Risk of Waterborne Illness Via Drinking Water in the United States

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I. Introduction

The quality of drinking water in the United States is among the best in the world; however, waterborne disease outbreaks continue to occur, and many more cases of endemic illness are estimated. Documented waterborne disease outbreaks are primarily the result of technological failures or failure to treat the water (Craun et al. 2006). Current federal regulations require that all surface waters used for a drinking water supply be treated to reduce the level of pathogens so as to reduce the risk of infection to 1:10,000 per year (Regli et al. 1991). To achieve this goal, water treatment must, at a minimum, reduce infectious viruses by 99.99% and protozoan parasites by 99.9% (Regli et al. 2003). If *Cryptosporidium* concentrations exceed a certain level in the source water, additional reductions are required. This degree of treatment is usually achieved by a combination of physical processes (coagulation, sedimentation, and filtration) and disinfection (chlorination, ozonation). Filtration is essential for the removal of protozoan parasites due to their resistance to chlorination and ozonation at doses normally used in drinking water treatment (Barbeau et al. 2000; Korich et al. 1990; Rennecker et al. 1999). A variance from filtration is allowed in some cases if the watershed is protected and carefully monitored for protozoan pathogens.

Before finalization of the U.S. Environmental Protection Agency (USEPA) Ground Water Rule in November 2006, disinfection was not required for drinking water from groundwater sources if coliform bacteria were not detected, as long as the source water was not directly under the influence of surface water. The Groundwater Rule, however, requires all municipal groundwater sources to be disinfected, unless they meet certain monitoring and sanitary survey requirements by December 1, 2009 (USEPA 2006a).

Despite the increase in source water treatment requirements in the U.S., with current and newly promulgated regulations, questions remain as to how much illness is caused by microorganisms in drinking water in the U.S. and what additional approaches may be used to further reduce this risk, especially to sensitive subpopulations who may be at greater risk of infection and more serious adverse health outcomes. The objective of this review is to assess current threats to the water supply in the U.S., provide estimates of total drinking water illness, and suggest approaches for risk reduction.

II. Population Impacts of Waterborne Pathogens

A pathogen is a microorganism capable of causing disease in a host. Relative to the microbial population on earth, only a small number are capable of causing disease in humans. Waterborne pathogens are excreted in the feces of humans and transmitted via ingestion. In contrast, water-based pathogens occur naturally in water and are usually not transmitted from person to person (e.g., *Legionella* spp.). This review primarily deals with

waterborne pathogens. Currently, more than 140 known microorganisms are recognized as waterborne pathogens.

Waterborne pathogens have emerged in importance for a number of reasons, including (1) an increase in the size of sensitive subpopulations; (2) recognition of the importance of additional health effects, including chronic sequelae; (3) an increase in the importation of foods from developing countries, where poor water quality plays a role in foodborne illness; (4) natural evolution of microbes with increased virulence; and (5) the use of molecular source tracking to improve methods for identification of outbreaks and their sources.

In recent decades there has been a steady growth in the number of sensitive populations, now thought to comprise 20%–25% of the total U.S. population. Sensitive populations include the elderly, the very young, the chronically ill, recipients of immunosuppressive therapies, and pregnant women (Table 1). Studies show that these subpopulations are more likely to be infected and experience increased morbidity and mortality following exposure to microbial pathogens than the general population (Gerba et al. 1996a; Nwachuku and Gerba 2006). Total diarrheal deaths in aged populations (>74 yr) are about 50% compared to less than 5% in those between the ages of 5 and 24 (Lew et al. 1991). Adenovirus infections have proved problematic for immunocompromised populations, in which a 60% and 53% case-fatality rate is prevalent in bone marrow transplant and cancer patients, respectively (Table 2). In addition, *Cryptosporidium* is identified in 2.2% of all diarrhea cases in developed countries compared to a 7% rate in children and 14% (range, of 6%–70%) in acquired immunodeficiency syndrome (AIDS) patients (Chen et al. 2002).

Table 1. Sensitive Subpopulations in the United States.

Number	Population
35,061,000	Persons >65[a]
20,186,469	Children <5[b]
18,200,000	Persons with diabetes[c]
15,000,000	Cancer patients[d]
6,000,000	Pregnant women[e]
1,039,000	AIDS patients[f]
123,120[h]	Organ transplants[g]

[a]Velkoff and DeBarros (2005).
[b]US Census Bureau (2005).
[c]CDC (2005).
[d]Jemal et al. (2005).
[e]American Pregnancy Association (2006).
[f]Glynn and Rhodes (2005).
[g]US Department of Health and Human Services (2005).
[h]Five-year total recipients, 2000–2004.

Table 2. Case-fatality Rates among Immunocompromised Patients with Adenovirus Infection.

Patient group	Overall % fatality	Mean age of patients (yrs)
Bone marrow transplant	60	15.6
Liver transplant	53	2.0
Renal transplant	18	35.6
Cancer patients	53	25.0
AIDS patients	45	31.1

Source: Modified from Hierholzer (1992).

Although diarrhea is the major symptom associated with waterborne pathogens, other chronic sequelae are possible (Parkin 2000). Chronic sequelae are diseases that develop in the days, weeks, or years after initial infection. Chronic sequelae, such as diabetes, heart disease, autoimmune disease, and cancer, can have a significant impact on the individual's quality of life and are sometimes related to infectious disease agents. In addition, exposure to some pathogens can lead to adverse effects on the endocrine system (i.e., *Giardia lamblia* is linked to hypothyroidism and coxsackievirus is linked to orchitis) (Lindsay 1997).

Globalization of commerce and travel contributes to the spread of waterborne disease, as does the introduction of change in drinking water treatment technology or food supply production. For example, efforts to address concerns over protozoan contamination of water and chlorine resistance have led to an increase in the use of ultraviolet light for compliance with water quality standards. An increased reliance on UV light treatment has subsequently raised concern over virus resistance, in particular, adenovirus (Nwachuku et al. 2005; Thurston-Enriquez et al. 2003). Therefore, changes in current applications must be carefully evaluated. Expansion of our food supply sources to include regions with deteriorated irrigation water quality and poor hygiene has been linked to foodborne outbreaks where water played a role in the transmission of disease. An example of this is the protozoan parasite *Cyclospora caryentensis*, which was imported into the U.S. on produce from developing countries (Mansfield and Gajadhar 2004).

Microbes are highly adaptable to environmental pressures and continue to evolve. The evolution of microbes can lead to a genetic reassortment that may increase the virulence of, or expand the host base for, that organism. A recent example of this is the severe acute respiratory syndrome (SARS) virus, which moves from the bat population to other animals and humans (Bennett 2006). The development of molecular methods for pathogen detection and source tracking has aided in the monitoring of water supplies and identifying causative agents in outbreak situations. Cultural methods are often necessary for the determination of pathogen viability in water, but for some of the most

prevalent pathogenic microbes, laboratory methods for cultural detection have not been developed or standardized (i.e., noroviruses).

III. Agents of Waterborne Disease

Pathogens capable of causing waterborne or water-based illnesses include viruses, bacteria, and protozoa (Table 3). Also of concern in some geographical regions are helminths and blue-green algae. Since 1971, the

Table 3. Agents of Waterborne or Water-based Disease.

| Category	Pathogen
Bacteria	*Vibrio cholerae*
	Salmonella spp.
	Shigella spp.
	Toxigenic *Escherichia coli*
	Campylobacter spp.
	Yersinia enterocolitica
	Plesiomonas shigelloides
	Legionella
	Helicobacter pylori
Protozoa	*Giardia lamblia*
	Cryptosporidium parvum
	Entamoeba histolitica
	Cyclospora cayetanensis
	Isospora belli
	Microsporidia
	Ballantidium coli
	Toxoplasma gondii
	Naegleria fowleri
Viruses	Norovirus
	Sapprovirus
	Poliovirus
	Coxsackievirus
	Echovirus
	Paraechovirus
	Enteroviruses 69-91
	Reovirus
	Adenovirus
	Hepatitis A
	Hepatitis E
	Rotavirus
	Astrovirus
	Picobirnavirus
	Coronavirus
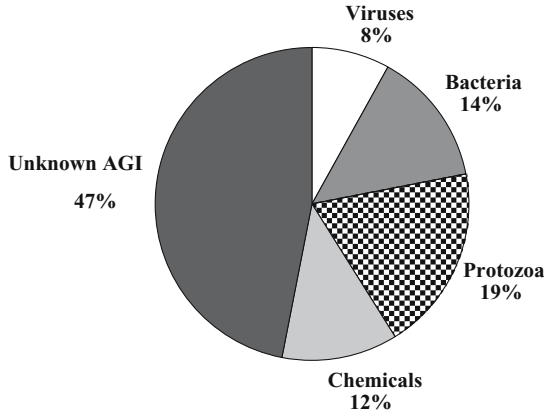
Fig. 1. Drinking water outbreaks by etiological agent, 1971–2002 ($n = 764$). AGI, acute gastrointestinal illness. (From Blackburn et al. 2004; Calderon 2004.)

Centers for Disease Control (CDC), USEPA, and other agencies have been collecting data regarding waterborne disease outbreaks in the U.S. From 1971 to 2002 there have been 764 documented waterborne outbreaks associated with drinking water, with 12% caused by chemicals, 14% by bacteria, 19% by protozoa, and 8% by viral pathogens (Fig. 1). Nearly half of all documented waterborne outbreaks since 1971 were caused by an undetermined etiology, i.e., acute gastrointestinal illness (AGI). The characteristics of these outbreaks of unknown AGI are often consistent with a viral etiology, some of which are known to be nonculturable. Outbreaks during 1971–2002 are known to have resulted in 575,457 cases of illness and 79 deaths; however, the true impact of waterborne disease is estimated to be much higher. For example, Morris and Levin (1995) estimate that 7 million people become ill and more than 1,000 die each year as a result waterborne microbial infections.

A. Viruses

Viruses range from 0.01 to 0.1 μm in size, are obligate, intracellular parasites, and are capable of long-term survival in the water environment (weeks to months). Viruses of greatest concern in water, and their associative illnesses, include enteroviruses (diarrhea, meningitis, myocarditis, fever, respiratory disease, nervous system disorders, birth defects), hepatitis A virus (hepatitis, liver damage), noroviruses (diarrhea), astrovirus (diarrhea), adenovirus (diarrhea, respiratory disease, eye infections, heart disease), and rotavirus (diarrhea).

Viruses have the greatest infectivity, requiring the fewest number to cause infection, of all waterborne microorganisms, are excreted in the feces

in the largest numbers (up to 10^{11}/g), and generally have the longest survival in the environment; most only infect humans. They are not efficiently removed by conventional filtration and are more resistant to disinfectants than bacteria. Because of their small size and ease of transport in the subsurface, viruses are of primary concern in groundwater. Viruses are known to be the causative agent in 8% of drinking water outbreaks reported in recent years (Fig. 2).

B. Bacteria

Bacteria are prokaryotic, single-celled organisms surrounded by a membrane and cell wall, ranging in size from 0.1 to 10 µm. Enteric bacteria are able to colonize the human intestinal and gastrointestinal tract. Generally, enteric bacteria do not survive long in the environment, although some have resistant spores or can form dormant stages that aid in their survival. Waterborne outbreaks caused by enteric bacteria primarily occur because of failed or absent treatment processes. Examples of waterborne enteric bacteria include *Salmonella* (typhoid, diarrhea), *Shigella* (diarrhea), *Campylobacter* (diarrhea, nervous system disorders), *Vibrio cholerae* (diarrhea), and *Escherichia coli* (certain strains: diarrhea, hemorrhagic colitis). *Legionella* (pneumonia, respiratory infections) is an important water-based bacteria, and reports of *Legionella* outbreaks have only recently been added to the CDC surveillance summaries; however, six water-associated outbreaks were recorded in 2001–2002 (Blackburn et al. 2004). Non-*Legionella* bacteria are known to have caused 17% of the waterborne outbreaks documented from 1991 to 2002 (see Fig. 2).
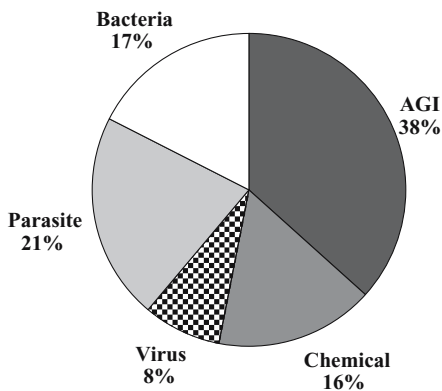

Fig. 2. Waterborne outbreaks associated with drinking water by etiological agent, 1991–2002 (*n* = 183). AGI, acute gastrointestinal illness. (From Barwick et al. 2000; Blackburn et al. 2004; CDC 1993; Kramer et al. 1996; Lee et al. 2002; Levy et al. 1998.)

Helicobacter pylori is a bacterium that has recently been recognized as the primary cause of duodenal (90%) and gastric ulcers (80%) (CDC 2001). It is considered a class A carcinogen, meaning that infections can lead to gastric cancer, the second most common cancer worldwide. Although the disease contribution related to the waterborne route of exposure is uncertain, studies have found 10%–60% of individual groundwater wells contaminated with *H. pylori* (Park et al. 2001).

C. Protozoa

Protozoan parasites are single-celled animals that live in the gastrointestinal tract of infected individuals. They range in size from 1 to 100 μm and produce an environmentally stable cyst or oocyst stage. The thick cyst or oocyst walls are highly resistant to disinfectants used in conventional water treatment. *Crytosporidium* and *Giardia lamblia*, both causing diarrhea, are the primary protozoa of concern with regard to water quality in the U.S. *Cyclospora caryentensis* is another parasite that has been linked to a possible waterborne outbreak in the U.S. (Mansfield and Gajadhar 2004). *Naegleria fowleri* is a water-based pathogen of primary concern because of a high fatality rate in diagnosed cases. Two deaths occurred in an outbreak of *Naegleria* in 2002 (Blackburn et al. 2004). Overall, protozoa caused 21% of drinking water outbreaks from 1991 to 2002 (see Fig. 2).

IV. Drinking Water Outbreaks

During the most recent 12-yr survey of waterborne disease (1991–2002), there were 183 documented outbreaks associated with drinking water. Most (76%) were from a groundwater source, with 18% linked to surface water systems (Fig. 3).

Public noncommunity systems, including nontransient noncommunity water systems (NTNCWS) serving water to at least 25 of the same people at least 6 mon/yr, but not year round (i.e., schools, hospitals, and offices with their own water systems), and transient noncommunity water systems (TNCWS), serving persons who do not remain for long time periods (i.e., campgrounds, gas stations, etc.), collectively caused 39% of drinking water-associated outbreaks from 1991 to 2002, followed by public community water systems (CWS) serving the same population year round (36%) and individual systems (25%) (Fig. 4). Approximately 264 million people in the U.S. are served by a CWS, with 19.8 million served by a noncommunity water source (12.9 million by a TNCWS and 6.9 million by a NTNCWS) in the U.S.

Although a drinking water outbreak was more likely to occur in a noncommunity supply utilizing a groundwater source, outbreaks involving the greatest number of individuals exposed occurred in CWS from a surface water source (Table 4).

Fig. 3. Documented disease outbreaks associated with drinking water by source, 1991–2002 (*n* = 183). (From Barwick et al. 2000; Blackburn et al. 2004; CDC 1993; Kramer et al. 1996; Lee et al. 2002; Levy et al. 1998.)
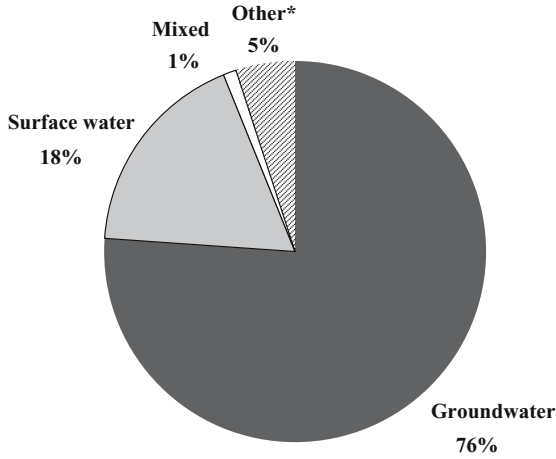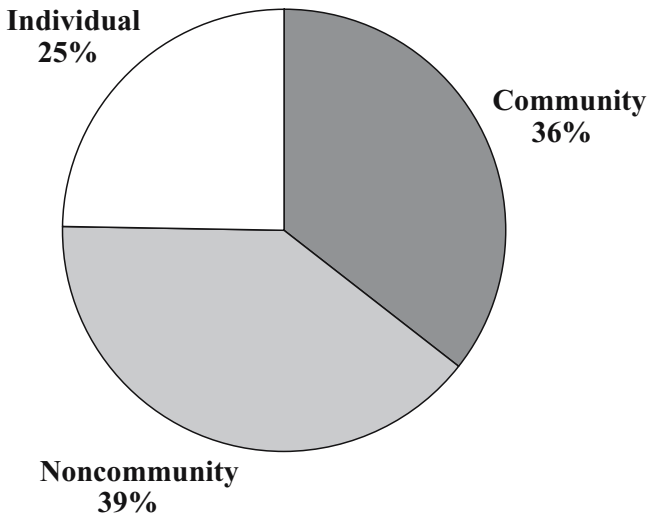

Fig. 4. Documented disease outbreaks associated with drinking water by system type, 1991–2002 (*n* = 183). (From Barwick et al. 2000; Blackburn et al. 2004; CDC 1993; Kramer et al. 1996; Lee et al. 2002; Levy et al. 1998.)

Table 4. Illness Cases Associated with Drinking Water Outbreaks, 1991–2002.

Source type	Illness cases			
	Community	Individual	Noncommunity	Total
Groundwater	3,967	364	9,468	**13,817**
Surface water	415,420	65	304	**415,789**
Mixed	3,013	0	0	**3,013**
Other	0	288	0	**288**
Total	**422,400**	**717**	**9,790**	**432,907**

Source: Barwick et al. (2000); Blackburn et al. (2004); CDC (1993); Kramer et al. (1996); Lee et al. (2002); Levy et al. (1998).

In the most recently published survey period (2001–2002), 23 of 25 (92%) outbreaks associated with drinking water were from a groundwater source, and 9 (39%) of these were associated with individual homeowner systems not regulated by the USEPA (Blackburn et al. 2004).

V. Sources of Microbial Contamination

Regarding pathogen exposure, contamination is not evenly distributed but rather affected by the number of pathogens in the source water, the age of the distribution system, the quality of the delivered water, and climatic events that can tax the treatment plant operations. Because it is not practical to monitor water supplies in real time and at the point-of-use for all groups of pathogens, episodic contamination events are difficult to predict or identify. From 1991 to 2002, the majority of outbreaks occurred because of a lack of treatment (primarily groundwater) or a treatment failure (Fig. 5). Efforts to control microbial contamination in drinking water are focused at four primary sites: (1) the source water, (2) treatment plant, (3) distribution system, and (4) point-of-use. Source water protection is the first step in control of the water quality.

A. Source Water

All surface waters, no matter how pristine, contain waterborne pathogens, because most of the significant waterborne pathogens are zoonoses, meaning they can be transmitted to humans from animals. Birds are a significant source of *Campylobacter*, as cattle are of *Cryptosporidium*. The more animal husbandry taking place near a watershed, the greater the concentration of zoonotic waterborne agents that can be expected in the water (Cox et al. 2005). Sewage discharges can also be a source of pathogens, even though they may be disinfected. Although chlorination is effective in reducing
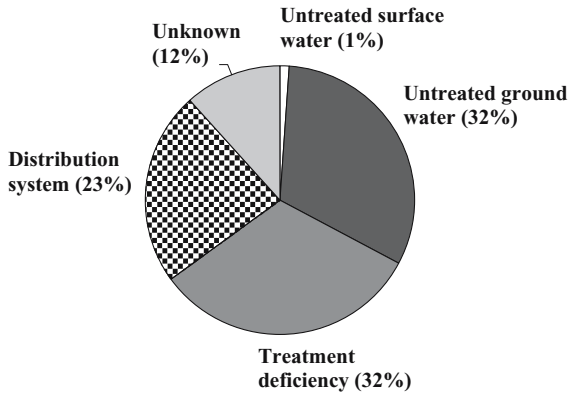
Fig. 5. Documented disease outbreaks associated with drinking water by deficiency, 1991–2002 ($n = 183$). (From Barwick et al. 2000; Blackburn et al. 2004; CDC 1993; Kramer et al. 1996; Lee et al. 2002; Levy et al. 1998.)

the number of bacterial pathogens, it has little effect on protozoan parasites and limited effectiveness on viral pathogens, as normally practiced (Fallacara et al. 2004). *Giardia* is more abundant in sewage discharges than *Cryptosporidium* (Smith and Grimason 2003). With the exception of hepatitis E virus, enteric viruses are not zoonotic and only originate from sewage sources, i.e., sewage treatment plants, combined sewer overflows, and septic tanks.

The occurrence of enteric pathogens in surface waters is highly variable, depending heavily on rainfall events. The elevated concentrations of pathogens after such events can pose a major challenge to water treatment plants. Extreme rainfall events and waterborne disease outbreaks from drinking water have been positively correlated in both the U.S. and Canada (Curriero et al. 2001; Thomas et al. 2006).

In contrast to surface waters, groundwater supplies were historically thought to be free of pathogenic microbes for reasons of the natural filtering ability of the subsurface environment and distance a microbe would have to travel to reach the groundwater source. Microbial contaminants that find their way into groundwater may originate as a result of lack of wastewater treatment or improper management of wastewater disposal, septic tank contamination, underground storage tank or landfill leaks, mismanagement of animal waste disposal, shallow wells, etc. Improved surveillance using molecular and cultural detection methods has led to increased evidence of human enteric viruses and other potentially harmful microbes in groundwater. Private groundwater wells are a concern because they are rarely, if ever, monitored and treated.

Table 5. Frequency and Duration of Pathogen Contamination Events in a Surface Drinking Water System.

Type of incident	Frequency[a]	Duration (hr/incident)
Suboptimal treatment:		
Wrong coagulant dosage	6	0.6
Filter operation	60	5
Chlorination failure	2	0.4
Pipe contamination:		
Cross-connection	0.00016	3 d
Main line	0.021	14 d

[a]Per 1,000,000 persons/y.
Source: Westrell et al. (2003).

B. Treatment

Much attention has been focused on enhancing current treatment processes to eliminate pathogens that are resistant to conventional water treatment, i.e., filtration for *Cryptosporidium*, and to expand treatment recommendations to source waters that were previously considered protected from harmful microbes, i.e., protected surface waters and groundwater. Populations are still at risk of pathogen exposure partly because of lack of treatment, i.e., no filtration of large municipal water supplies, such as New York and Boston, and currently no disinfection of municipal groundwater supplies. In addition, individual homeowners with private wells are at risk where contamination events would go largely unnoticed due to a lack of monitoring and reporting.

Even in the event of administering multibarrier treatment processes, it is not possible to remove 100% of the pathogens from the source water 100% of the time (Haas and Trussell 1998). Table 5 shows the documented frequency of various contamination events in a surface drinking water treatment system in Sweden, including treatment failures and distribution system contamination. Quantitative microbial risk assessment suggests that, depending on the original raw water quality, such events could cause serious health consequences (Westrell et al. 2003).

C. Distribution System

Even water that is adequately protected and treated is subject to pathogens entering the distribution system. From 1971 to 2002 there were 133 (17% of all outbreaks) documented waterborne outbreaks in the U.S. linked to distribution system contamination (Barwick et al. 2000; Blackburn et al. 2004; CDC 1993; Kramer et al. 1996; Lee et al. 2002; Levy et al. 1998). Preliminary data from the 2003–2004 survey period indicate that 38% of the

reported outbreaks associated with drinking water systems were also associated with distribution systems (NRC 2006; Liang et al. 2006).

Municipal Distribution Systems

During the most recently published survey period (2001–2002), 5 of 25 (20%) of the documented waterborne outbreaks were associated with drinking water distribution system deficiencies and, of the 7 outbreaks reported involving community water systems, 4 (57.1%) were linked to distribution system problems (Blackburn et al. 2004). Although the overall number of reported outbreaks associated with community water systems has decreased in the last decade, the proportion of outbreaks associated with distribution systems has increased (Fig. 6). The reduction in total waterborne outbreaks is largely attributed to the promulgation of numerous regulations by the USEPA, including the surface water treatment rule, primarily aimed at reducing the risks of waterborne protozoa and improving water treatment (Pierson et al. 2001; Blackburn et al. 2004), but the current regulatory requirements do not appear to reduce the proportion of outbreaks associated with distribution systems.

The distribution system includes both the pumping, piping, and storage networks that deliver finished water to end users. There are approximately 1 million miles of distribution system networks in the U.S. and an estimated
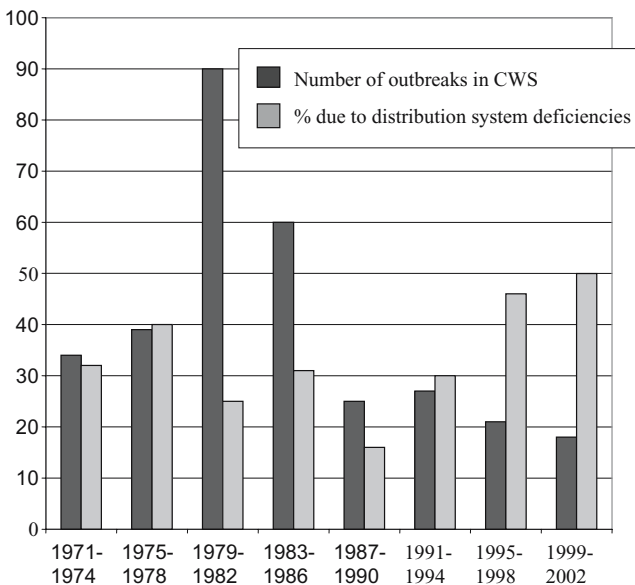

Fig. 6. Waterborne disease outbreaks in community water systems (CWS) associated with distribution system deficiencies. (Modified from NRC 2006.)

154,000 finished water storage facilities, with more than 13,000 miles of new pipes installed each year (AWWA 2003; Grigg 2005; Kirmeyer et al. 1994). In a 2005 report on the nation's infrastructure, the USEPA acknowledged the need for significant investment in installing, upgrading, or replacing infrastructure for delivering and storing drinking water at an estimated 20-yr cost of $208.4 billion (USEPA 2001, 2004). In the U.S. there is a wide range of distribution pipe age and materials with varying life expectancies. Pipes in the U.S. are replaced at an average rate of once every 200 yr (Grigg 2005); however, the life expectancies range from 75 to 120 yr (AWWA 2001; AWWSC 2002). Approximately 26% of the distribution pipes in the U.S. are in poor condition, and the annual number of documented main breaks has significantly increased from about 250 in 1970 to 2,200 in 1989 (AWWSC 2002). It is estimated that even well-run water distribution systems experience about 25–30 breaks per 100 miles of piping/yr (Deb et al. 1995). Using a value of 27 main breaks/100 miles/yr, Kirmeyer et al. (1994) estimated 237,000 main breaks/yr in the U.S.; however, variation between utilities is considerable. Haas (1999) reported results from a survey of water systems that showed a range of average main breaks of 488/yr for systems serving more than 500,000 people, to 1.33/yr for systems serving fewer than 500 people. The public health significance of these breaks in the distribution system is not currently known.

Maintaining the hydraulic integrity (positive pressure) of water distribution is important given that insufficient pressure has led to disease epidemics worldwide (reviewed in Lee and Schwab 2005). Negative hydraulic pressure creates a backflow of nonpotable water into the potable water supply via back-siphonage, where significant pressure drops siphon contaminants into the system at cross-connections or leakage points, or back-pressure from pressures in the system that exceed the supply pressure (Herrick 1997). Even minor pressure fluctuations create back-siphonage where intrusion rates are estimated at >1 gpm (LeChevallier et al. 2003a). During power outages, up to 90% of nodes have been shown to draw a negative pressure (LeChevallier et al. 2003b).

A survey of 26 water utilities in the U.S. found that the percent of leakage (unaccounted-for water) ranged from <10% to as high as 32% (Kirmeyer et al. 2001). Water systems commonly lose >10% of the total water produced through leaks in the pipelines (AWWA and AWWARF 1992). At least 20% of distribution mains are reported to be below the water table, but it is assumed that all systems have some pipe below the water table for some time throughout the year, thus providing an opportunity for intrusion of exterior water under low or negative pressure conditions (LeChevallier et al. 2003b). In addition, pipes buried in soil are subject to contamination with fecal indicators and pathogens from the surrounding environment (Karim et al. 2003; Kirmeyer et al. 2001). A survey of water utilities in North America found that 28.8% of cross-connections resulted in bacterial contamination (Lee et al. 2003). Negative hydraulic pressure can draw pathogens from the surrounding environment into the water supply where

residual disinfection efficacy is uncertain and variable, depending on the magnitude of such events (Gadgil 1998; Haas et al. 1998; Trussell 1999). Little is known about the extensiveness of distribution system inadequacies and whether they are sporadic or continuously occurring (Lee and Schwab 2005), but outbreaks have been documented following external contamination in the distribution system despite the presence or requirement of residual disinfectant (Craun and Calderon 2001; Levy et al. 1998).

Decline in residual disinfectant is related to many factors, including the distance traveled, water flow velocity, residence time, age and material of pipes, and water pressure (Egorov et al. 2002). Although residual chlorine is present in the distribution system of treated water, the levels do not provide significant inactivation of pathogens in intrusion events (Payment 1999; Snead et al. 1980). More recent modeling studies have evaluated intrusion events at specific locations, with consideration to mixing, contact time, and other distribution system variables, before consumption. Under these realistic exposure scenarios, monochloramine disinfectants performed poorly against *Giardia* and *Escherichia coli*. Typical concentrations of chlorine residual (0.5 mg/L) inactivated *E. coli* in simulated sewage intrusion events but were again ineffective for *Giardia* (Baribeau et al. 2005; Propato and Uber 2004). Intentional contamination events in the distribution system are also a concern where public water supplies are potentially vulnerable to bioterrorism threats.

According to a Centers for Disease Control (CDC) survey, cross-connections and back-siphonage caused the majority (51%) of outbreaks linked to the distribution system from 1971 to 2000, followed by water main contamination (a collective 33%) and contamination of storage facilities (16%) (Fig. 7). Data compiled by the USEPA indicate that only a small percentage of contamination from cross-connections and back-siphonage are actually reported and that the CDC data underreports known instances of illnesses caused by backflow contamination events. For example, from 1981 to 1998, only 97 of 309 (31%) documented incidents were reported to public health authorities (USEPA 2002). Of the 97 reported incidences, 75 (77%) reported illnesses (4,416 estimated cases); however, only 26 (27%) appear in the CDC summaries of waterborne disease outbreaks.

Water quality may degrade in treated water storage facilities because of loss of disinfectant residual, increased temperature, and external contamination from birds, insects, animals, wind, rain, algae, etc. Storage tanks are particularly vulnerable to contamination in the absence, or failure, of a protective cover or barrier, open hatches, and vents; however, birds have been known to contaminate even covered public water supply distribution storage tanks (AWWA and EES 2002; Clark et al. 1996).

Home Distribution Systems

Bacterial colonization of pipes, connections, and faucets positioned along the channels of drinking water distribution, including the utility's
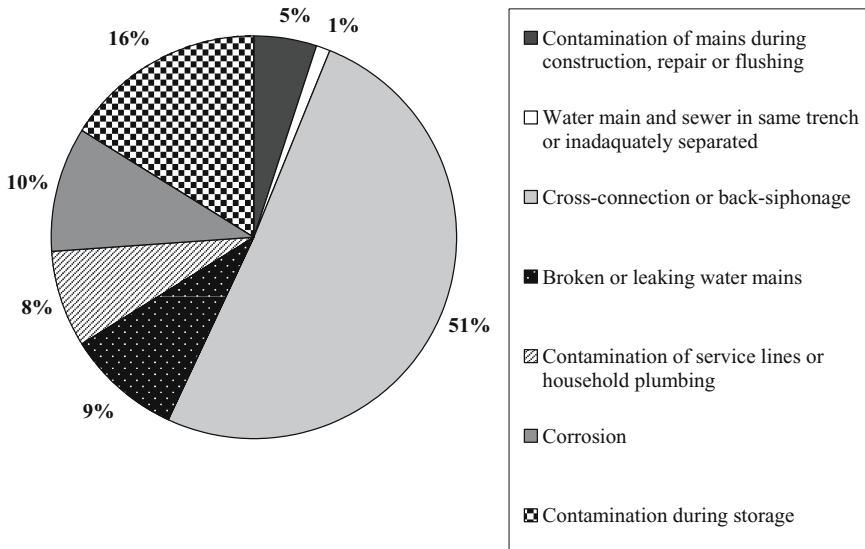
Fig. 7. Waterborne outbreaks caused by distribution system deficiencies, 1971–2000 (*n* = 120). (From Calderon 2004.)

Table 6. Tracking Deteriorating Water Quality to the Tap.

Sample site	HPC (cfu/mL)
Groundwater source	1–10
Distribution system	10–100
Household tap	1,000–1,000,000

Source: Pepper et al. (2004).

distribution system, the homeowner's premise plumbing, and fixtures in the home is well documented. Pepper et al. (2004) found that the bacteriological quality of water significantly deteriorates in the home plumbing relative to the distribution system, as evidenced by survey of heterotrophic plate count (HPC) bacteria (Table 6). Stagnant water in premise plumbing provides an environment where bacteria can grow to values several orders of magnitude higher than in the municipal distribution system (Edwards et al. 2005). Although HPC bacteria in drinking water is not considered a direct health risk (WHO/NSF 2003), opportunistic pathogens such as *Legionella* and *Mycobacterium* are associated with human disease and have been found in premise plumbing biofilms (Flannery et al. 2006; Pryor et al. 2004; Thomas et al. 2006; Tobin-D'Angelo et al. 2004; Vacrewijck et al. 2005).

Since 2001, *Legionella* outbreaks have been documented in the CDC surveillance summaries of waterborne disease and comprise a significant portion of drinking water outbreaks (19% in 2001–2002). All six of the documented *Legionella* outbreaks in 2001–2002 were related to regrowth of *Legionella* in the distribution systems of large buildings or institutions (Blackburn et al. 2004).

VI. Geographical Distribution of Reported Violations

Predicting the most at-risk populations based on geographical distribution is difficult for reasons of the relative significance of source water type and quality, treatment plant reliability, climatic events, distribution system integrity, reporting bias, and other factors. The Safe Drinking Water Information System provides data on CWS reporting health based violations of the National Primary Drinking Water Regulations (NPDWRs). The NPDWRs are legally enforceable standards that apply to public water systems subject to inorganic, organic, radionuclide, microbial, or other health-effecting contaminant**s**. These primary standards set maximum contaminant levels (MCLs), the maximum permissible level of a contaminant in water delivered to any user of a public water system. In fiscal year 2003, 3,986 CWS (8% of total systems reporting) serving 24.4 million people (9% of the population) delivered drinking water in violation of at least one of the health-based standards (Fig. 8). Although about half of these violations
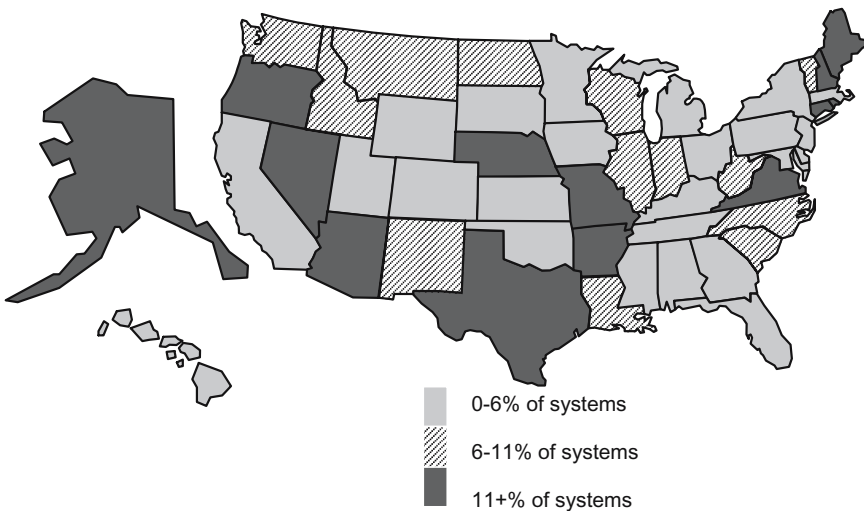

0-6% of systems

6-11% of systems

11+% of systems

Fig. 8. Reported community water systems violating maximum contaminant levels or treatment standards in FY 2002. (From USEPA 2004.)

were the result of monitoring and reporting errors, the top two reported violations were under the category of the total coliform rule (9,056 reported violations) and the surface water treatment rule (1,747 reported violations). U.S. commonwealths and territories (i.e., American Samoa, Puerto Rico, U.S. Virgin Islands) were documented with an average of 44% of CWS reporting health-based violations, potentially impacting 71% of the population (USEPA 2004). Most of the U.S. population receives water from a CWS. Although there are 54,064 community water systems, serving a total of 263.9 million people, just 7% serve 81% of the population (USEPA 2006b).

VII. Evidence of Groundwater Vulnerability

Community water systems have more groundwater than surface water sources, but more people drink from a surface water system. A reported 11,403 systems, serving 178.1 million people, relied on surface water compared to 42,661 systems, serving 85.9 million people, reliant upon groundwater sources (USEPA 2006b). States with groundwater sources serving the greatest number of individuals are diagramed in Fig. 9. Before the newly promulgated Ground Water Rule (USEPA 2006), utilities with a groundwater source were not required to disinfect the water supply and many small communities and individual homeowners continue to consume untreated groundwater. Several national surveys have documented evidence of viruses in groundwater (Table 7). The newly promulgated Ground Water Rule applies to more than 147,000 public water systems and more
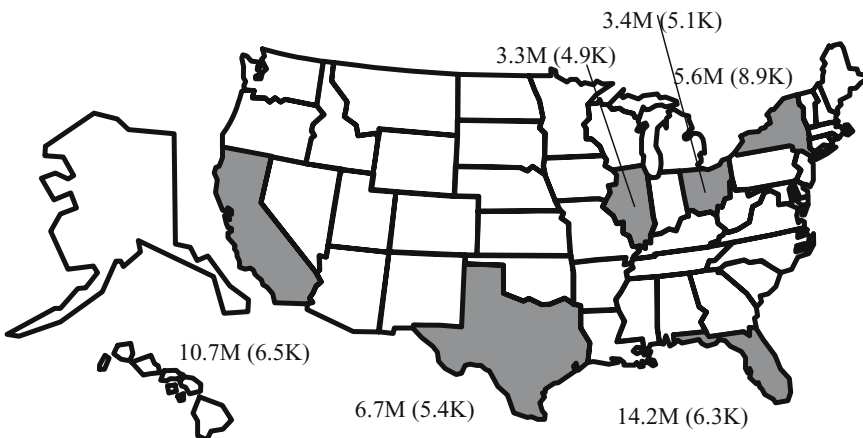

Fig. 9. States with the highest populations served by groundwater. (From USEPA 2004.)

Table 7. Evidence of Enteric Virus Contamination in U.S. Groundwater Wells.

Sample description	Virus positive	Source
448 utility wells, 35 states	32% enteric virus	Abbaszadegan et al. (2003)
50 homeowner wells	8% enteric virus	Borchardt et al. (2003a)
29 utility wells	16% enteric virus	Fout et al. (2003)
48 midwest utility wells	42% enterovirus	Borchardt et al. (2004)
	6% norovirus group 1	
211 Californian utility wells	10% enterovirus	Yates (unpublished, 2004)

than 100 million consumers, utilizing municipal groundwater sources. The rule requires that sanitary surveys be conducted by December 31, 2012, for most CWS and by 2014 for CWS with outstanding performance and for all noncommunity water systems, to help identify deficiencies that may lead to impaired water quality. Source water monitoring for indicator microbes, corrective actions for systems with significant deficiencies or source water fecal contamination, and compliance monitoring are further required. The USEPA estimates that the Ground Water Rule will reduce waterborne viral illnesses by approximately 42,000 cases each year, a 23% reduction from the current baseline estimate.

One survey of 448 utility wells in 35 states, using molecular methods of detection (reverse transcriptase-polymerase chain reaction, RT-PCR), found evidence of enteric viruses, including enterovirus, rotavirus, and hepatitis A RNA, in approximately 32% of groundwater supplies (Abbaszadegan et al. 2003). Molecular methods for virus detection do not determine viability, and thus the public health significance of these results is not known, but the presence of viral RNA in groundwater suggests a potential for exposure and adverse health risks.

An additional survey of 321 samples from 29 U.S. utility wells, collected over 1 yr, detected human enteric viruses including enterovirus, reovirus, norovirus, and hepatitis A virus in 72% of the sites and 16% of the samples using RT-PCR (Fout et al. 2003). Similarly, 50% of samples from 48 midwest utility wells tested positive for human viruses (Borchardt et al. 2004). In the latter study, three samples were found positive for culturable hepatitis A virus. Another study of 50 private homeowner wells found enteric viruses in 8% of the samples collected (Borchardt et al. 2003a). In addition to human viruses, protozoan parasites have been documented in groundwater. Of 199 groundwater samples surveyed, 5% of vertical wells, 20% of springs, 50% of infiltration galleries, and 45% of horizontal wells tested positive for *Cryptosporidium* oocysts, calling for a reevaluation of the notion that groundwater is inherently free of protozoan parasites (Hancock et al. 1998).

Helicobacter pylori has been found in biofilms of water distribution systems (Park et al. 2001) and individual groundwater wells. Epidemiological

studies in Germany have linked infection in children with drinking untreated well water serving individual homes (Herbarth et al. 2001), as did a study in West Virginia linking contaminated homeowner wells (Elitsur et al. 1998). Studies of groundwater quality have implicated an association with septic systems and disease. Borchardt et al. (2003b) found that viral diarrhea in children from 14 contiguous zip codes in Wisconsin positively correlated with septic tank density. Water holding tanks and bacterial diarrhea were also positively correlated. Raina et al. (1999) showed *E. coli* in well water was correlated to diarrhea in rural families. The closer the septic system was in proximity to the drinking water well, the greater the incidence of disease. Overall, 46% of wells were contaminated if the septic system was within 20 m.

VIII. Estimating Waterborne Disease risk in the United States

Variable approaches have been used to estimate gastrointestinal illness from waterborne pathogens including epidemiological studies and exposure analysis. Information is lacking, however, regarding risk estimates considering gastroenteritis and other illnesses related to microbial contaminants in drinking water.

A. Estimates of Gastroenteritis from Epidemiological Studies

Estimating the incidence of endemic acute gastrointestinal illness attributable to drinking water has been approached using information obtained from household intervention trials (Colford et al. 2002, 2005; Hellard et al. 2001; Payment et al. 1991, 1997). Determining the illness attributable to drinking water involves estimating the baseline of gastrointestinal illness within communities, and such information can be useful when conducting quantitative microbial risk assessments of drinking water quality. The household intervention trials conducted in the research investigations cited above are types of epidemiological studies that involve randomly designating one group of households as the "intervention group" where household members utilize drinking water obtained via an in-home treatment system and then having another group of households use water directly from their tap or through a fake device that provides no additional water treatment. In the latter situation, the study is *blinded*, meaning that neither group knows during the study whether their in-home device is actually providing treatment.

Such household intervention trials have been conducted in the U.S., Canada, and Australia. Table 8 lists and highlights various aspects of these studies. For all these trials, the human health outcome of interest was gastrointestinal illness, with some variation regarding the specific symptoms in defining that outcome. All participants were immunocompetent individuals who kept health diaries throughout the study to record symptoms related

Table 8. Household Drinking Water Intervention Trials Addressing Gastrointestinal Illness.

Study	Payment et al. (1991)	Payment et al. (1997)	Hellard et al. (2001)	Colford et al. (2002)	Colford et al. (2005)
Location	Montreal, Canada	Montreal, Canada	Melbourne, Australia	California, United States	Iowa, United States
Sample size (individuals)	2,408	5,253	2,811	236	1,296
Treatment via intervention	Reverse osmosis	Tap water with/without purge valve; Bottled plant water and bottled purified water	Ultraviolet and 1-μm filter	Ultraviolet and 1-μm filter	Ultraviolet and 1-μm filter
Sham device?	No	No	Yes	Yes	Yes
Means of assessing illness	Health diary	Health diary	Health diary	Health diary	Health diary
Source water	Surface water (river) w/fecal coliforms and viruses	Surface water (river) w/protozoa and viruses	Surface water from catchments	Surface water w/*Cryptosporidium*	Surface water (river) w/indicators of fecal contamination and protozoa
Source water treatment applied	Combination of flocculation, filtration, ozonation, and chlorination	Combination of flocculation, settling, filtration, ozonation, and chlorination	Chlorination	Conventional treatment	Conventional treatment
Finished water quality	Met standards	Met standards	No total coliforms detected	Met standards	Met standards

Table 8. (*cont.*)

Study	Payment et al. (1991)	Payment et al. (1997)	Hellard et al. (2001)	Colford et al. (2002)	Colford et al. (2005)
Distribution system water quality	Not reported	No report of fecal contamination	Total coliforms and relatively high heterotrophic plate count bacteria detected in some samples	Not reported	Met standards
Attributable risk	0.26	0.08 for tap water 0.12 for tap water w/purge valve 0.02 for bottled plant water	0.03	0.85	Two periods: 0.02 (I) 0.14 (II)
Cases attributable to tap water	34%	12% for tap water 17% for tap water w/purge valve 3% for bottled plant water	4%	24%	0.008% (I) 0.08% (II)

Source: Modified from Colford et al. (2006).

to gastrointestinal illnesses. The source (surface) waters were reported to have varying levels of microbial contamination.

Payment et al. (1991) were first to conduct a household intervention trial addressing (gastrointestinal) illness attributable to drinking tap water. The tap water met both Canadian and U.S. regulations, but the source water was subject to contamination from sewage. The limitation of this study is that it was not blinded, so those persons drinking tap water (therefore no treatment device) may have been more inclined to report poorer health symptoms. An overall conclusion from this study is that an estimated 35% of the gastrointestinal illnesses occurring within the tap water group may be attributable to their drinking water.

Payment et al. (1997) conducted a follow-up study to address the results from their previous study (Payment et al. 1991). A goal of this investigation was to evaluate the role of distribution system water quality in gastrointestinal incidence, which resulted in a study design involving four groups of participants: a tap water group and a bottled purified water group (to address those exposed and unexposed, respectively), and a plant bottled water group and a tap water group using a purge valve (to address distribution system water quality). The attributable risk percent ranged from 3% for the bottled plant water group (rate of illness for this group is the same as for those drinking the bottled purified water), to 12% for the tap water group, to 17% for those in the tap water group with a purge valve. The investigators concluded that the excess number of gastrointestinal illnesses observed in the first study may not have been associated with surface water contamination but rather was associated with contamination within the distribution system because the rate of illness of the bottled plant water group was similar to those drinking bottled purified water. A limitation, however, is that about half the participants in the bottled plant water group dropped out during the course of the study. In addition, as with their previous study (Payment et al. 1991), this study was also unblinded.

Hellard et al. (2001) designed the first blinded household intervention study, which was conducted in Australia. Some participants used a water treatment device that involved an ultraviolet application and filtration while others were given a fake (no treatment) device. As with the Payment et al. studies (1991, 1997), participants recorded gastrointestinal illness symptoms in diaries, although this study used a slightly more strict definition of gastrointestinal illness. Participants were followed for more than 1 yr, another strength of the study besides the blinding of participants, and the investigators observed similar rates of illness of the participants using the fake device as those using the water treatment device.

Colford et al. (2002, 2005) conducted two household intervention trials in the U.S. Their first study was designed as a pilot to obtain information regarding the practicality of a study design to include blinding of participants. The investigators utilized a blinding index (James et al. 1996), which led to the conclusion that the study they designed could incorporate

effective participant blinding. The investigators observed an attributable risk of 0.85 and concluded that 24% of the gastrointestinal illnesses could be attributable to tap water.

The goal of the Colford et al. (2005) follow-up study was to determine if water treatment at the tap could reduce the number of gastrointestinal illnesses. Again, the investigators used a blinding approach, and participants recorded gastrointestinal health symptoms in diaries. The investigators observed no difference in the rate of illness between those participants using the fake device and those using the treatment device. The authors offered the explanation that perhaps their study owed this conclusion to successful water treatment practices and a well-maintained water distribution system. In addition, it was recognized that water consumption by the participants outside the home may have had some effect on the study results.

Colford et al. (2006) reviewed the household intervention trials described above as well as presenting an approach for estimating the occurrence of acute gastrointestinal illness in the U.S. that can be attributable to drinking water. Their proposed approach considers the following: (a) the estimated incidence of acute gastrointestinal illness in the U.S. of 0.65 episodes per person-year based on data collected from the Foodborne Diseases Active Surveillance Network (FoodNet) (Hawkins et al. 2002; Jones et al., 2007); (b) the attributable risks determined from the household intervention trials (median attributable risk of 0.08 and a median attributable risk percent of 12%); (c) the proportion of risks of acute gastrointestinal illness associated with source water and/or water treatment quality; (d) the number of people in the U.S. served by community water systems and consuming drinking water from surface water sources and groundwater sources; and (e) the number of people in the U.S. served by community water systems that are known to have either poor quality source water or poor water treatment.

Based on considerations just listed and various assumptions, Colford et al. (2006) estimated that as many as 11.69 million cases of acute gastrointestinal illness, occurring each year, may be attributable to drinking tap water in the U.S. Assumptions include the applicability of the attributable risk percent estimates from the household intervention trials to the entire U.S. population. In addition, the authors created scenarios assuming different risk levels associated with either poor source water quality/poor water treatment or problems with quality within a distribution system. The latter resulted in the 11.69 million cases of acute gastrointestinal illnesses/yr estimation and a lower estimate of 4.26 million cases/yr associated with poor source water quality/poor water treatment (Colford et al. 2006). The authors emphasize that the primary purpose of their estimation of acute gastrointestinal illness incidence attributable to drinking tap water in the U.S. is to demonstrate a methodology that can be improved upon with more data.

Besides household intervention trials, community intervention studies have also been conducted to address waterborne gastrointestinal disease

risks (Calderon 2001; Frost et al. 2006; Goh et al. 2005; Hellard et al. 2002; Kunde et al. 2006; McConnell et al. 2001). These types of studies offer some advantages over household intervention trials including that they may be simpler and less costly to conduct (Calderon and Craun 2006): they have included cohort, case-control, and ecological types of designs. Two of these (Calderon 2001; Goh et al. 2005) concluded that a reduction in gastrointestinal illnesses was observed as a result of additional water treatment. A preliminary report from the Kunde et al. (2006) study also indicates a decrease in diarrheal illness risk in participants over age 35 following the intervention. Conversely, preliminary data analysis from the Frost study (2006) does not indicate a significant difference; however, analysis is reported to be ongoing for both of these aforementioned studies (reviewed in Calderon and Craun 2006).

B. Estimates of Gastroenteritis from Exposure

Messner et al. (2006) described an approach for estimating the incidence of gastrointestinal disease in the U.S. from drinking water. These investigators assume that for each population served by a community water system, a distribution of incidence rates of acute gastroenteritis can be estimated that can then be used to derive an overall national estimate of this disease attributable to drinking water in the U.S. They emphasize the need for addressing "mixtures" of pathogens as opposed to considering health risks from exposure to an individual pathogen as one of the premises for the approach described in this paper. The authors speculate that the mean incidence of acute gastrointestinal illness attributable to drinking water among community water systems ranges widely because of variations in source water quality, water treatment efficiencies, water quality within a distribution system, and water quality management practices.

Messner et al. (2006) propose the development of a "risk matrix" to categorize community water systems (CWS) based on relative microbial risk levels. The authors suggest connecting the information obtained from epidemiological studies regarding the incidence rate of acute gastrointestinal illness to risk factors identified in the epidemiological studies that have been conducted and to other CWS. Identification of these risk factors will allow for risk-based categorizing of other CWS that have similar characteristics, therefore assuming that generalizations can be made regarding all U.S. CWS and the populations they serve. Completing this process involves overcoming several challenges from the lack of data related to both pathogen occurrence and variation in survivability and infectivity, as well as knowing the actual efficiency of water treatment applications, as opposed to theoretical information. Messner et al. (2006) utilize in their approach specific information obtained during the Payment et al. studies (1991, 1997) regarding factors associated with source water/water treatment quality and factors related to distribution system deficiencies, and also therefore utilize

the specific definition of gastrointestinal illness as defined in these studies, for highly credible gastrointestinal illness.

To estimate the incidence of acute gastrointestinal illness in the U.S. caused by drinking water, Messner et al. (2006) selected 2004 as their reference year and assumed that a certain number of cases are the result of source water/water treatment quality and a certain number are caused by distribution system deficiencies. In addition, the investigators assume a lognormal distribution to address the variability of relative microbial risk related to both, leading to an estimation of a statistical distribution of acute gastrointestinal illness among CWS within the U.S.. The authors consider that there is an approximate 5-log range regarding mean pathogen concentrations in source waters and a 2- to 6-log range regarding mean pathogen reduction. They used Monte Carlo simulations to ultimately compute this estimate of the distribution of acute gastrointestinal illness.

Based on the described assumptions, Messner et al. (2006) estimate that the mean national estimate of gastrointestinal illness, using the Payment et al. (1991, 1997) definition of highly credible gastrointestinal illness, attributable to drinking water is 0.11 cases/person/yr (with a 95% credible bound of 0.03–0.22) (Table 9). The investigators relate their 0.11 cases/person/yr estimate to the reported rate of diarrheal "episodes" of 1.3/person/yr (Imhoff et al. 2004) and estimate that the percentage of "episodes" attributable to drinking water is 8.5%. If this same percentage is assumed and applied to the Imhoff et al. (2004) reported incidence, due to all causes, for acute gastrointestinal illness of 0.72 cases/person/yr, the investigators estimate that the incidence of acute gastrointestinal illness attributable to drinking water is 0.06 cases/person/yr (95% credible interval of 0.02–0.12). When applying the 0.72 cases of acute gastrointestinal illness/person/yr

Table 9. Estimates of Gastrointestinal Illness Attributable to Drinking Water.

Health outcome and drinking water attribute	Mean illness incidence (cases/person-yr)	95% credible bounds
Total highly credible gastrointestinal illness[a]	0.11	0.03, 0.22
Due to water source/ treatment	0.048	0.011, 0.086
Due to distribution system	0.062	0.005, 0.16
Total acute gastrointestinal illness	0.06	0.02, 0.12
Due to water source/ treatment	0.03	0.006, 0.05

[a]Estimated using data from Payment et al. (1991, 1997) studies.
Source: Modified from Messner et al. (2006).

from all causes reported in Imhoff et al. (2004) to the 272.5 million people served by CWS (based on data in USEPA 2006b), this results in an estimate of approximately 196 million cases/yr of total acute gastrointestinal illness. Assuming, based on estimates provided above, that 8.5% of the cases are attributable to drinking water, this translates into approximately 16 million cases of acute gastrointestinal illness/yr, which is a little higher than the upper end estimate computed by Colford et al. (2006) (11.69 million cases/yr).

C. Estimates of Waterborne Disease from Exposure

The following section represents our estimates of waterborne infection and illness risks in the U.S. categorized by source water type (Fig. 10). These estimates are based on the total number of water systems in the U.S. and total populations exposed. Illness risk estimates represent all possible illnesses associated with the microbial infection, not only gastroenteritis.

Groundwater risk estimates are based on predicted number of viral infections and illnesses associated with viruses in groundwater. For both the community system and noncommunity system groundwater risks, it was assumed that 10% of wells are positive for infectious viruses, assuming one infectious virus for every positive well. Dose–response data for rotavirus (Gerba et al. 1996b) were used, an exposure volume of 1.4 L/person/d was assumed (Covello and Merkhofer 1993) and the yearly risk was calculated based on a 350-d exposure (Aboytes et al. 2004).

When considering the number of people served by groundwater supplies, the number of viral infections estimated is 10.7 million/yr and 2.2 million/yr for community and noncommunity systems, respectively. Assuming that half of all infections lead to illness (Haas et al. 1993), this results in 5.4 million cases/yr associated with community groundwater systems and 1.1 million cases/yr associated with noncommunity groundwater systems. These infection and illness estimates may offer higher estimates of risk due to the high infectivity associated with rotavirus exposure. In addition, this exercise represents a methodology for estimating risks associated with exposure to any waterborne virus and infections that may lead to a wide range of clinical outcomes, not only gastroenteritis.

The estimated number of infections and illnesses associated with exposure to pathogens in municipal surface waters were also determined. This exercise utilized the same assumptions described for the groundwater risks as well as dose–response data for *Cryptosporidium* (exponential model; Messner et al. 2001) and *Campylobacter* (beta-Poisson model; Medema et al. 1996). Assuming a 1% frequency of contamination among the more than 11,000 CWS in the U.S. using surface water, and combining risk estimates associated with *Cryptosporidium*, *Campylobacter*, and rotavirus, 26 million *infections*/yr are estimated. When assuming that 50% of these infections will result in some type of illness, 13 million illnesses/yr are predicted.

Risk calculation 1: Estimated number of viral infections and illnesses associated with community groundwater systems

- Assume
    - Of 42,661 groundwater systems serving 86 million people (USEPA 2006b), 10% contain infectious virus
    - One infectious virus per liter (100-L samples analyzed)
    - 1.4 L water consumed per day (Covello and Merkhofer 1993)
    - 50% infections result in illness (Haas et al. 1993)
- Annual risk of infection = 0.12

- **10.7 million <u>infections</u> per year**
- **5.4 million <u>illnesses</u> per year**

Risk calculation 2: Estimated number of viral infections and illnesses associated with noncommunity groundwater supplies

- Assume
    - Of 111,036 groundwater systems serving 18 million people (USEPA 2006b), 10% contain infectious virus
    - One infectious virus per liter (100-L samples analyzed)
    - 1.4 L water consumed per day (Covello and Merkhofer 1993)
    - 50% infections result in illness (Haas et al. 1993)
- Annual risk of infection = 0.12

- **2.2 million <u>infections</u> per year**
- **1.1 million <u>illnesses</u> per year**

Risk calculation 3: Estimated number of infections and illnesses associated with municipal surface water supplies

- 178,000,000 persons supplied by surface water supplies in the U.S. (USEPA 2006b)
- Combined risk of *Cryptosporidium*, *Campylobacter*, and rotavirus infections
- Based on 1% frequency of contamination events
- Assuming 50% infections result in illness (Haas et al. 1993)

- **26.0 million <u>infections</u> per year**
- **13.0 million <u>illnesses</u> per year**

Fig. 10. Estimates of waterborne infection and illness risks in the U.S. categorized by source water type.

**Total estimated number of waterborne illnesses
per year in the U.S.**

- Groundwater (municipal) = 5,400,000
- Groundwater (noncommunity) = 1,100,000
- Surface water supplies = 13,000,000

    Total estimate = 19,500,000

**Risk of viral infection associated with exposure to contaminated groundwater
using rotavirus dose–response data**

- beta-Poisson model for rotavirus (Gerba et al. 1996b):

    Probability of infection (P_i) $= 1 - (1 + N/\beta)^{-\alpha}$
        where $\alpha = 0.26$ and $\beta = 0.42$

- Probability of infection for 1 virus ($n = 1$): **0.27**

- Concentration of viruses in groundwater:
    - Assuming 4,266 positives/total volume analyzed (100 L per sample)
    - Assuming one virus per positive sample and 10% are positive = **0.001**

- Daily risk:
    [Concentration (0.001 viruses/L)][P_i for 1 virus (0.27)][1.4 L/d ingestion]
    = **0.000378 infections**

- Annual risk:
    $1 - (1 - \text{daily risk})^{350}$ = **0.12 infections per year**

Fig. 10. (*cont.*)

When combining illness estimations from all water sources addressed in this exercise, the total is 19.5 million cases/yr in the U.S. associated with drinking water. This estimation is higher than both the Colford et al. (2006) illness estimate, upper estimate of almost 12 million cases/yr, and the Messner et al. (2006) illness estimate, 16 million cases/yr, yet our estimate

potentially reflects all health outcomes associated with exposure to pathogens in drinking water rather than just gastrointestinal illness.

IX. Water Treatment at the Point-of-Use

Water treatment technologies at the point-of-use can provide an additional barrier of protection from waterborne contaminants, particularly those entering the distribution system and present in premise plumbing. Point-of-use (POU) water treatment devices may be installed at the end of the faucet, plumbed in-line, or stand-alone pitchers, or they may be point-of-entry (POE) systems installed where water from the distribution system enters the premise plumbing. Many POU/POE systems are designed for aesthetic (i.e., taste, odor, hardness) improvements only, while others employ technologies to remove organic and inorganic chemicals, pathogens, bacteria, and radionuclides. According to a survey by the Water Quality Association (2001), 41% of homes in the U.S. report having a water treatment device in place at the point-of-use or the point-of-entry and 39% drink bottled water (Fig. 11). Most report the use of a tabletop pitcher, which are currently not designed or marketed for eliminating microbial pathogens from drinking water. Generally, systems designed to eliminate a wide variety of physical, chemical, and biological contaminants are costly and require routine professional maintenance. Membranes used for filtration in POU/POE devices must be changed at regular intervals, and systems with ultraviolet light disinfection must be routinely inspected for buildup on the lamps that could prevent effective light emission. Improper maintenance of
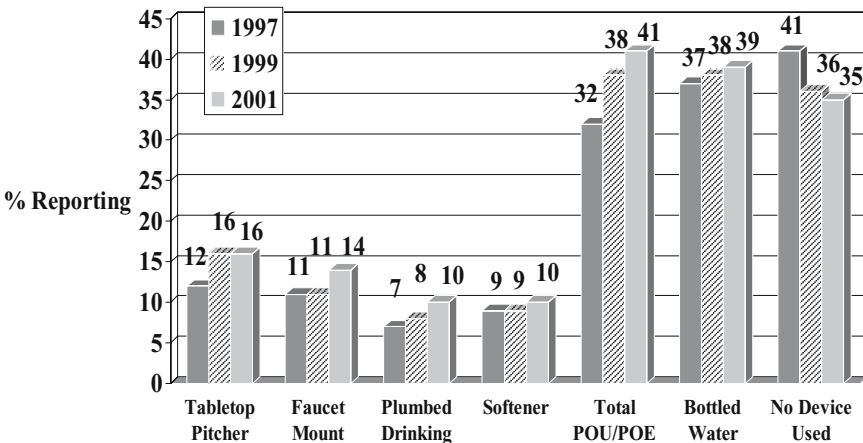

Fig. 11. Use of point-of-use (POU) water treatment devices in the U.S., 1997–2001 (WQA 2001.)

POU/POE treatment systems could result in exposure to a greater concentration of pathogens. In addition, heterotrophic plate count (HPC) bacteria often increase by several orders of magnitude in POU/POE water treatment devices.

A. Significance of Regrowth in POU/POE Water Treatment Devices

Several factors are related to bacterial regrowth in water, including, filtration, temperature, disinfectant type and residual, assimilable organic carbon level, corrosion control, and distribution pipe material. HPC bacteria are able to persist and grow in and on point-of-use/entry treatment device media, membranes, filters, and other surfaces to concentrations 10 fold or more higher in effluent waters. Granulated activated carbon (GAC) is a common medium used in POU/POE treatment devices known to support growth of HPC bacteria. Among other contaminants, GAC removes chlorine disinfectant residuals from tap water. Although this is desirable to improve the taste and odor of drinking water, the lack of disinfectant residual and the collection of bacterial growth substrates provides a suitable environment for HPC bacteria to attach to the media and grow, especially following periods of non-use and stagnation. HPC bacteria may also grow in water storage vessels, distribution pipes, pressure tanks, and hot water heaters.

Although many studies have documented the presence of large numbers of HPC bacteria in POU-treated water, there has been no correlation to increased disease (Allen et al. 2004; Calderon 1991; Colford et al. 2002; Edberg and Allen 2004; WHO/NSF 2003; Payment et al. 1991, 1997). Relative to HPC levels in common foods, water plays a minor role as a source of ingested bacteria (Stine et al. 2005). Certain HPC bacteria, such as *Pseudomonas*, *Klebsiella*, and *Aeromonas*, are opportunistic pathogens, meaning they are capable of causing disease in an immunocompromised host. Although these organisms can be isolated from treated water systems (Chiadez and Gerba 2004), ingestion is not their route of disease transmission. There is insufficient evidence linking these opportunistic pathogens to disease transmission via drinking water (Allen et al. 2004).

Several studies have shown that HPC bacteria in POU/POE treatement devices can outcompete human pathogens and may offer a protective effect to consumers (Camper et al. 1985; Gerba 2003; Rollinger and Dott 1987). Gerba (2003) found commercially available POU carbon filter devices placed on home faucets and used for 3–6 wk established a background culture of HPC bacteria within the systems. *Salmonella typhimurium*, *E. coli*, poliovirus, and hepatitis A virus, all known human enteric pathogens, were added to sterile tap water, regular tap water, and POU-treated tap water that was high in HPC organisms. HPC bacteria in the POU-treated water were clearly antagonistic to the pathogenic bacteria used in this study, reducing their counts >10 fold in 1 d and >10,000 fold in 2 d. A similar, but less dramatic, trend was seen with the pathogenic viruses.

Other studies supporting the antagonistic effect of HPC bacteria on pathogens have been conducted (Camper et al. 1985). Three enteric bacterial pathogens, *Yersinia enterocolitica*, *Salmonella typhimurium*, and enterotoxigenic *E. coli*, readily grew on sterile GAC; however, in the presence of water containing populations of HPC organisms, the pathogen counts gradually decreased. The most dramatic results were seen when bacterial populations from river water were previously established on GAC and a mixture of HPC and pathogenic bacteria were added to the media. Pathogens not only decreased at a more rapid rate but were prevented from initial attachment compared to sterile GAC filters. These studies suggest an antagonistic effect on pathogenic bacteria caused by the presence of HPC bacteria on the filters, possibly because pathogenic bacteria do not compete well in the presence of high HPC bacteria.

B. Health Benefits of POU/POE Water Treatment Devices

Few studies have directly targeted the benefits of POU water treatment systems for reduction of waterborne disease. Most of the available data are from epidemiological studies with a few incidental pieces of information from outbreak events. For example, survey data showed that no one who died in the waterborne *Cryptosporidium* outbreak in Milwaukee was using any type of fine filtration device for water treatment in the home (WQA 2002). In the same outbreak, persons who did have a point-of-use filtration device in place reported significantly lower incidences of diarrhea compared to those without (Addiss et al. 1996).

Epidemiological studies, in Canada, by Payment et al. (1991, 1997) suggest that 35% of all gastrointestinal illnesses could be waterborne when source water quality was degraded (see previous discussion). The 1997 study also found that children gain the most by having a POU water treatment system in place. In 2- to 5-yr-old children, drinking tap water resulted in an excess of 40% of gastrointestinal illness compared to those drinking tap water filtered at the point-of-use, and an excess of 17% was seen with children drinking bottled tap water versus POU-treated water.

Two epidemiological studies using randomized, blinded, controlled trials to evaluate risks related to tap water consumption determined that the risks were equal among groups supplied with POU-treated (1-μm filtration and UV disinfection chamber) water compared to untreated tap water (Colford et al. 2005; Hellard et al. 2001). Some of the uncertainties of these studies are that only a single water system was evaluated and, in the Hellard study, a pristine water source. The Colford study evaluated the Iowa-American Water Company, reported to be one of the best in the country, utilizing conventional filtration and a combination of chlorine and chloramine disinfectants. The study included intensive monitoring of the distribution system water quality and pressures and indicated high-quality delivery of the finished product.

   More studies are needed to assess the impact of POU filtration systems for waterborne disease reduction. Future studies should evaluate multiple water systems over a wide geographical area to determine the efficacy of POU water filtration systems over varying finished water qualities. Direct monitoring of POU filters, placed in residential or commercial applications in regions where source water quality or distribution system integrity is questionable, would provide much-needed pathogen occurrence and exposure data.

X. Conclusions

Although current protocols in municipal treatment requirements are effective at eliminating pathogens from water if properly applied, inadequate, interrupted, or intermittent treatment has repeatedly been associated with waterborne disease outbreaks. Factors to consider with regard to pathogen exposure is that contamination is not evenly distributed but rather affected by the number of pathogens in the source water, the age of the distribution system, the quality of the delivered water, and climatic events that can tax the treatment plant operations.

   Weather events are difficult to predict but are known to influence exposures to microbial pathogens by their increased transport and dissemination via rainfall and runoff and the survival and/or growth through temperature changes (CGER 2001). Effects of increased rainfall on watershed protection, infrastructure, and storm drainage systems affected by increased rainfall may lead to increased risk of contamination events. Extreme precipitation events preceded 51% of outbreaks from 1948 to 1994 (Curriero et al. 2001).

   Current regulatory standards and monitoring requirements do not guarantee the absence of human pathogens in tap water. For example, the Total Coliform Rule, mandating the use of bacterial indicators of water quality, does not predict vulnerability to an outbreak (Craun et al. 2002). In fact, few community and noncommunity water systems that reported an outbreak from the survey period 1991–1998 had violated the coliform standard in the 12-mon period before the outbreak.

   In 2002, the USEPA reported that 94% of the U.S. population served by community water systems received drinking water that met all applicable health-based drinking water standards through treatment and source water protection. An internal audit indicated that the figure was believed to be closer to 81% (USEPA 2004). Furthermore, little is known about exposures to waterborne pathogens in populations not served by public water systems where there is a general lack of monitoring.

   Finally, of particular concern are sensitive populations in the U.S. that are susceptible to higher rates of infections and to more serious health outcomes from waterborne pathogens. These subpopulations include not only individuals experiencing adverse health status, but also those experiencing "normal" life stages, e.g., pregnancy, or those very young or old.

Individuals in any of these situations may want to consider additional strategies to prevent waterborne illness attributable to drinking water, such as the utilization of a point-of-use water treatment device. Better communication between water quality professionals and healthcare providers is needed to develop and distribute materials to inform the public of mitigation options beyond the current multibarrier approach of municipal water treatment.

Summary

Outbreaks of disease attributable to drinking water are not common in the U.S., but they do still occur and can lead to serious acute, chronic, or sometimes fatal health consequences, particularly in sensitive and immunocompromised populations. From 1971 to 2002, there were 764 documented waterborne outbreaks associated with drinking water, resulting in 575,457 cases of illness and 79 deaths (Blackburn et al. 2004; Calderon 2004); however, the true impact of disease is estimated to be much higher. If properly applied, current protocols in municipal water treatment are effective at eliminating pathogens from water. However, inadequate, interrupted, or intermittent treatment has repeatedly been associated with waterborne disease outbreaks. Contamination is not evenly distributed but rather affected by the number of pathogens in the source water, the age of the distribution system, the quality of the delivered water, and climatic events that can tax treatment plant operations. Private water supplies are not regulated by the USEPA and are generally not treated or monitored, although very few of the municipal systems involved in documented outbreaks exceeded the USEPA's total coliform standard in the preceding 12 mon (Craun et al. 2002).

We provide here estimates of waterborne infection and illness risks in the U.S. based on the total number of water systems, source water type, and total populations exposed. Furthermore, we evaluated all possible illnesses associated with the microbial infection and not just gastroenteritis. Our results indicate that 10.7 M infections/yr and 5.4 M illnesses/yr occur in populations served by community groundwater systems; 2.2 M infections/yr and 1.1 M illnesses/yr occur in noncommunity groundwater systems; and 26.0 M infections/yr and 13.0 M illnesses/yr occur in municipal surface water systems. The total estimated number of waterborne illnesses/yr in the U.S. is therefore estimated to be 19.5 M/yr. Others have recently estimated waterborne illness rates of 12 M cases/yr (Colford et al. 2006) and 16 M cases/yr (Messner et al. 2006), yet our estimate considers all health outcomes associated with exposure to pathogens in drinking water rather than only gastrointestinal illness.

Drinking water outbreaks exemplify known breaches in municipal water treatment and distribution processes and the failure of regulatory requirements to ensure water that is free of human pathogens. Water purification

technologies applied at the point-of-use (POU) can be effective for limiting the effects of source water contamination, treatment plant inadequacies, minor intrusions in the distribution system, or deliberate posttreatment acts (i.e., bioterrorism). Epidemiological studies are conflicting on the benefits of POU water treatment. One prospective intervention study found that consumers of reverse-osmosis (POU) filtered water had 20%–35% less gastrointestinal illnesses than those consuming regular tap water, with an excess of 14% of illness due to contaminants introduced in the distribution system (Payment 1991, 1997). Two other studies using randomized, blinded, controlled trials determined that the risks were equal among groups supplied with POU-treated water compared to untreated tap water (Hellard et al. 2001; Colford et al. 2003). For immunocompromised populations, POU water treatment devices are recommended by the CDC and USEPA as one treatment option for reducing risks of *Cryptosporidium* and other types of infectious agents transmitted by drinking water. Other populations, including those experiencing "normal" life stages such as pregnancy, or those very young or very old, might also benefit from the utilization of additional water treatment options beyond the current multibarrier approach of municipal water treatment.

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