated or at least systematic approach is necessary to facilitate efficient, effective, and sustainable solutions.

The State of U.S. Public Water Infrastructure

Investment by the United States in maintenance and repair of public water infrastructure has generally been inadequate over the past half century (*11–13*). The 1996 amendments to the Safe Drinking Water Act (*14*) required the U.S. Environmental Protection Agency (U.S. EPA) to regularly conduct a survey of the infrastructure needs of public water supplies. In its recent survey on these needs, the U.S. EPA estimated that the nation's water utilities must increase investments at least $151 billion over the next two decades to maintain our public water infrastructure and to ensure safe and healthful community water supplies (*4*). Of this total, about $38 billion is for water treatment, $83 billion to repair and/or replace components of the distribution system, and $28 billion to protect watersheds and maintain storage reservoirs. Only a small part of the total—20.7%—is for investments required by the SDWA.

Two other studies support these estimates. The Water Information Network (WIN), a coalition of engineering and construction firms, an environmental group, and water utilities, recently estimated that total annual spending for capital investments and operations by U.S. community water supply systems, currently about $36 billion, must increase by $15 billion (*15*). The estimated needs for wastewater infrastructure are even larger: an increase of $19 billion over the current annual expenditure of $25 billion. [In contrast to drinking water, a large portion of the wastewater expenditures are attributable to requirements of the Clean Water Act (CWA) (*16*).]

The American Society of Civil Engineers (ASCE) just released its *2001 Report Card for America's Infrastructure* (*13*), which included analyses not only for drinking and wastewater but also for bridges, schools, roads, and so forth. The ASCE estimated an annual shortfall of $11 billion for drinking water and $12 billion for wastewater, due to the need to replace aging facilities and to comply with existing and upcoming federal regulations. Both ASCE and WIN advocate enormous subsidies of local water supplies by the federal government, amounts that would dwarf existing federal programs that provide grants or low-interest loans to local governments for water supply and treatment.

Federal subsidies alone, however, are unlikely to address the real causes of the inadequate maintenance: the institutional arrangements that govern local public water providers and their managerial practices. Federal subsidies alone cannot foster the changes necessary to ensure sustainable investment and maintenance practices. Unsustainable practices include the pricing of the product, the disposition of the revenues, the consolidation of the industry, and ownership.

Table 1. Profile and characteristics of U.S. public drinking water systems.[a]

System size	No. of systems (% total)	Millions of people served (% total)	No. of systems (% total)	Millions of people served (% total)
	Groundwater		Surface water	
25–500	28,829 (53%)	4.5 (2%)	3,075 (6%)	0.6 (<1%)
501–3,300	10,414 (19%)	14.1 (6%)	3,626 (7%)	5.7 (2%)
3,301–10,000	2,512 (5%)	14.4 (6%)	1,844 (3%)	11.0 (4%)
10,001–100,000	1,372 (3%)	34.5 (14%)	1,904 (4%)	56.6 (22%)
>100,000	68 (<1%)	18.9 (7%)	279 (<1%)	93.6 (37%)
Total	43,195 (80%)	86.4 (34%)	10,728 (20%)	167.4 (66%)
	Publicly owned		Privately owned	
25–500	7,353 (14%)	1.8 (<1%)	23,023 (44%)	3.2 (1%)
501–3,300	9,892 (19%)	14.6 (6%)	3,761 (7%)	4.7 (2%)
3,301–10,000	3,671 (7%)	21.5 (9%)	598 (1%)	3.4 (1%)
10,001–100,000	2,804 (5%)	77.3 (31%)	421 (1%)	12.5 (5%)
>100,000	284 (<1%)	92.8 (37%)	56 (<1%)	16.8 (7%)
Total[b]	24,004 (46%)	207.9 (84%)	27,859 (54%)	40.6 (16%)

[a]Under the Safe Drinking Water Act (3), "public water systems" are defined as those regularly serving at least 25 people or 15 service connections. [b]2,060 systems serving 5.3 million people had unspecified ownership. Reproduced from the U.S. EPA Safe Drinking Water Information System, 2000.

Table 2. Water use and rates in selected Organisation for Economic Cooperation and Development countries.

Country	Estimated per capita water use in 1997 (L/day)	Average household tariff ($/m³)[a]
Germany	129	1.69
United Kingdom	153	3.11
France	156[b]	3.11
Sweden[b]	191	2.60
Greece	200	1.14
Italy	213	0.84
Spain	237[b]	1.07
Australia	268	1.64
Japan	278	2.10
Canada	326	0.70
United States	382[c]	1.25

[a]Estimates for 1996, 1997, or 1998. [b]Data for 1995. [c]U.S. Geological Survey 2000 (119).
Reprinted from Herrington et al. (25), unless otherwise noted (21), with permission of the Organisation for Economic Cooperation and Development.

Pricing

In many water supply systems and for many years, water rates have been insufficient to cover long-run costs (12,13,17). In addition to adequately financing the maintenance of public infrastructure, water pricing should include the costs of watershed or aquifer management (5,18).

Water system revenues are also sometimes used for other purposes not related to water supply or wastewater disposal. In some cities, for example, water system revenues are not separated from other public funds, an arrangement that allows water supply to subsidize—or be subsidized by—other municipal activities.

In addition to cost recovery, a well-designed pricing system can also encourage water conservation, which will not only reduce pressure on water resources but also reduce future infrastructure requirements. A recent survey of studies found the long-run demand for water to be inelastic but not totally unresponsive to price, with elasticities ranging from –0.2 to –0.4 for residential users and from –0.5 to –0.8 for industrial users (19).

Table 2 compares the average water use per capita and price per cubic meter among selected Organisation for Economic Cooperation and Development (OECD) countries. The lowest per capita use rates shown in Table 2, as well as the highest prices, are found in the countries of northern Europe. Highest average use rates are found in North America, and the prices there are among the lowest. Table 2 shows that while prices exert a strong effect on consumption, they are not the only factor. Furthermore, comparison between North America and northern Europe, regions of comparable wealth, suggests that water prices considerably higher than those in the United States are both conceivable and precedented, and that substantial opportunities for water conservation likely exist in the United States (20).

Conservation opportunities exist on both the supply and the demand sides. Among utilities, leakage is a major issue: drinking water systems lose 6–25% of their finished water through leaks and breaks (21). Leaks are also a potential health risk, a source of contamination in systems subject to occasional negative pressure episodes (22,23). Water conservation among users can reduce requirements not only for water supply facilities but also for wastewater facilities.

Water utilities are increasingly adopting pricing structures that encourage conservation and are moving from flat-fee pricing (a fixed amount per month) to rate structures that charge consumers according to the amount of water consumed. Utilities are also slowly moving to an "increasing block" rate design, where per-unit rates are higher for greater rates of consumption. Compared with a uniform rate structure, increasing block rates reduce the economic hardship associated with high prices while retaining most of their incentive effects.

Surveys from 1987 and 1998 show that the fraction of U.S. utilities using increasing block rates increased from 17 to 37% (24) during this 11-year period, but the penetration appears to have stagnated for the past few years (25). The reluctance of utilities to adopt conservation-oriented rate structures may arise from the potential conflict between the conservation objective and the revenue objective. That is, higher rates encourage a demand response, but that very response makes it more difficult to predict revenues. If conservation is too successful, revenue shortfalls are possible (26).

Consolidation

In 1997, there were about 54,000 permanent community water supplies in the United States (Table 1), only 1,500 more than 10 years earlier (27,28). Over 90% of these systems serve fewer than 10,000 customers and together account for less than 20% of the U.S. population. By comparison, the United Kingdom has fewer than 30 public water systems. The greater area and relatively low population density of the United States only partially explains the very large number of water systems; the U.S. water supply industry has remained quite decentralized even while other local public services such as schools and police have consolidated substantially.

Despite the obvious forces favoring decentralization, this situation may change in the coming decades. First, greater population densities, especially on the coasts, will necessitate coordinated water supply decisions for both surface and groundwater systems. In addition, utility consolidation will be driven by the search for operational efficiencies in such areas as billing, customer service, and water testing, as have other industries from banks to airlines to local trash collection. With over 50,000 supply systems, there must be much duplication of effort. Finding efficiencies will become especially important given the increasingly stringent drinking water regulations of the SDWA, which will require ever greater expertise by utility operators. Monitoring and testing requirements are already a burden on small systems, many of which do not even have full-time operators. The pressures to coordinate demands on water resources and to find operating efficiencies will, we believe, inevitably lead to some consolidation of the industry, which in turn will make it somewhat easier to meet infrastructure (and watershed or aquifer) needs.
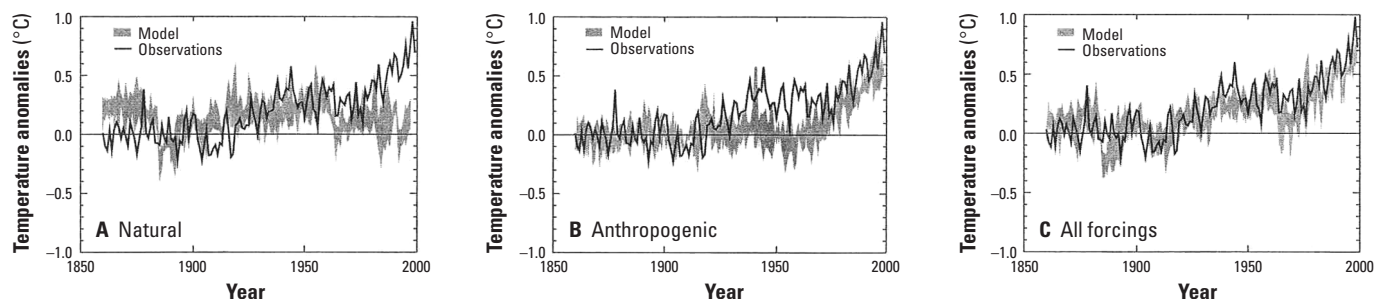
Figure 1. Simulated annual global mean surface temperatures. Simulating the earth's temperature variations, and comparing the results to measured changes, can provide insight into the underlying causes of the major changes. (*A*) Natural forcings only (i.e., natural temperature variability and volcanic activity). (*B*) Anthropogenic forcings only (greenhouse gases and sulfate aerosols). (*C*) All forcings combined, which best fits the actual data (includes both natural and anthropogenic forcings). Reproduced from Albritton et al. (*37*) with permission of the Intergovernmental Panel on Climate Change.

Ownership

Community water systems (as defined by the SDWA, i.e., systems regularly serving at least 25 people or 15 connections) can be public entities, as part of the municipal government, an independent agency, or a special district, or they can be privately owned. Over half the community water supplies in the United States are privately owned; however, together they serve only 16% of the population (Table 1). The private companies are operated much like public utilities and are subject to rate-of-return regulations administered by state public utility commissions. Although situations vary among publicly owned water utilities, generally those not subject to public utility regulation must answer to the voters.

At present, both theory and evidence are inconclusive on the superiority of private versus public ownership. Because both drinking water and wastewater services are natural monopolies, they will almost certainly be provided by a single enterprise. Without the threat of competition, the social benefits of private ownership are not likely to be realized.

However, we think it is likely that private systems have more success in raising investment funds. It is harder for public systems to set rates that maintain their systems properly, for many reasons. That the rate payers are also voters provides a constant downward pressure on rates (*17*). The limited terms of most politicians adds to the myopia, as the benefits of system maintenance will only appear after they have left office. Finally, after World War II many large cities suffered from stagnating local economies and an exodus of the middle class; these difficult economic conditions also inhibited investment in infrastructure.

Private water utilities, on the other hand, are somewhat insulated from public anger. They are usually subject to public utility regulation, which is a much easier environment in which to raise rates for investment funds. The United Kingdom, which in 1989 opted for 100% privatization of drinking water

supply, provides an example: within 2 years, investment expenditure increased by more than 80% (*29*). After comparing public with private water companies, the Congressional Budget Office reported that rates of private water supply companies in the United States exceed by 30–80% those of public suppliers, whose rates often do not permit them to cover the cost of depreciation (*30*). Higher utility rates do not guarantee that the needed investments will be made, but they are a necessary condition for it.

The institutional factors determining the management behaviors of local water providers have not produced adequate expenditure levels to maintain public infrastructure, appropriate investments to develop new drinking water technologies (*17*), or successful strategies to protect watersheds and aquifers (*18*). Therefore, employing these alternatives in a serious way will likely require institutional changes.

Global Climate Effects on U.S. Drinking Water Quality and Quantity

During the 1990s, data on the gradual warming of the earth's atmosphere have shown a dramatic acceleration at the end of the twentieth century. These data include the "fingerprint" studies that show *a*) the warming pattern in the mid-troposphere in the Southern hemisphere (*31*), *b*) the disproportionate rise in nighttime and winter temperatures (*32*), and *c*) the statistical increase in extreme weather events occurring globally (*33,34*). Even more recently, multiple "paleothermometers" have shown that the twentieth century is the warmest in over 1,000 years (*35*). Other data demonstrate a significant increase in the *rate* at which warming is occurring, increasing from about 1°C per century through the 1980s to 3°C per 100 years during 1997 and 1998 (*36*).

Figure 1 shows (simulated) annual global mean temperatures over the period 1850–2000, indicating that models incorporating anthropogenic loadings better

approximate actual temperatures than models using only data on natural temperature variability and volcanic activity (*37*). Table 3 shows examples of impacts resulting from projected changes in extreme climate events (*38*).

If these trends continue, the resulting global warming may adversely affect water distribution, availability, and quality in the United States. Various studies are showing changes in hydrologic cycles, shifting the timing, intensity, seasonality, and spatial distribution of precipitation throughout the world (*39*). These changes are likely to further perturb already stressed ecosystems (*40–42*).

Global warming may affect both surface water and groundwater. A warmer atmosphere holds more water vapor (about 6–8% per 1°C), so evaporation rates will be higher. Droughts followed by severe weather events can result in more polluted runoff to surface waters and less infiltration to replenish aquifers. Conversely, where overall precipitation increases, depleted aquifers may be recharged. Warming of the oceans results in sea level rise from thermal expansion and the melting of glaciers and ice sheets (*43*). A rise in ocean levels may then result in increased salt water infiltration of coastal aquifers (*44*).

Warmer temperatures of surface water sources may also contribute to increased harmful algal blooms, which already appear to be occurring worldwide (*45–48*). Algal blooms in inland aquatic systems can degrade drinking water odor and taste and have caused fatalities in farm animals that drank directly from the water (*49*). The risk to humans from drinking contaminated water is less definitive; certainly, deaths of children and other vulnerable populations are documented from consumption of cyanobacteria toxin (*49*). Several algal bloom biotoxins, associated primarily with consumption of contaminated shellfish, are also known neurotoxins (*50*). Some aerosolized red tide toxins produce asthmalike and other respiratory effects (*51*). Some algal blooms also cause dermatitis (*52*) or are cytotoxic (*53*).

Table 3. Examples of impacts resulting from projected changes in extreme climate events.

Projected changes during the twenty-first century in extreme climate phenomena and their likelihood[a]	Representative examples of projected impacts[b] (all *high confidence* of occurrence in some areas[c])
Simple extremes	
Higher maximum temperatures, more hot days and heat waves[d] over nearly all land areas (*very likely*[a])	• Increased incidence of death and serious illness in older age groups and urban poor • Increased heat stress in livestock and wildlife • Shift in tourist destinations • Increased risk of damage to a number of crops • Increased electric cooling demand and reduced energy supply reliability
Higher (increasing) minimum temperatures; fewer cold days, frost days, and cold waves[d] over nearly all land areas (*very likely*[a])	• Decreased cold-related human morbidity and mortality • Decreased risk of damage to a number of crops, and increased risk to others • Extended range and activity of some pest and disease vectors • Reduced heating energy demand
More intense precipitation events (*very likely,*[a] over many areas)	• Increased flood, landslide, avalanche, and mudslide damage • Increased soil erosion • Increased flood runoff could increase recharge of some floodplain aquifers • Increased pressure on government and private flood insurance systems and disaster relief
Complex extremes	
Increased summer drying over most mid-latitude continental interiors and associated risk of drought (*likely*[a])	• Decreased crop yields • Increased damage to building foundations caused by ground shrinkage • Decreased water resource quantity and quality • Increased risk of forest fire
Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities (*likely,*[a] over some areas)[e]	• Increased risks to human life, risk of infectious disease epidemics and many other risks • Increased coastal erosion and damage to coastal buildings and infrastructure • Increased damage to coastal ecosystems such as coral reefs and mangroves
Intensified droughts and floods associated with El Niño events in many different regions (*likely*[a])	• Decreased agricultural and rangeland productivity in drought- and flood-prone regions • Decreased hydropower potential in drought-prone regions
Increased Asian summer monsoon precipitation variability (*likely*[a])	• Increase in flood and drought magnitude and damages in temperate and tropical Asia
Increased intensity of midlatitude storms (little agreement between current models)[d]	• Increased risks to human life and health • Increased property and infrastructure losses • Increased damage to coastal ecosystems

[a]Likelihood refers to judgmental estimates of confidence used by Working Group 1: *very likely* (90–99% chance); *likely* (66–90% chance). Information on climate phenomena is taken from the Summary for Policymakers of Working Group I. [b]These impacts can be lessened by appropriate response measures. [c]*High confidence* refers to probabilities between 67 and 95%. [d]Information from Working Group I, Technical Summary, Section F.5. [e]Changes in regional distribution of tropical cyclones are possible but have not been established.
Reprinted from McCarthy et al. (*38*) with the permission of the Intergovernmental Panel on Climate Change.

Theoretically, warmer temperatures and especially warmer winters may result in higher microbial and nutrient loadings in drinking water supplies, promoting biofilm growth within the distribution system and, in turn, supporting survival of some pathogens and their indicators. Warmer temperatures will also mean increased water use (e.g., drinking water consumption, bathing, watering lawns, irrigating crops, swimming, etc.), increasing demands on drinking water systems.

Snowpack, especially in mountains, holds water until late spring or even summer and then melts over several months, generating stream flow seasonally when water typi-cally is much needed but less available from rainfall. Warmer winters, particularly if precipitation decreases, may produce less snowpack and earlier snowmelt, which would then provide less water during the drier growing season and hence strain other freshwater supplies (*54*).

In addition, sequential extremes—droughts punctuated by heavy rains—can destabilize natural biological controls of pests and pathogens (*55*). Evidence since the 1980s suggests that the geographic range and virulence of some established diseases (e.g., malaria) are expanding (*56*). Heavy rain events and flooding are associated with waterborne disease outbreaks (*57*)

and algal blooms, often resulting in "dead zones" (*46,58,59*).

Because of the global nature of the changes, even well-protected watersheds will not be immune to these conditions. And the effects are likely to be distributed widely across the country.

Waterborne Disease

Improvements in public drinking water during the twentieth century, including more protected water intakes, filtration, and chemical treatment, virtually eliminated the most deadly waterborne diseases such as typhoid and cholera from the United States (*1*).

Nonetheless, numerous surveys have shown widespread contamination of U.S. surface waters by multiple pathogens, even in pristine waters (*60–65*). In addition, while surface water supplies are the major risk for waterborne infectious disease (WBID), myriad data show that wells, especially relatively shallow wells, are also vulnerable to microbial contamination. In data published by the U.S. Centers for Disease Control and Prevention (CDC), about half the documented waterborne disease outbreaks have a groundwater source (*66–70*). A recent study found that 5–50% of wells and springs tested were contaminated with *Giardia* or *Cryptosporidium*, suggesting that groundwater systems also need to be monitored for microbial contamination (*71*). Furthermore, studies have shown that many microorganisms can exist for prolonged periods under harsh conditions in a viable but nonculturable form (*65,72*).

The full extent of WBID in the United States presently is not known. Data from the CDC (collected through a passive, voluntary, self-reported system) are widely thought to underrepresent actual incidence (*63–67,73*). Many WBID outbreaks are never detected (*73–76*). Current incidence estimates are three to four orders of magnitude higher than the CDC data (*77–79*). Empirical evidence from a variety of water systems meeting federal drinking water standards suggests that 6–40% of gastrointestinal illness in the United States may be water related (*74–76,80–82*); recent data from Canada present a similar picture there (*83*).

In the United States, disinfection is required of all public water supplies served by surface water or by groundwater "under the influence of surface water" (*84*). By far, the most common disinfection approach in the United States is the use of chlorine species.

A complication of drinking water disinfection is the emerging evidence of carcinogenic and possibly other health effects associated with disinfection by-products (DBPs) such as trihalomethanes (THMs)

(*78,85–88*). Common sense as well as several cost–benefit analyses (*17,89,90*) suggest that present disinfection rates cannot be compromised. Furthermore, numerous investigations have shown that low-level WBID continues in the United States even at current disinfection levels (*74,76,80–82*). Nonetheless, we believe that the new evidence of carcinogenic and other health effects from exposure to disinfected water cannot be ignored and will likely challenge the public health and water utility communities in the twenty-first century.

In addition, as the limits of disinfectants to control some of the most common waterborne pathogens (e.g., *Giardia, Cryptosporidium*, and probably some viruses) become clearer, the advantages of a multiple barrier approach to WBID are again highlighted (*91–94*). Filtration and disinfection efforts will need to be strengthened along with enhanced watershed protection.

Our ability to detect waterborne diseases is constrained by the limits of current methods for each specific pathogen (*95*), and one third or more of documented WBID outbreaks in the United States have an unidentified etiology (*66–70,73*). Current methods for bacteria focus only on those that can be cultured in the laboratory, although there is evidence that many microorganisms can survive in a viable but nonculturable form (*65,72*). Current methods for protozoa and viruses are expensive and require concentration of large volumes of finished water through adsorption, filtration, centrifugation, and coagulation/precipitation or a combination of these techniques, followed by separation and quantification. Each of these multistage procedures can contribute to significant losses in recovery. As a result, the lower limit acceptance criteria for ongoing precision and recovery is, for instance, 19% for *Cryptosporidium* and 16% for *Giardia*, using the accepted methodology (*96*). Molecular methods based on polymerase chain reactions show promise for improving our ability to detect specific pathogens (*97*) and, in certain cases, their viability (*98*). In combination with cell-culture techniques, infectivity of certain organisms may also be assessed (*99*). These techniques, however, are still primarily applicable for research studies and are beyond the scope of all but the most highly trained staff and most affluent utility laboratories.

Emerging and Resurging Pathogens

Levels of the most deadly WBIDs in the United States, such as cholera and typhoid, are currently extremely low—indeed, virtually nonexistent. However, open and easy worldwide commerce compromises the invulnerability of individual nations (or even continents) to dangers from elsewhere.

There are unsettling trends throughout the world in the emergence and resurgence of diseases, including waterborne diseases, and in the expanding geographic range and virulence of some established diseases. There has also been a resurgence of older diseases in certain parts of the world, for example, cholera in South America (*100*). It is more difficult, however, to define what is really the emergence of a new disease (*101,102*).

Altered or new routes of exposure to previously uncharacterized pathogens may result in the emergence of disease. An increase in the number of susceptible individuals (the very young, pregnant women, the immunocompromised population and—in the United States especially—the elderly) (*103*) will extend the human reservoir for opportunistic pathogens and change virulence patterns, even in developed countries. Indeed, the U.S. elderly population is likely to triple between 1985 and 2015. In addition, increased adaptation to the human host by pathogens could increase infection rates in populations with no underlying susceptibilities.

Many infectious agents have been categorized as emerging diseases and have not been recognized until recently, or at least not in association with water, including *Legionella pneumophila, Cryptosporidium parvum, Escherichia coli* O157, *Vibrio cholerae* O139, hepatitis E, and *Helicobacter pylori*. The dangers of emerging diseases have been discussed widely in the popular and scientific press (*104,105*).

We should possibly add to this list every waterborne pathogen that has developed resistance to antibiotics, or changed apparent virulence, as they emerge as a higher mortality risk (*75*). Resistance to multiple antibiotics has been well documented in waterborne pathogens (*106–109*) and represents a major public health threat. There are many pathways for antibiotics and antibiotic-resistant organisms to enter the drinking water supply (*110,111*). Source water can become contaminated through antibiotic use in the human population (pharmaceuticals and biologics) as well as the use of a diverse group of bioactive chemicals, including active ingredients in personal care products such as diagnostic agents, "nutriceuticals," fragrances, sun screen agents, and so forth (*112*), with subsequent discharge in sewage. However, massive and unregulated use of antibiotics in agriculture and aquaculture may present the greatest risk to the aquatic environment (*113*).

The water distribution system itself may provide an opportunity for exchange of both antibiotic resistance and virulence factors among microbes. The biofilms or "slimes" that form on the inner surfaces of pipes are potential sites for gene exchange (*114,115*).

Land Use Issues

The twentieth century provided engineering solutions to lower-quality sources of drinking water, principally filtration and disinfection with chlorine. This afforded cities the alternative to continue using more contaminated source waters, as did Philadelphia, Pennsylvania, or to seek more pristine and higher-quality sources far upstream, as did New York City and Boston, Massachusetts (*116*). This financial decision still faces water utilities (and the U.S. EPA) at the beginning of the twenty-first century.

Land use pressures will also challenge U.S. drinking water systems in the next century (*117*). Multiple economic and social indicators suggest that the population will continue to grow, the size of households is likely to continue to fall, per capita water use will at least remain constant but may also continue to increase accompanying a rising standard of living, and even leisure activities that require water are likely to increase as travel costs decrease. In addition, technological advances in the provision of water (and an infusion of significant federal resources) have facilitated large population shifts to arid areas, increasing the pressure on their limited water resources. These factors may result in water scarcity in certain locales.

Control of unregulated and other "nonpoint" sources of discharge to surface waters, such as agricultural activities and much street runoff, will become more important to water quality as "point" sources are controlled (*117,118*). Systems sharing watersheds or aquifers will need to work together to protect their common resource. As population densities increase, especially along the coasts, coordinated land use strategies will be necessary. For instance, water diverted from infiltration into the soil and occurring as runoff to surface water will result in more rapidly depleting aquifers and more contaminated surface waters. A recent survey found a variety of pesticides in both surface water and groundwater in all basins with appreciable agricultural activities or urbanized development (*119*). In these circumstances, competition among sources (drinking water, agriculture, fish and wildlife habitats, residential development, energy production, leisure, etc.) is likely to increase (*117*).

An interesting case study of land use issues, including competing needs and externalized costs, is New York City's recent decision to invest in upgraded protection of its Catskills watershed to avoid the high costs of building a filtration plant (*120,121*). The city estimated that building the filtration plant would cost $6 billion to $8 billion in capital, with annual operating expenses of about $300 million. Costs to repair the degraded watershed to ensure a higher-quality water source

were estimated at $1 billion to $1.5 billion, for land acquisition, new watershed rules and regulations, and financial assistance to watershed communities to promote environmental quality and their local economies. New York City chose to invest in the protection of its drinking water source, a decision supported, at least in the short run, by a scientific review by the National Research Council (*121*).

Alternatively, given finite water and land resources, a growing population, and a vast array of technological developments, the United States can anticipate new interpretations of the maxim that drinking water should be obtained from the best-quality source available. Reclaimed water and water reuse, for instance, can enhance both groundwater and surface water supplies. Current potable reuse projects and studies have demonstrated the capability to produce reclaimed water of excellent measurable quality and to ensure system reliability but only with frequent, careful, and thorough monitoring (*122*). Water reuse plans are already being investigated in several states, including Arizona, California, Florida, Texas, Utah, and Virginia.

These alternative solutions, however, come with high price tags. Because U.S. water pricing over the past century has not been adequate to maintain the public water infrastructure and to cover the costs of watershed and aquifer management, inefficient and ultimately more expensive (and unsustainable) water consumption behaviors have developed (*5,18,26,120,121*). In addition, substantial costs have been deferred, such as the cost of preserving the quality of watersheds, that are now coming due. We believe that, in the next century, economic and related political forces will force the rest of the United States to evaluate local and national policies on, for instance, agriculture, development (especially in naturally arid areas), and other high–water-demand activities, as New York City did recently. Inevitably, consumers and polluters must pay to fully protect our shared resources.

Groundwater Issues

Groundwater currently is the drinking water source for almost 80% of the public water systems in the United States, although only about one third of the U.S. population is served by those systems. The average groundwater system serves under 500 people (Table 1). Figure 2 shows the general distribution of systems served by groundwater versus surface water in the United States.

Some U.S. aquifers are refilled (recharged) regularly by rainfall, from surface water bodies, or both. Other aquifers, however, contain water that is thousands of years old ("fossil water") and that cannot be replenished. Once the fossil water in the

latter aquifers has been exhausted, the areas dependent on them will have to procure alternative drinking water sources.

Even in aquifers that can be recharged, however, at present the rate of groundwater extraction exceeds long-term rates of recharge from precipitation and other sources in many basins (*117*). This is exacerbated by a reduction in natural recharge rates due to an increase in nonpermeable areas associated with land development. Depletion of groundwater in storage increases the costs of extraction and may induce water quality degradation (such as seawater intrusion), land subsidence, and eventually loss of the resource. Use of simplified concepts such as "safe yield" to determine allowable groundwater withdrawals ignores the dynamics and the interconnection of all components of groundwater budgets (*123*).

Surface-water withdrawals
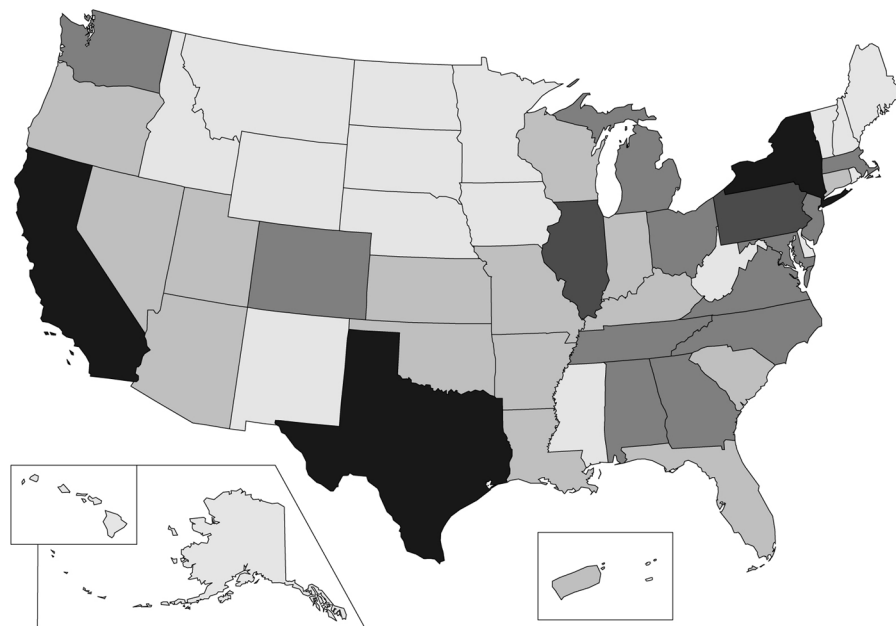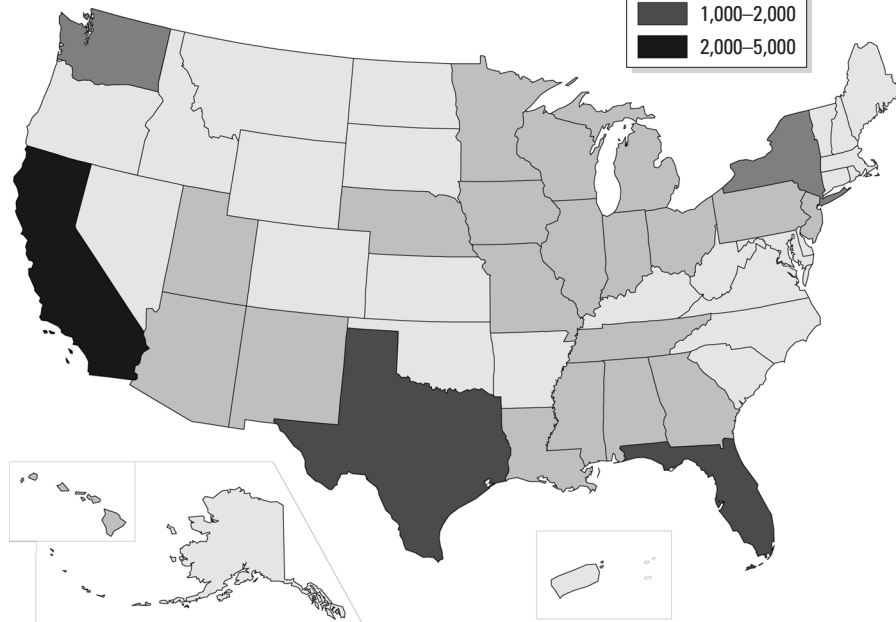

Groundwater withdrawals

Figure 2. Estimated water use in the United States in 1995, by source. Reproduced from Solley et al. (*150*).

Contamination of groundwater supplies will continue to be an important issue in the United States in the twenty-first century. Much contamination results from local human activities, including industrial activities, hazardous waste sites, residential development, and transportation. There also are more pervasive contaminants to groundwater supplies, including nonpoint sources associated with agriculture and animal husbandry (*124,125*), and naturally occurring contaminants such as arsenic and other trace metals (*126*). Finally, recharge of contaminated water into groundwater systems can introduce harmful chemical and microbial contaminants into drinking water supplies (*127*).

Groundwater and surface water function as linked resources, so contamination of surface water bodies can contaminate groundwater (*128*). Because residence times in groundwater tend to be much longer than in surface water, "short-term" contamination events in surface water can result in long-term contamination of groundwater, with consequent negative impacts on drinking water supplies.

The link between groundwater and surface waters permits the design of strategies that maximize the advantages of each resource (*129*). The National Research Council defines conjunctive use as "a plan that capitalizes on the combination of surface and groundwater resources to achieve a greater beneficial use than if the interaction were ignored" (*129*). For example, this could involve artificially recharging aquifers (via percolation ponds or injection wells) with surface water, thereby using the groundwater system as a storage and conveyance facility, and also exploiting the natural filtering ability of aquifers to clean polluted surface water. It seems likely to us that these actions can have significant benefits for providing drinking water, including better reliability of supply, reduced costs, and potentially improved water quality.

Closely linked to conjunctive use projects is the increasing use of reclaimed sewage effluent as a source of groundwater recharge and, ultimately, a source of drinking water. This is particularly the case in the western United States, where reclaimed water is considered the main "new" water supply. Faced with increasing demand, limited increases in traditional water supply sources, and potentially large costs of building/enlarging sewage outfalls, water managers are likely to accelerate their use of reclaimed water for groundwater recharge (and other uses, such as direct irrigation). Research is beginning to address public health concerns about the microbial and chemical fate and transport of contaminants in reclaimed water that is recharged into aquifers (*122,130,131*).

Climate change and climate variability may have complex impacts on U.S. groundwater resources. Net impacts on groundwater will depend on the local, relative changes in recharge and pumping demand that occur in a given basin (*132,133*). Potential rises in sea level may result in increased rates of seawater intrusion, depending on the change in gradients and onshore groundwater levels (*44*). Global warming may also result in reduced recharge (e.g., due to increased evaporation) and/or increased pumpage (e.g., due to increased consumption).

Extensive and effective monitoring is required to ensure that groundwater supplies remain available for drinking water. Monitoring of groundwater is fundamentally different from that for surface water; the three-dimensional physical, chemical, and microbial characteristics of the resource must be estimated from point measurements at individual wells. Therefore, assessing the quality of a groundwater basin is more complex and inherently uncertain. We suggest that the millions of U.S. residents who use private wells for drinking water and are not covered by the SDWA are particularly vulnerable; they have no systematic monitoring and thus the potential for a large undetected population exposure to chemical or microbial contaminants exists.

Surface Water Supplies

In June 1969, the Cuyahoga River caught fire, because of the wide array of flammables in the water and on its surface; it burned for 4 days. Shortly thereafter, the CWA was passed to address the widely and heavily polluted surface waters in the United States. Since then, controls on point sources and extensive sewage treatment have reduced U.S. water pollution significantly (*134*). A major unresolved issue is nonpoint source contamination, that is, unregulated discharges such as runoff from agriculture and animal husbandry, roads and other developed areas, and other sources (*118,124,134*).

About 167 million Americans use surface water as their public drinking water source (Table 2, Figure 2). Virtually none of the surface water in the United States is drinkable without treatment. Indeed, federal rules require disinfection of surface water used for drinking.

The 1996 amendments to the SDWA (*14*) placed a new focus on identifying and protecting drinking water sources. In coordination with water pollution control programs implemented under the CWA and other water quality protection laws, the 1996 SDWA amendments required that all states assess the problems that impair the designated uses of water, with a priority for use as drinking water. These assessments, done on a watershed basis, were required under both the SDWA (§1453) and CWA (§305[b]) and strengthened U.S. drinking water protection efforts, especially watershed protection.

The reports submitted by all 50 states listed siltation, nutrients, pathogens, oxygen-depleting substances, metals, habitat alteration, pesticides, and organic toxic chemicals as the most common causes of surface water quality impairment (*118,135,136*). This pollution results primarily from runoff related to human activities (Table 4). Nationwide, agriculture is the most extensive source of water pollution, affecting 70% of impaired rivers and streams and 49% of impaired lake acres. Other national or regional causes of water quality degradation include municipal point sources, hydrologic and habitat modification, urban runoff and storm water (especially sanitary sewer overflows during rain events), resource extraction, and removal of streamside vegetation. Decreasing water quality and increasing eutrophication of many freshwater bodies are also resulting in increased algal blooms, especially cyanobacteria (*45–48,137,138*).

As with groundwater, technological advances are occurring rapidly in the treatment of surface waters. For instance, over the next century, we believe that technological improvements may reduce the costs of desalination to the point where seawater becomes an economically viable source of drinking water supply in some U.S. coastal areas.

Regulatory History and Horizon

In the first half of the twentieth century, the U.S. Treasury Department and the U.S. Public Health Service (U.S. PHS) adopted drinking water guidelines for a few contaminants, including coliform bacteria (first issued in 1914) and some chemicals, such as arsenic (set in 1942) (*139,140*). These standards were binding on "interstate carrier conveyances" such as trains and aircraft, but states could adopt or reject federal standards

Table 4. Five leading causes of surface water quality impairment in the United States, reported by states.

Rank	Rivers	Lakes	Estuaries
1	Agriculture	Agriculture	Industrial dischargees
2	Municipal point sources	Unspecified nonpoint sources	Urban runoff/storm sewers
3	Hydrologic modification	Atmospheric deposition	Municipal point sources
4	Habitat modification	Urban runoff/storm sewers	Upstream sources
5	Resource extraction	Municipal point sources	Agriculture

From Clean Water Action Plan (*118*).

for stationary public water systems. In fact, most states had not adopted or enforced these federal standards before 1974 (*141*).

In 1974, Congress passed the SDWA (*3*). Over the next 12 years, the U.S. EPA ratified most of the 30 or so older U.S. PHS guidelines as "interim standards" and adopted one new standard (for THMs in 1979) (*142*). These standards then became enforceable nationally on all public water systems. In 1986, the U.S. Congress, frustrated by the slow pace of drinking water regulation, revised the SDWA significantly and mandated the U.S. EPA to establish new or revised standards for 83 specific contaminants; Congress also ordered the U.S. EPA to adopt 25 new contaminant standards every 3 years thereafter. The U.S. EPA issued over 80 new drinking water rules in the 10 years that followed.

A backlash ensued against the issuance of these new standards, resulting in an effort joined by many water utilities and state and local government officials to relax the 1986 requirements of the SDWA. However, this effort clashed with increasing public concern about drinking water safety. Events such as the 1993 cryptosporidiosis outbreak in Milwaukee, Wisconsin, that sickened over 400,000 people (*143*), and mounting evidence that some common contaminants posed significant health risks, created a countercurrent favoring more stringent protection of drinking water.

Congress overhauled the SDWA again in 1996. Important revisions included a new emphasis on public involvement and public "right to know" about drinking water quality through annual reports, which community water systems are now required to provide to their customers, as well as the "Boxer Amendment" requiring consideration of vulnerable populations such as pregnant women, children, and the chronically ill in setting standards. The law also established new provisions that allow consideration of costs and benefits and risk–risk trade-offs in setting tap water standards. The 1986 law's requirement for 25 new contaminants standards every 3 years was changed to require no fewer than 5 new contaminant standards to be considered every 5 years. The U.S. EPA is charged with reviewing and, if feasible, strengthening all tap water standards every 6 years. In addition, the 1996 law specifically requires the U.S. EPA to issue or update standards for arsenic (*144*), radionuclides, surface water treatment, filter cleaning and backwash practices, groundwater disinfection, and DBPs. Finally, the U.S. EPA is required to conduct a survey of the infrastructure needs of public water systems every 4 years.

An examination of the current status of individual state drinking water regulations revealed significant gaps between federal and state authority (*145*). There were also discrepancies among states.

We anticipate additional U.S. EPA standards in the coming decades. Certainly, microbial contaminants are likely to be the subject of upcoming standards (*78*). Rules related to disinfection of both groundwater and surface water supplies will likely be strengthened, for two reasons. First, filtration and disinfection practices that were believed to be adequate to control microbial risks have in some cases been shown to be inadequate (*78,90*). Second, there is ample evidence that groundwater systems are also vulnerable to microbial contamination (*71*).

Moreover, the U.S. EPA has agreed in 1992, as part of a regulatory negotiation, to adopt a rule that will address risks posed by distribution systems, such as cross connections, backflow, and other significant health risks from pipes that deliver treated water to customers (*146,147*). Existing standards for many other chemical contaminants are also likely to be strengthened, due either to legal requirements or to new evidence of health risks.

Given the long and ever-growing list of contaminants that the U.S. EPA is anticipated to regulate on a chemical-by-chemical and microbe-by-microbe basis, however, we note that a fundamental shift in regulatory approach may be preferable. Instead of continuing to rely upon the case-by-case approach with constantly changing standards as our knowledge of contaminants increases, water utilities (and public health) may be better served by adopting broad-spectrum risk reduction, treatment, and prevention approaches that ameliorate many contaminants simultaneously. For example, a vigorous source water protection program may be able to reduce multiple chemical and microbial risks. In addition, membrane filters, advanced water treatment trains such as granular activated carbon, advanced filtration, and ultraviolet radiation disinfection can reduce or eliminate a wide array of chemical and microbial risks at once. Other possible approaches include risk-based strategies (as in New Zealand), allowing utilities a flexible method to sum across risks.

However, a continuing challenge has been persistent noncompliance with the U.S. EPA current regulations. Although 80% of U.S. public water systems have no reported violations, about 30 million Americans drink water each year from systems that report violations of health-based standards (*148*). The U.S. EPA reports that in 1998, over 10,000 systems violated health-based drinking water standards (*149*). In addition, there were 86,000 violations of federal requirements to monitor water or to report results. Overall, the data likely underestimate noncompliance because data audits show that states reported to the U.S.

EPA only 55% of major violations and 10% of monitoring and reporting violations (*147*).

Conclusions

Among the major public health achievements of the United States in the twentieth century was the access of virtually all U.S. residents to a safe, reliable water source. Nonetheless, the nation faces numerous challenges to the continued provision of safe drinking water in the coming century:

• The state of the public water infrastructure is inadequate to meet even our current needs. A major increase of resources is necessary. Changes in pricing, consolidation, and ownership may help to address some of these issues.

• Global warming may have significant impacts on drinking water quality and quantity, affecting both groundwater and surface waters in the United States.

• The risks of WBIDs, which have become more evident recently, are underestimated and underappreciated. Resurging and emerging diseases, along with a significant growth in the size of the U.S. population sensitive to infectious disease, may also necessitate additional public health attention.

• A particular complication relates to drinking water disinfection. Growing evidence suggests that U.S. drinking water currently is associated with mild to moderate levels of WBID in the United States, even in systems meeting federal standards. At the same time, several studies are finding carcinogenic and other health effects associated with exposure to DBPs.

• Land use pressures will also challenge U.S. drinking water systems in the next century and will require the coordinated actions of all those sharing watersheds or aquifers.

• Groundwater aquifers are being depleted and contaminated; remediation will be expensive at best. Also, those using private wells may require regulatory or public health attention.

• Surface waters have been cleaned up somewhat since the low point in 1969 when the Cuyahoga River caught fire. Still, virtually none of the surface water in the United States is drinkable without treatment.

• We need better, more efficient and sensitive monitoring tools and strategies, especially to assess microbial risks and groundwater contamination.

* U.S. EPA will need to update many regulations to address legal requirements and new health data; the current case-by-case approach may need to be reevaluated. Compliance with current regulations, especially in small systems, remains a challenge.

It is likely that solutions to at least some of these will require institutional changes.

REFERENCES AND NOTES

1. U.S. Centers for Disease Control and Prevention. Ten great public health achievements—United States, 1900–1999. Mor Mortal Wkly Rep 48(12):241–243 (1999).
2. American Water Works Association. Water Works Practice Manual. Washington, DC:AWWA Publishing, 1925;14–15.
3. Public Health Service Act (Title XIV) [Safe Drinking Water Act]. 42 USC δ300f to 300j-26, 1974.
4. U.S. EPA. Drinking Water Infrastructure Needs Survey. EPA-816-R-01-004. Washington, DC:U.S. Environmental Protection Agency, 2001. Available: http://www.epa.gov/safewater/needs.html
5. Johnson N. Managing water for people and nature. Science 292:1071–1072 (2001).
6. Falkenmark M, Widstrand C. Population and Water Resources: A Delicate Balance. Population Bulletin. Washington, DC:Population Reference Bureau, 1992.
7. Mannion JB. A big water bang theory [Editorial]. J Am Water Works Assoc 85(4):8 (1993).
8. Bolden JR, Farrell WC. Ensuring water quality in urban environments [Editorial]. J Am Water Works Assoc 86(1):8 (1994).
9. Norling NM, Stephens TE, Davis VW. Safer water at a higher price—anticipating the impact of the Safe Drinking Water Act. Publ Util Fortnightly 22 Dec 1988; 11–17.
10. Sim M, Fairley C, McNeil J. Drinking water quality: new challenges for an old problem. Occup Environ Med 53:649–651 (1996).
11. NCPWI. Rebuilding the Foundations: A Special Report on State and Local Public Works Financing and Management. OTA-SET-447. Washington DC:National Council on Public Works Improvements, Office of Technology Assessment, 1990.
12. ASCE. ASCE's 1998 Report Card for America's Infrastructure. Washington, DC:American Society of Civil Engineers, Civil Engineering Research Foundation, 1998.
13. ASCE. ASCE's 2001 Report Card for America's Infrastructure. Washington, DC:American Society of Civil Engineers, Civil Engineering Research Foundation, 2001.
14. 1996 Amendments to the Public Health Service Act (Title XIV) [Safe Drinking Water Act]. 42 USC δ300f to 300j-26, 1996.
15. WIN (Water Infrastructure Network). Clean and Safe Water for the 21st Century. American Metropolitan Water Agencies, 2000. Available: http://www.amwa-water.org/features/win/win.html#report
16. Federal Water Pollution Control Act [Clean Water Act]. 33 USC δ1251 to 1387, 1972.
17. Levin R, Kleiman M. Drinking water treatment: balancing infectious disease, cancer and cost. In: The Substance of Public Policy (Nagle S, ed). New York:Nova Science Publishers, 1999;117–137.
18. Heal G. Nature and the Marketplace. Washington, DC:Island Press, 2000.
19. Beecher JA, Mann PC, Hagazy Y, Stanford JD. Revenue Effects of Water Conservation and Conservation Pricing: Issues and Practices. Columbus, OH:National Regulatory Research Institute, 1994.
20. Certainly the United States is not alone in underpricing water. Indeed, a major cause of local water scarcity and related freshwater ecosystem decline is that water is undervalued the world over. See references (5) and (18).
21. Economic and Engineering Services and Kennedy/Jenks/Chilton. Economics of Internal Corrosion Control. Denver, CO:American Water Works Association Research Foundation, October 1989.
22. Davies C, Fraser DL, Hertzler PC, Jones RT. US EPA's Infrastructure Needs Survey. J Am Water Works Assoc 89(12):30–38 (1997).
23. Clark RM, Rizzo GS, Belknap JA, Cochrane C. Water quality and the replacement and repair of drinking water infrastructure: the Washington, DC, case study. J Water SRT–Aqua 48(3):106–114 (1999).
24. Raftelis Financial Consulting. 1998 Water and Wastewater Rate Survey. Charlotte, NC:Raftelis Associates, 2000.
25. Herrington P. Household Water Pricing in OECD Countries. Paris:Working Party on Economic and Environmental Policy Integration. OECD. ENV/EPOC/GEEI(98)12/FINAL, 1999.
26. Chestnutt TW, Beecher JA. Conservation rates in the real world. J Am Water Works Assoc 90(2):60–70 (1998).
27. U.S. EPA. Community Water System Survey, Vol 2, Detailed Survey Result Tables and Methodology Report. Washington, DC:U.S. Environmental Protection Agency, 1997.
28. U.S. EPA. Financial Descriptive Summary: 1986 Survey of Community Water Systems. Washington, DC:U.S. Environmental Protection Agency, 1987.
29. Haarmeyer D. Privatizing infrastructure: options for municipal water-supply systems. Policy Study 151. Los Angeles:The Reason Foundation, 1992.
30. U.S. CBO. Financing municipal water supply systems. Washington, DC:U.S. Congressional Budget Office, 1987.
31. Santer BD, Taylor KE, Wigley TML, Johns TC, Jones PD, Karoly DJ, Mitchell JFB, Oort AH, Penner JE, Ramaswamy V, et al. A search for human influences on the thermal structure of the atmosphere. Nature 382:39–46 (1996).
32. Easterling DR, Horton B, Jones PD, Peterson TC, Karl TR, Parker DE, Salinger MJ, Razuvayev V, Plummer N, Jamason P, et al. Maximum and minimum temperature trends for the globe. Science 277:363–367 (1997).
33. Karl TR, Knight RW, Easterling DR, Quayle RG. Trends in U.S. climate during the twentieth century. Consequences 1:3–12 (1995).
34. Karl TR, Knight RW, Plummer N. Trends in high-frequency climate variability in the twentieth century. Nature 377:217–220 (1995).
35. Mann ME, Bradley RS, Hughes MK. Global-scale temperature patterns and climate forcing over the past six centuries. Nature 392:779–787 (1998).
36. Karl TR, Knight RW, Baker B. The record breaking global temperatures of 1997 and 1998: evidence for an increase in the rate of global warming? J Geophys Res Lett 27:719–722 (2000).
37. Albritton DL, Allen MR, Baede APM, Church JA, Cubasch U, Dai X. Report of Working Group I of the Intergovernmental Panel on Climate Change. Summary for Policy Makers, Third Assessment Report. Climate Change 2001: The Scientific Basis. Geneva:IPCC, 2001.
38. McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS, eds. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Intergovernmental Panel on Climate Change, Working Group II. Cambridge, UK:Cambridge University Press, 2001.
39. Watson RT, Zinyowera MC, Moss RH, Dokken DJ, eds. IPCC Special Report on the Regional Impacts of Climate Change: An Assessment of Vulnerability. Paris:IPCC Press, 2000.
40. McMichael AJ, Haines A, Slooff R, Kovats S, eds. Climate Change and Human Health. Geneva:World Health Organization, 1996.
41. Epstein PR. Is global warming harmful to health? Sci Am 283(2):50–57 (2000).
42. Patz JA, McGeehin MA, Bernard SM, Ebi KL, Epstein PR, Grambsch A, Gubler DJ, Reiter P, Romieu I, Rose JB, et al. The potential health impacts of climate variability and change for the United States: executive summary of the Report of the Health Sector of the U.S. National Assessment. Environ Health Perspect 108(4):367–376 (2000).
43. Levitus S, Antonov JI, Boyer TP, Stephens C. Warming of the world's ocean. Science 287:2225–2229 (2000).
44. Borrelli P. Crossroads: Environmental Priorities for the Future. Washington, DC:Island Press, 1988.
45. Epstein PR, Sherman BH, Siegfried ES, Langston A, Prasad S, Mckay B, eds. HEED 1998. Health, Ecological and Economic Dimensions of Global Change Programs. In: Marine Ecosystems: Emerging Disease as Indicators of Change. Health of the Oceans from Labrador to Venezuela. Year of the Ocean Special Report. NOAA-OGP and NASA grant no NA56GP 0623. Boston, MA:Center for Health and the Global Environment, Harvard Medical School, 1998.
46. Harvell CD, Kim K, Burkholder JM, Colwell RR, Epstein PR, Grimes J, Hofmann EE, Lipp E, Osterhaus ADME, Overstreet R, et al. Emerging marine diseases: climate links and anthropogenic factors. Science 285:1505–1510 (1999).
47. Lagos N. Microalgal blooms: a global issue with negative impacts in Chile. Biol Res 31(4):375–386 (1998).
48. Pierce RH, Kirkpatrick GJ. Innovative techniques for harmful algal toxin analysis. Environ Toxicol Chem 20(1):107–114 (2001).
49. Chorus I, Bartram J, eds. Toxic Cyanobacteria in Water. A Guide to Their Public Health Consequences, Monitoring and Management. London:E & FN Spon/WHO, 1999.
50. Perovic S, Tretter L, Brummer F, Wetzler C, Brenner J, Donner G, Schroder HC, Muller ME. Dinoflagellates from marine algal blooms produce neurotoxic compounds. Environ Toxicol Pharmacol 8(2):83–94 (2000).
51. Asai S, Krzanowski JJ, Anderson WH. Effects of toxin of red tide, Ptychodiscus brevis, on canine tracheal smooth muscle: a possible new asthma-triggering mechanism. J Allergy Clin Immunol 69:418–428 (1982).
52. Grauer FH, Arnold HLJ. Seaweed dermatitis. Arch Dermatol 84:62–74 (1961).
53. Chong MW, Gu KD, Lam PK, Yang M, Fong WF. Study on the cytoxicity of microcystin-LR on cultured cells. Chemosphere 41(1–2):143–147 (2000).
54. Adler R. Here comes the rain. New Scientist 172(2322):11 (2001).
55. Epstein PR. Climate and health. Science 285:347–348 (1999).
56. Epstein PR, Diaz HF, Elias S, Grabherr G, Graham NE, Martens WJM, Mosley-Thompson E, Susskind EJ. Biological and physical signs of climate change: focus on mosquito-borne disease. Bull Am Meteorol Soc 78:409–417 (1998).
57. Rose JB, Daeschner S, Easterling DR, Curriero FC, Lele S, Patz JA. Climate and waterborne disease outbreaks. J Am Water Works Assoc 92(9):77–87 (2000).
58. Joyce S. The dead zones: oxygen starved coastal waters. Environ Health Perspect 108(3):A120–A125 (2000).
59. Curriero FC, Patz JA, Rose JB, Lele S. The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. Am J Public Health 91(8):1194–1199 (2001).
60. Harvey S, Greenwood JR, Pickett MJ, Mah RA. Recovery of Yersinia enterocolitica from streams and lakes of California. Appl Environ Microbiol 32(3):352–354 (1976).
61. Rose JB, Gerba CP, Jacobowski W. Survey of potable water supplies for Cryptosporidium and Giardia. Environ Sci Technol 25(8):1393–1400 (1991).
62. LeChevallier MW, Norton WD, Lee RG. Occurrence of Giardia and Cryptosporidium spp. in surface water supplies. Appl Environ Microbiol 57(9):2610–2616 (1991).
63. Hurst CJ. Presence of enteric viruses in freshwater and their removal by the conventional water treatment process. Bull World Health Org 69(1):113–119 (1991).
64. Ongerth JE. Giardia cysts concentrations in river water. J Am Water Works Assoc 81(9):81–86 (1989).
65. Thomas C, Gibson H, Hill DJ, Mabey M. Campylobacter epidemiology: an aquatic perspective. J Appl Microbiol Symp 85(suppl):168S–177S (1999).
66. Herwaldt BL, Craun GF, Stokes SL, Juranek DD. Waterborne disease outbreaks, 1989–90. Mor Mortal Wkly Rep Surveill Summ 40(suppl 3):1–22 (1991).
67. Moore AC, Herwaldt BL, Craun GF, Calderon RL, Highsmith AK, Juranek DD. Surveillance for waterborne disease outbreaks—1991–1992. Mor Mortal Wkly Rep Surveill Summ 42(suppl 5):1–22 (1993).
68. Kramer MH, Herwaldt BL, Craun GF, Calderon RL, Juranek DD. Waterborne disease: 1993 and 1994. J Am Water Works Assoc 88(3):66–80 (1996).
69. Levy DA, Bens MS, Craun GF, Calderon RL, Herwaldt BL. Surveillance for waterborne-disease outbreaks—United States, 1995–1996. Morbid Mortal Wkly Rep Surveill Summ 47(5):1–34 (1998).
70. Barwick RS, Levy DA, Craun GF, Beach MJ, Calderon RL. Surveillance for waterborne-disease outbreaks—United States, 1997–1998. Morbid Mortal Wkly Rep Surveill Summ 49(suppl 4):1–35 (2000).
71. Hancock CM, Rose JB, Callahan M. Crypto and Giardia in US groundwater. J Am Water Works Assoc 90(3):58–61 (1998).
72. Rollins DM, Colwell RR. Viable but non-culturable stage of C. jejuni and its role in survival in the aquatic environment. Appl Environ Microbiol 52:521–538 (1986).
73. Frost FJ, Craun GF, Calderon RL. Waterborne disease surveillance. J Am Water Works Assoc 88(9):66–75 (1996).
74. Goldstein ST, Juranek DD, Ravenholt O, Hightower AW, Martin DG, Mesnik JL, Griffiths SD, Bryan AJ, Reich RR, Herwaldt BL. Cryptosporidiosis: an outbreak associated with drinking water despite state-of-the-art water treatment. Ann Intern Med 124(5):459–468 (1996).
75. Cotte L, Rabodonirina M, Chapuis F, Bailly F, Bissuel F, Raynal C, Gelas P, Persat F, Piens M-A, Trepo C. Waterborne outbreak of intestinal microsporidiosis in persons with and without HIV infection. J Infect Dis 180:2003–2008 (1999).
76. Morris RD, Naumova EN, Levin R, Munasinghe RL.

Temporal variation in drinking water turbidity and physician diagnosed gastrointestinal infections in Milwaukee. Am J Public Health 86(2):237–239 (1996).

77. Morris RD, Levin R. Estimating the incidence of waterborne infectious disease related to drinking water in the United States. In: Assessing and Managing Health Risks from Drinking Water Contamination: Approaches and Applications (Reichard E, Zapponi G, eds). Wallingford, Oxfordshire, UK:IAHS Press, 1995;75–88.

78. U.S. EPA. Interim Enhanced Surface Water Treatment Rule. 63 FR 69477. Washington, DC:U.S Environmental Protection Agency, 16 December 1998.

79. Ford TE. Microbiological safety of drinking water: United States and global perspectives. Environ Health Perspect 107(suppl 1):191–206 (1999).

80. Schwartz J, Levin R, Hodge K. Drinking water turbidity and pediatric hospital use for gastrointestinal illness in Philadelphia. Epidemiology 8:615–620 (1997).

81. Schwartz J, Levin R, Goldstein R. Drinking water turbidity and gastrointestinal illness in Philadelphia's elderly. J Epidemiol Commun Health 54:45–51 (2000).

82. Payment P, Richardson L, Semiatycki J, Dewar R, Edwardes M, Franco E. A randomized trial to evaluate the risk of gastrointestinal disease due to the consumption of drinking water meeting current microbiological standards. Am J Public Health 81:703–708 (1991).

83. Aramini J, McLean M, Wilson J, Holt J, Copes R, Allen B, Sears A. Drinking Water Quality and Health Care Utilization for Gastrointestinal Illness in Greater Vancouver. Guelph, Ontario, Canada:Health Canada, 2000.

84. Federal Register 63:69478 (1998).

85. Morris RD, Ardet A, Angelillo IF, Chalmers TC, Mosteller F. Chloramination, chlorination by-products and cancer: a meta-analysis. Am J Public Health 82:955–963 (1992).

86. Bove FJ, Fulcomer MC, Klotz JB, Esmart J, Dufficy EM, Savrin JE. Public drinking water contamination and birth outcomes. Am J Epidemiol 141(9):850–862 (1995).

87. Swan SH, Waller K, Hopkins B, Windham G, Fenster L, Schaefer C, Neutra RR. A prospective study of spontaneous abortion: relation to amount and source of drinking water in early pregnancy. Epidemiology 9:126–133 (1998).

88. Waller K, Swan SH, DeLorenze G, Hopkins B. Trihalomethanes in drinking water and spontaneous abortion. Epidemiology 9:134–140 (1998).

89. Havelaar AH, De Hollander AE, Teunis PF, Evers EG, Van Kranen HJ, Versteegh JF, Van Koten JE, Slob W. Balancing the risks and benefits of drinking water disinfection: disability adjusted life-years on the scale. Environ Health Perspect 108(4):315–321 (2000).

90. U.S. EPA. Comparative Risk Framework Methodology and Case Study. Cincinnati, OH:U.S. Environmental Protection Agency, National Center for Exposure Assessment, 9 November 1998.

91. Wolman A. Water, Health and Society. Bloomington, IN:Indiana University Press, 1969.

92. Solo-Gabriele H, Neumeister S. US outbreaks of cryptosporidiosis. J Am Water Works Assoc 88(9):76–86 (1996).

93. Craun GF, Berger PS, Calderon RL. Coliform bacteria and waterborne disease outbreaks. J Am Water Works Assoc 89(3):96–104 (1997).

94. Craun GF, Hubbs SA, Frost F, Calderon RL, Via SH. Waterborne outbreaks of cryptosporidiosis. J Am Water Works Assoc 90(9):81–91 (1998).

95. Allen MJ, Clancy JL, Rice EW. The plain, hard truth about pathogen monitoring. J Am Water Works Assoc 92(9):64–76 (2000).

96. U.S. EPA. Method 1623: *Cryptosporidium* and *Giardia* in water by filtration/IMS/FA. EPA-821-R-99-006. Washington, DC:U.S. Environmental Protection Agency, April 1999.

97. Jothikumar N, Cliver DO, Mariam TW. Immunomagnetic capture PCR for the rapid concentration and detection of hepatitis A virus from environmental samples. Appl Environ Microbiol 64:504–508 (1998).

98. Kaucner C, Stinear T. Sensitive and rapid detection of viable *Giardia* cysts and *Cryptosporidium parvum* oocysts in large-volume water samples with wound fiberglass cartridge filters and reverse transcription-PCR. Appl Environ Microbiol 64:1743–1749 (1998).

99. Rochelle PA, Ferguson DM, Handojo TJ, De Leon R, Stewart MH, Wolfe RL. An assay combining cell culture with reverse transcriptase PCR to detect and determine the infectivity of waterborne *Cryptosporidium parvum*. Appl Environ Microbiol 63:2029–2037 (1997).

100. Colwell RR. Global climate and infectious disease: the cholera paradigm. Science 274:2025–2031 (1996).

101. Wilson ME, Levins R, Spielman A, eds. Disease in Evolution: Global Changes and Emergence of Infectious Diseases. Ann N Y Acad Sci 740:503pp (1994).

102. Levins R, Auerbach T, Brinkman U, Eckhardt I, Epstein PR, Ford T, Makhoul N, dePossas C, Puccia C, Spielman A, et al. The emergence of new disease. Am Sci 82(1):52–60 (1994).

103. Gerba CP, Rose JB, Haas CN. Sensitive populations: who is at greatest risk? Int J Food Microbiol 30:113–123 (1996).

104. Morse SS. Factors in the emergence of infectious diseases. Emerg Infect Dis 1:7–15 (1995).

105. Pimentel D, Tort M, D'Anna L, Krawic A, Berger J, Rossman J, Mugo F, Doon N, Shriberg M, Howard E, et al. Ecology of increasing disease: population growth and environmental degradation. BioScience 48(10):817–826 (1998).

106. Gaudreau C, Gilbert H. Antimicrobial resistance of clinical strains of *Campylobacter jejuni* subsp. *jejuni* isolated from 1985 to 1997 in Quebec, Canada. Antimicrob Agents Chemother 42:2106–2108 (1998).

107. Weber JT, Mintz ED, Canizares R, Semiglia A, Gomez I, Sepertegui R, Davila A, Greene KD, Puhr ND, Cameron DN, et al. Epidemic cholera in Ecuador: multidrug-resistance and transmission by water and seafood. Epidemiol Infect 112:1–11 (1994).

108. Legros D, Ochola D, Lwanga N, Guma G. Antibiotic sensitivity of endemic *Shigella* in Mbarara, Uganda. East Afr Med J 75:160–161 (1998).

109. Khalil K, Khan SR, Mazhar K, Kaijser B, Lindblom GB. Occurrence and susceptibility to antibiotics of *Shigella* species in stool of hospitalized children with bloody diarrhea in Pakistan. Am J Trop Med Hyg 58:800–803 (1998).

110. Hignite C, Azarnoff DL. Drugs and drug metabolites as environmental contaminants: chlorophenoxyisobutyrate and salicyclic acid in sewage water effluent. Life Sci 20(2):337–341 (1997).

111. Halling-Sorenson B, Nielsen SN, Lanzky PF, Ingerslev F, Holten Lutzhoft HC, Jorgenson SE. Occurrence, fate and effects of pharmaceutical substances in the environment—a review. Chemosphere 36(2):357–393 (1998).

112. Daughton CG, Ternes TA. Pharmaceuticals and personal care products in the environment: agents of subtle change? Environ Health Perspect 107(suppl 6):807–938 (1999).

113. Levy SB. Multidrug resistance—a sign of the times. N Engl J Med 338:1376–1378 (1998).

114. Lisle JT, Rose JB. Gene exchange in drinking water and biofilms by natural transformation. Water Sci Technol 31:41–46 (1995).

115. Doolittle MM, Cooney JJ, Caldwell DE. Tracing the interaction of bacteriophage with bacterial biofilms using fluorescent and chromogenic probes. J Ind Microbiol 16:331–341 (1996).

116. Okun DA. From cholera to cancer to cryptosporidiosis. J Environ Eng 122(6):453–458 (1996).

117. U.S. EPA. SAB Report: Safe Drinking Water (Future Trends and Challenges). EPA-SAB-DWC-95-002. Washington, DC:U.S. Environmental Protection Agency, 1995.

118. Clean Water Action Plan. U.S. Departments of Agriculture, Commerce, Defense, Energy, Interior, Energy, Justice, and Transportation, Environmental Protection Agency, Tennessee Valley Authority. Washington, DC:Government Printing Office, 1998.

119. U.S. Geological Survey. The Quality of Our Nation's Waters—Nutrients and Pesticides. Washington, DC:U.S. Geological Survey, 1999.

120. Heal G. Nature and the Marketplace. Washington, DC:Island Press, 2000.

121. U.S. National Research Council. Watershed Management for Potable Water Supply. Committee to Review the New York City Watershed Management Strategy, Water Science and Technology Board, National Research Council. Washington, DC:National Academy Press, 2000.

122. U.S. National Research Council. Committee to Evaluate the Viability of Augmenting Potable Water Supplies with Reclaimed Water. Washington, DC:National Academy Press, 1998.

123. Braedehoeft JD, Papadopulos SS, Cooper HH. Groundwater—the water budget myth. In: Scientific Basis of Water Resource Management. Washington, DC:National Academy Press, 1982;51–57.

124. Loague K, Corwin DL, Ellsworth TR. The challenge of predicting nonpoint source pollution. Environ Sci Technol 32(5):130A–133A (1998).

125. Gilliom RJ, Barbash JE, Kolpin DW, Larson SJ. Testing water quality for pesticide pollution. Environ Sci Technol 33(7):164A–169A (1999).

126. Welch AH, Westjohn DB, Helsel DR, Wanty RB. Arsenic in ground water of the United States: occurrence and geochemistry. Ground Water 38(4):589–604 (2000).

127. Betts, K. Growing concern about disinfection byproducts. Environ Sci Technol 32(23):546A–548A (1998).

128. Winter TC, Harvey JC, Franke OL, Alley WM. Ground water and surface water: a single resource. U.S. Geol Surv Circ 1139:79pp (1998).

129. National Research Council. Valuing Ground Water: Economic Concepts and Approaches. Washington, DC:National Academy Press, 1997.

130. Pinholster G. Drinking recycled water. Environ Sci Technol 29(4):174A–179A (1995).

131. Sloss EM, Geschwind SA, McCaffrey DF, Ritz BR. Groundwater Recharge with Reclaimed Water: An Epidemiologic Assessment in Los Angeles County, 1987–1991. Santa Monica, CA:Rand Corporation, 1996.

132. Vaccaro J. Sensitivity of groundwater recharge estimates to climate variability and change, Columbia Plateau, Washington. J Geophys Res 101:7163–7174 (1992).

133. Rosenberg NJ, Epstein DJ, Want D, Vail L, Srinivasan R, Arnold JG. Possible impacts of global warming on the hydrology of the Ogalla Aquifer. Clim Change 42:677–692 (1999).

134. U.S. EPA. Liquid Assets 2000: America's Water Resources at a Turning Point. EPA 840-B-00-001. Washington, DC:U.S. Environmental Protection Agency, 2000.

135. U.S. EPA. National Water Quality Inventory, 1996 Report to Congress. Washington, DC:U.S. Environmental Protection Agency. Available: *http://www.epa.gov/305b/96index.html*

136. U.S. EPA. National Water Quality Inventory: 1998 Report to Congress. EPA 841-S-00-001. Washington, DC:U.S. Environmental Protection Agency, 2000.

137. Paerl HW. Nuisance phytoplankton blooms in coastal, estuarine and inland waters. Limnol Oceanogr 33(4, pt 2):823–847 (1988).

138. Carmichael WW. A Status Report on Planktonic Cyanobacteria (Blue-Green Algae) and Their Toxins. EPA/60/R-92/079. Washington, DC:U.S. Environmental Protection Agency, 1992.

139. U.S. Treasury Department. Public Health Report. 29:2959–2966 (1914).

140. U.S. PHS. Drinking Water Standards. U.S. Public Health Service Pub. No. 956. Washington DC:U.S. Public Health Service, 1962.

141. House Committee on Interstate and Foreign Commerce. "Safe Drinking Water Act." Report No. 93-1185, 93rd Congress, Second Session, 10 July 1974.

142. Larson C. Historical development of the national primary drinking water regulations. In: Safe Drinking Water Act: Amendments, Regulations and Standards (Calabrese EJ, Gilbert CE, Pastides H, eds). Chelsea, MI:Lewis Publishers, 1989;3–16.

143. MacKenzie WR, Hoxie NJ, Proctor ME, Gradus MS, Blair KA, Peterson DE, Kazmierczak JJ, Addiss DG, Fox KR, Rose JB, et al. A massive outbreak in Milwaukee of *Cryptosporidium* infection transmitted through the public water supply. N Engl J Med 331:161–167 (1994).

144. The U.S. EPA established a more stringent arsenic standard in January 2001 but has since withdrawn and announced its intention to revisit the new standard.

145. Gostin LO, Lazzarini Z, Neslund VS, Oarweholm MT. Water quality laws and waterborne diseases: *Cryptosporidium* and other emerging pathogens. Am J Public Health 90(6):847–853 (2000).

146. U.S. EPA Microbial and Disinfection By-product Advisory Committee. Agreement in Principle. Washington, DC:U.S. Environmental Protection Agency, 2000.

147. Cohen BA, Olson ED. Victorian Water Treatment Enters the 21st Century. Washington, DC:Natural Resources Defense Council, 1994.

148. U.S. EPA. National Public Water System Annual Compliance Report and Update on Implementation of the 1996 Safe Drinking Water Act Amendments. Washington DC:U.S. Environmental Protection Agency, 1997. Available: *http://www.epa.gov/safewater/annual*

149. U.S. EPA. Providing Safe Drinking Water in America: 1998 National Public Water Systems Compliance Report. Washington, DC:U.S. Environmental Protection Agency, 2000. Available: *http://www.epa.gov/safewater/annual*

150. Solley WB, Pierce RR, Perlman HA. US Water Use. U.S. Geol Surv Circ 1200:22 (1998).