# Current knowledge on groundwater microbial pathogens and their control

**Bruce A. Macler · Jon C. Merkle**

**Abstract** Those who drink groundwater that has not been disinfected are at increased risk of infection and disease from pathogenic microorganisms. Recent studies have shown that up to half of all US drinking-water wells tested had evidence of fecal contamination. A significant fraction of all waterborne disease outbreaks is associated with groundwater. An estimated 750,000 to 5.9 million illnesses per year result from contaminated groundwaters in the US. Mortality from these illnesses may be 1400–9400 deaths per year. Control of these pathogens starts with source-water protection activities to prevent fecal contamination of aquifers and wells. These include assessment of wellhead vulnerability to fecal contamination and correction of identified deficiencies. Correction may include control of sources or rehabilitation of the well itself. Disinfection can serve as a useful barrier and is recommended as a prudent public-health policy for all groundwater systems.

**Résumé** Ceux qui boivent une eau souterraine non désinfectée présentent un risque accru d'infection et de maladie par des germes pathogènes. De récentes études ont montré que près de la moitié de tous les puits américains testés, captés pour l'eau potable, sont soumis à une contamination fécale. Une fraction significative de l'ensemble des premières manifestations de maladies liées à l'eau est associée aux eaux souterraines. On estime qu'entre 750 000 et 5,9 millions de personnes sont malades chaque année aux tats-Unis à cause d'eaux souterraines polluées. La mortalité parmi ces malades doit être de l'ordre de 1400 à 9400 décès par an. La protection contre ces germes pathogènes commence avec des mesures prises au niveau du captage pour empècher la pollution des aquifères et des puits. Celles-ci comprennent une évaluation de la vulnérabilité des tètes de puits à la pollution fécale et une correction des insuffisances mises en évidence. Cette correction peut comprendre une maîtrise des sources de pollution ou la réhabilitation du puits lui-même. La désinfection peut ètre une précaution utile et est recommandée comme une mesure prudente de santé publique pour toutes les nappes aquifères.

**Resumen** Beber agua subterránea no desinfectada supone un riesgo de infección por microorganismos patógenos. Estudios recientes muestran que la mitad de los pozos de abastecimiento analizados en los EEUU presentan evidencia de contaminación fecal. Un porcentaje significativo de la aparición de enfermedades transmitidas por el agua puede asociarse a las aguas subterráneas, estimándose que por contaminación de las mismas se registran, sólo en ese país, entre 750.000 y 5.9 millones de personas enfermas y entre 1400-9400 muertos por año. El control de estos patógenos empieza con la protección de la fuente para prevenir la contaminación fecal de pozos y acuíferos. Esto supone evaluar la vulnerabilidad y corregir las posibles deficiencias detectadas, lo que incluye controlar los trabajos de rehabilitación del propio pozo. La desinfección puede servir como una barrera a los microorganismos patógenos, por lo que se recomienda como una política prudente de salud pública en zonas abastecidas con aguas subterráneas.

**Key words** health · fecal pathogens · disinfection · groundwater protection · water supply

## Introduction

The majority of articles in this issue of *Hydrogeology Journal* discuss soil and groundwater microbiology with respect to the ability of various organisms to transform inorganic and organic materials in the subsurface, with potentially beneficial consequences. This article discusses quite a different topic, the potential pathogenicity, consequences, and control of microorganisms in groundwater.

Protection from waterborne microbial disease has been a US public-health goal for decades. A variety of control approaches are in place today, including pro-

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tection of the source waters from microbial contamination, treatment to remove or inactivate microbial pathogens, and development of operational criteria for drinking-water systems to prevent contamination at the wellhead or in distribution. However, as recently as 1990, the US Environmental Protection Agency's (USEPA) Science Advisory Board, an independent panel established by Congress, cited drinking-water contamination as one of the highest-ranking remaining environmental risks (USEPA 1990). The Science Advisory Board reported that microbiological contaminants (e.g., bacteria, protozoa, and viruses) are likely to be the greatest remaining health risk-management challenge for drinking-water suppliers. These risks are most likely associated with groundwater. Whereas stringent regulations to control microbial contaminants apply to drinking-water systems using surface water, only limited regulations apply to systems using groundwater.

This article reviews the current understanding of microbial contamination of groundwater and the implications for public health. It also discusses some approaches that have been successful in controlling pathogens in groundwater.

## Organisms and Their Associated Diseases

A large number of microbial pathogens are known to contaminate or may plausibly contaminate groundwater (Bennett et al. 1987; Herwaldt et al. 1992; Moore et al. 1993; Benenson 1995; Kramer et al. 1996). Some of these are listed in *Table 1*. These include more than 100 viral and several bacterial pathogens. This list also includes protozoa, such as *Giardia* and *Cryptosporidium*, although contamination of groundwater with protozoa generally indicates surface-water influence (USEPA 1989a, 1994). Most of these organisms are of fecal origin and are transmissible via a fecal–oral route of exposure.

The possible microbial illnesses that result from infection vary with the organism and vary markedly in their severity (*Table 1*). The predominant recognized illness is generalized acute gastrointestinal illness (AGI), resulting in fever, nausea, diarrhea, and/or vomiting. Most cases of AGI are of short duration, self-resolving, and may not be of major consequence to otherwise healthy individuals. However, for others this may not hold true. AGI may be chronic, severe, or fatal to some people. These include the elderly, infants, pregnant women, and especially the immuno-suppressed and immuno-compromised (Kaplan et al. 1983; Modlin and Kinney 1987; Lew et al. 1991; Gerba et al. 1996). Studies reported by Sobsey et al. (1991) indicate that more sensitive subpopulations, including infants and those over 70 years old, have mortalities of 3–5% from diarrhea requiring hospitalization.

An additional concern is that some organisms produce other illnesses beyond AGI that may have more serious consequences. Coxsackie virus infection, for example, is associated with heart and circulatory disease (myocarditis, pericarditis), aseptic meningitis, and insulin-dependent diabetes melitis. Hepatitis A infection may result in fever, jaundice, or liver damage, or it may progress to death. The Center for Disease Control and Prevention (CDC) calculated death rates from hepatitis A illnesses in the US at 0.3% of those who are ill (Bennett et al. 1987). Pregnant women have a 10–20% mortality to hepatitis E infections (Craske 1990). The CDC presents data that indicate that overall death rates from waterborne illnesses from a variety of organisms approach 0.1% (Bennett et al. 1987). Estimated annual waterborne disease deaths in the US are 900–1800 (Bennett et al. 1987; Morris and Levin 1995).

**Table 1** Pathogenic microorganisms of concern in groundwater

| Organism | Associated health effects |
|---|---|
| <E6> Viruses</E6> | |
| Coxsackie | Fever, pharyngitis (sore throat), rash, respiratory disease, diarrhea, hemorrhagic conjunctivitis, myocarditis, pericarditis, aseptic meningitis, encephalitis, reactive insulin-dependent diabetes, hand, foot and mouth disease |
| Echo | Respiratory disease, aseptic meningitis, rash, fever |
| Norwalk | Gastroenteritis (fever, vomiting, diarrhea) |
| Hepatitis A | Fever, nausea, jaundice, liver failure |
| Hepatitis E | Fever, nausea, jaundice, death |
| Rota | Gastroenteritis (fever, vomiting, diarrhea) |
| Enteric adeno | Respiratory disease, hemorrhagic conjunctivitis, gastroenteritis |
| Calici | Gastroenteritis (diarrhea) |
| Astro | Gastroenteritis (diarrhea) |
| <E6>Bacteria</E6> | |
| *Escherichia coli* | Gastroenteritis (diarrhea) |
| *Salmonella* spp. | Enterocolitis (fever, diarrhea, vomiting), endocarditis, meningitis, pericarditis, reactive arthritis, pneumonia |
| *Shigella* spp. | Gastroenteritis (diarrhea, fever, vomiting), reactive arthritis |
| *Campylobacter jejuni* | Gastroenteritis (diarrhea, fever, vomiting), Guillain-Barre syndrome |
| *Yersinia* spp. | Diarrhea, reactive arthritis |
| *Legionella* spp. | Legionnaires' disease, Pontiac fever, death |
| Vibrio cholera | Diarrhea, vomiting, death |
| <E6>Protozoa</E6> | |
| *Cryptosporidium parvum* | Diarrhea |
| *Giardia lamblia* | Chronic diarrhea |

## Occurrence of Microbial Pathogens in Groundwater

Contamination of groundwater with pathogenic microorganisms is generally believed to result from migration or introduction of fecal material into the subsurface. Primary sources of fecal contamination of health concern to humans include other humans and some animals. Whereas human diseases result largely from organisms specific to humans, the reoviruses, *Cryptosporidium, Giardia,* and several bacterial species pathogenic to humans occur in cattle, other mammals, and some birds.

Fecal contamination can reach groundwater from many routes. Of primary concern are concentrated point sources, such as failed septic systems, leaking sewer lines, and cesspools. Animal feedlots, dairy farms, and other intensive animal-husbandry operations may be significant sources in some settings but are far less common. Transport to groundwater is primarily a function of the hydrogeological setting and climatic conditions.

Although the authors are aware of data from more than two dozen studies of microbial contamination of groundwater, relatively few have been published (Hibler 1988; Bauder et al. 1991; Rose et al. 1991; Abbaszadegan et al. 1998, 1999; Hancock et al. 1998; USGS 1998). Pathogenic viruses and their indicators, indicators of fecal bacterial contamination, *Giardia,* and *Cryptosporidium* occur in significant fractions of tested wells, both public and private, throughout the US.

All public drinking-water systems are required to monitor for total and fecal coliform bacteria under the Total Coliform Rule (TCR) (USEPA 1989b). Analysis of EPA data on drinking-water enforcement shows that about 40,000 of the 156,000 groundwater systems have had TCR maximum contaminant level (MCL) violations, indicating coliform bacterial contamination of their groundwater, well, storage, or distribution system during the last 5 years. Because of limited monitoring requirements and state surveillance of non-community systems (systems that serve water to people on a less-than-full-time basis, such as schools or rest stops), these violations came primarily from the 44,000 community groundwater systems. For the larger, urban groundwater systems, violations were more often associated with distribution systems and may have been related to biofilm growth or from cross-connection events. For the smaller, rural groundwater systems, contamination is more often at the wellhead, indicating well- or source-water contamination. The majority of these violations involved detection of total coliform bacteria rather than fecal coliforms or *E. coli*. Because many coliform bacteria are not pathogenic, the implications of their occurrence for public health are not direct.

Some argue that protozoa such as *Cryptosporidium* or *Giardia* should not occur in true groundwaters, because their relatively large sizes make them more subject to natural filtration by soils than would be so for the smaller bacteria and viruses. One of the criteria to determine if a groundwater is under the direct influence of surface water is to consider the presence of protozoa. It appears, however, that some hydrogeological settings that would not indicate a surface-water influence do allow protozoan contamination. These include fractured rock and karst with limited unconsolidated soil overlayers. Hancock et al. (1998) report *Cryptosporidium* and/or *Giardia* detections in 12% of 199 groundwater sites across the country. Although the majority of detections were in springs, infiltration galleries, and horizontal wells, which are generally considered to be more subject to direct surface-water influence, *Cryptosporidium* was also detected in 5% of vertical wells, some of which could not be associated with surface sources. This result is consistent with the earlier findings of Hibler (1988) and Rose et al. (1991).

In terms of public health, most concern for groundwater has focused on pathogenic viruses resulting from fecal contamination. Their small sizes relative to the larger bacteria and protozoa may allow freer movement through unsaturated and saturated media. A major study of the occurrence of groundwater pathogens, supported by the American Water Works Association Research Foundation (AWWARF) and the USEPA, tested about 550 public water-supply wells (prior to any treatment) for various indicators of fecal contamination. These indicators included total coliform bacteria, *E. coli*, enterococci, somatic and male-specific coliphage (viruses infecting coliform bacteria), and human viruses detected by polymerase chain reaction (PCR) and cell-culture techniques. Wells were generally sampled only once. Results from the first phase of this work (244 samples) have been published (Abbaszadegan et al. 1998, 1999). About 50% of wells initially considered more vulnerable to contamination and 40% of wells initially considered less vulnerable were positive for one or more of these indicators. More specifically, 38% were positive for one or more pathogenic viruses using PCR, the most sensitive and encompassing of the currently available techniques. About 18% were positive for coliphage using assays not yet fully optimized. Human viruses were detected by cell culture in about 7% of samples, even though this method detects a distinctly limited subset of the human viruses of concern. About 10% were positive for coliform bacteria and 18% for enterococci. No correlations were seen between occurrence of fecal indicators and either soil type or distance from fecal sources.

An earlier USEPA/AWWARF study (Lieberman et al. 1995) examined 30 public water-supply wells judged to be vulnerable to fecal contamination. These were sampled monthly for 1 year. The authors report 24% positive for culturable viruses, more than 50% positive for one or more coliphage, 50% positive for *E. coli*, and 70% positive for enterococci. Their results indicate that multiple samples of a source were necessary to determine contamination.

Other studies of groundwater microbial contamination are more limited in scope and/or unpublished at this time. Bauder et al. (1991) examined private wells in Montana and report about 40% contaminated with coliform bacteria. This level is nearly identical to that in an unpublished study by the CDC of more than 5500 private wells in the midwest US. The US Geological Survey (USGS 1998) reports about 8% of wells positive for culturable human viruses and 8% positive for coliphage in a study of 109 public wells in Missouri.

It is uncertain how representative these data are in characterizing the occurrence of fecal contamination in groundwaters in general across the US. Major factors affecting groundwater-system vulnerability include hydrogeological setting, well construction, well depth, and proximity to sources of fecal contamination (Wireman and Job 1997, 1998). The studies of Abbaszadegan et al. (1998, 1999) relied on volunteer utilities and predominantly examined larger urban groundwater systems that provided disinfection as a matter of best management practice. They selected wells that were generally deeper, better constructed, and better maintained in order to reduce vulnerability and wellhead-related effects. As a result, smaller systems, rural systems, and wells with poorer construction were less represented. Thus, their results probably under-represent national occurrence. At the other end of the spectrum, Lieberman et al. (1995) selected specifically for vulnerable wells. Their results were three- to five-fold higher for specific indicators, although the overall well-specific fecal contamination levels were similar. If these results are approximately representative of groundwaters used for drinking water, they are substantially higher than previously believed and challenge the idea that few groundwaters are contaminated with microbes.

## Public Health Concerns Regarding Microbial Pathogens in Groundwater

Although data exist that some drinking-water wells are contaminated with fecal material, it is not known how many of the 110 million people served by groundwater-based public water systems and the 20 million or so on private wells become sick each year, the key question for protection of public health. Epidemiological studies to determine this directly have not been carried out. However, several lines of evidence give us reason to believe that a health problem exists.

### *Outbreaks of Waterborne Disease*

Microbial pathogens in groundwater systems are known to have caused numerous disease outbreaks in the US. Craun and Calderon (1997) report 356 outbreaks from 1971 to 1994 caused by contaminated groundwater systems, 58% of the total of all waterborne outbreaks. Community systems were involved in 32% of these outbreaks, non-community systems in 68%. Contamination of the groundwater source was considered responsible for 70% of these outbreaks; contamination of the distribution system for 30% (Craun 1991; Craun and Calderon 1997). For community groundwater systems, inadequate disinfection was cited in 23% of outbreaks, lack of disinfection in an additional 20%. For non-community groundwater systems, these numbers were respectively 28% and 53%.

Acute gastroenteric illness was the most common disease described in these outbreaks, accounting for 35% in community systems and 75% in non-community systems. Frequently, no causative agent was identified. When a disease agent has been identified with an outbreak, *Shigella,* hepatitis A virus, norwalk virus, *Giardia lamblia, Campylobacter jejuni*, and *Cryptosporidium parvum* have been implicated. However, the number of individuals reported ill from these outbreaks is generally understood to underestimate the actual levels of microbial disease associated with drinking water for the overall population (Frost et al. 1996). Two reasons are offered: (1) the nature of outbreaks themselves, where significant numbers of individuals get sick over a short time, does not describe endemic levels of disease; and (2) reporting of disease outbreaks in the US is poor.

The CDC maintains a database of information regarding outbreaks of waterborne diseases in the US. This database is based upon responses to a voluntary survey that is completed by state and local public-health officials. To be considered a waterborne outbreak, acute illness must affect at least two persons and be epidemiologically associated with the ingestion of water (Frost et al. 1996; Craun and Calderon 1997). Outbreaks are generally recognized when a significant fraction (1–2%) of a population gets sick within a few weeks, such that local physicians or laboratories recognize that something unusual is happening. As noted above, groundwater outbreaks are typically associated with some sort of contamination event or treatment failure, where unusually high numbers of organisms may occur in the water delivered to consumers.

The majority of disease outbreaks is not reported to the CDC and, therefore, they are not represented in this survey. The likelihood that individual cases of illness will be epidemiologically linked and associated with water varies considerably among locales and is dependent on factors such as public awareness, physician interest, availability of laboratory-testing facilities, and surveillance activities of state and local health agencies. Therefore, the states that report the most outbreaks may not be those in which the most outbreaks actually occur (Frost et al. 1996). This often additionally requires that the disease itself be noteworthy or reportable (cholera, giardiasis, cryptosporidiosis) and not simply “viral gastroenteritis” or diarrhea. In large cities, small outbreaks may be obscured, because ill people may consult so many different physicians that nothing unusual is noticed. Outbreaks associated with community water systems are more likely to be recognized than those associated with non-community systems, because the latter generally serve transient populations. Outbreaks associated with private systems are believed most likely to be under-reported, because they generally involve few people and occur in a rural setting.

### *Endemic Illness*

Endemic illness, not necessarily associated with a massive contamination event leading to a disease outbreak, occurs at levels below that necessary to detect an outbreak. Epidemiological studies have shown that the average individual has 1.5 cases of diarrhea over the course of a year from any of a variety of sources (Bennett et al. 1987; Payment et al. 1991). Data indicate that drinking water may contribute 10–30% of these cases (Payment et al. 1991). However, no epidemiological studies have looked directly for waterborne disease. Annual waterborne microbial illnesses in the US have been estimated at between 7 and more than 27 million cases (Haas 1993; Morris and Levin 1995). The majority of these is probably associated with groundwater systems, because all systems using surface water are currently required under the Surface Water Treatment Rule (USEPA 1989a) to have substantial disinfection in place and maintain a disinfectant residual in their distribution systems. Most surface-water systems provide substantial physical removal (coagulation, sedimentation, and filtration) as well. As described later in this article, substantially fewer groundwater systems disinfect to these standards. About 22 million Americans were estimated to drink water that was not disinfected from community groundwater systems and perhaps as many from private wells.

Because direct information on waterborne disease is not available, estimates based on occurrence data and the pathogenic properties of the organisms may be useful. Methods exist to develop quantitative risk assessments for groundwater systems (Regli et al. 1991; Haas et al. 1993; Gerba et al. 1996; Hurst et al. 1996; Crabtree et al. 1997). However, available data on both the occurrence and the organisms of interest limit this approach.

Interpretation of the significance to public health of the occurrence studies is difficult for several reasons. Whereas the presence of indicators of fecal contamination in drinking water would not be acceptable from the standpoint of public health risk management, fecal contamination itself does not mean that the water contains pathogens, only the potential for pathogens. Many pathogens with specific infectious properties could be and probably are present, but any one organism may not be. Depending on the size of the population providing the fecal source material, the prevalence of specific diseases in that population, and other environmental factors, specific pathogens may not occur at all or only during certain times of the year. As a result, fecal-occurrence data alone cannot easily be used for quantitative assessments of health risk.

If quantitative assessments of risk are based solely on data for human pathogens, such as virus PCR and cell culture data, other problems arise. For example, PCR detects viral pathogen nucleic acids but does not require intact virus particles; hence, positive results may be obtained from non-infective material. The PCR results presumably are associated only with the presence of fecal material; thus, the method is useful as an indicator, but again quantitative risk calculations cannot be done. Reliance on cell culture data for viruses is also problematical, but for another reason. Very few of the pathogenic viruses of health concern can be successfully cultured at this time. Therefore, although quantitative risk assessments can be done using these data, they would be expected to underrepresent true risks.

Complicating issues also exist with respect to the pathogenicity of the organisms of interest. Limited data are available on the pathogen doses necessary to yield infection. Acceptable data exist on only a few viruses, bacteria, and protozoa (Regli et al. 1991). Additionally, only a limited understanding of the relationship between infection and the various forms of illness observed exists. Perhaps only about 50% of infections result in illness (Gerba et al. 1996; Hurst et al. 1996). Immunity to these pathogens is poorly understood, much less quantifiable. In some cases it may involve true immunity to infection. In other cases, infection may occur, but it is asymptomatic or sufficiently mild that it is not recognized. This may explain "tourist's syndrome," where residents of a small community or homeowners using private wells do not report illnesses, but visitors do.

## Groundwater Microbial Risk Assessments

If the uncertainties from these data limitations are accepted and plausible assumptions are used, assessments can be performed to estimate the magnitude of endemic waterborne illness from groundwater systems. Such assessments may at least provide a range of possible impacts useful for public policy and management discussions.

As an example, estimates were constructed of the annual number of people in the US that might become ill from consuming groundwater that has not been disinfected from community water systems and from all public water systems. These estimates were generally based on rotavirus, because data sets are most complete for this virus group. However, because groundwater outbreaks have occurred where other pathogenic microorganisms have been involved, estimates based solely on rotavirus are likely to under-represent true levels of waterborne illness.

The occurrence-input data were developed as follows:

- The range in the percentage of wells with evidence of fecal contamination was taken as from 7% (based only on the presence of culturable human viruses) to 46% (based on all indicators).
- The data are assumed to be representative of wells across the US.
- A recovered most probable number (MPN) of 0.4/100 L and a recovery rate of 0.5, based on Abbaszadegan et al. (1999), were assumed for all data sets.
- Because the species composition of the cell-culture data is unknown, rotavirus occurrence is assumed for positives based on the PCR results of Abbaszadegan et al. (1999): 18% of all wells detected rotavirus of the 38% total wells with one or more fecal detections =0.47.

The exposure assessment combines occurrence with populations and ingestion rates:

- Occurrence in wells that have not been disinfected was assumed to be the same as for disinfected wells.
- Disinfection, if in place, was assumed to be adequate to reduce the risk to zero.
- Twenty two million people were estimated to drink from community water systems (CWS) that had not been disinfected, for 350 days/year (from USEPA databases).
- Five million people were estimated to drink from non-transient, non-community (NTNC) water systems that had not been disinfected (schools, factories), for 250 days/year.
- The standard water consumption rate of 2 L/day was used for these populations. This value was converted to a "day-L" exposure: 15.4 billion day-L CWS exposures; 2.4 billion day-L NTNC exposures.
- Two hundred and fifty million people were estimated to drink from transient non-community (TNC) water systems that had not been disinfected, twice a year.
- A water-consumption rate of 1 L/day was used for this population and an equivalent day-L exposure was calculated: 500 million day-L TNC exposures.

Only dose-response data for rota- and echoviruses are available to represent human pathogens of concern.

- The dose response for rotavirus for annual risk of infection at 0.4/100 L MPN is 0.834 (Gerba et al. 1996).
- An illness rate of 50% infection rate was used (Haas et al. 1993).
- To estimate mortalities, the elderly were taken as the primary subpopulation of concern. A mortality rate for elderly populations of 0.01 the illness rate was used and a population of elderly of 16% assumed (Gerba et al. 1996).
- A 25% secondary infection rate was assumed.

Based on the above data and assumptions, risks are as follows:

1. Waterborne illnesses in groundwater-based community water systems were estimated to be 750,000–5.0 million illnesses/year [22 million people exposed × 7–46% contamination rate × 0.47 rota contribution × 0.5 illness/infection/0.5 recovery × (834 rota dose-response @ 0.4/100 L MPN) × 1.25 secondary spread rate = 750,000–5.0 million illnesses/year].
2. Waterborne illnesses for all public supplies using groundwater were estimated to be 890,000–5.9 million illnesses/year [calculated by multiplying the above CWS illness estimate by a ratio of day-L exposures for (CWS+NTNC+TNC/CWS) = (15.4 + 2.4 + 0.5)/15.4 × (750,000 – 5.0 million) = 890,000 – 5.9 million illnesses/year].
3. Mortality from waterborne illness was estimated to be 1400 – 9400 deaths/year [calculated by multiplying the above illness estimates by deaths divided by illness and percent elderly 0.01 × 0.16 × (890,000 – 5.9 million) = 1400 – 9400 deaths/year].

These estimates are consistent with CDC mortality data (Bennett et al. 1987) and with independent assessments of waterborne illness and mortality (Haas 1993; Morris and Levin 1995; Hurst et al. 1996; USEPA 1998).

## Approaches to Control Waterborne Microbial Pathogens

USEPA databases indicate that about 400,000 public drinking-water wells and many more private wells exist in the US. The public wells are spread between about 44,000 CWS, perhaps 19,000 NTNC water systems, and 93,000 TNC water systems (rest stops, campgrounds, restaurants, etc.). Almost all of these 156,000 systems are very small. Fewer than 400 community groundwater systems serve more than 50,000 people; another 4000 systems serve between 3300 and 50,000 people. About 40,000 community systems serve fewer than 3300. The NTNC and TNC systems generally serve relatively few people on a regular basis but may serve many people irregularly or infrequently.

The USEPA has articulated public-health goals for microbial contamination of drinking water from surface sources in the Surface Water Treatment Rule (SWTR) (USEPA 1989a) and Interim Enhanced SWTR (IESWTR) (USEPA 1998). Maximum contaminant level goals (MCLGs) have been established at zero for *Giardia*, *Legionella, Cryptosporidium*, total coliform bacteria, and viruses. MCLGs are not enforceable, but they provide the public-health directions for the enforceable National Primary Drinking Water Regulation (NPDWR) (Macler 1993). The corresponding NPDWR primary-treatment goal is to achieve no more than one *Giardia* (SWTR) or *Cryptosporidium* (IESWTR) infection per 10,000 exposed people per year. Prevention of outbreaks of waterborne-microbial diseases is another public-health goal of these regulations. The public-health goal for the TCR NPDWR (USEPA 1989b), which applies to both surface- and groundwater-based drinking-water systems, is to have no total or fecal coliform bacteria detected in the system. In public discussions for USEPA's Groundwater Rule, which will specifically address microbial contamination in groundwater-based public water systems, public-health goals to prevent outbreaks of waterborne diseases and to reduce levels of endemic waterborne disease were articulated. A regulatory goal to prevent fecal contamination from reaching the consumer by requiring a series of barriers was developed (Macler 1996; Macler and Pontius 1997).

Control of waterborne microbial pathogens thus centers on eliminating the route of exposure from fecal sources through groundwater to the consumer. This may be accomplished at every step in the process, for example, by eliminating sources of fecal contamination from the recharge zones or zones of influence around wells, siting wells to provide adequate natural attenuation of microorganisms, ensuring proper well construction to prevent surface contamination at the wellhead, controlling cross-connection contamination events in distribution systems, and providing disinfection treatment.

### Best Management Practices and Supporting Regulations

These and other public-health practices are employed by drinking-water utilities, either voluntarily or in response to regulatory requirements. These "best management practices" (BMPs), listed in *Table 2*, generally have had long, successful track records in protecting public health. Many have served successfully as regulations, policies, or guidelines at the state level. Until passage of the federal Safe Drinking Water Act (SDWA) of 1974, utilities and states acted as mostly independent experimentation laboratories of drinking-water protection. After 1974, the subsequent NPDWRs placed a minimum foundation under these activities. However, experimentation did not cease, as individual states continued to tighten their programs in response to local needs. To get a better understanding of the utility and commonality of these practices, the USEPA collected groundwater-related statutes, regulations, guidance, and disinfection practices from all states (Merkle et al. 1996; Merkle and Reeverts 1997).

### Source-Water Protection Barriers

Several BMPs act to control pathogen sources or their proximity to the wellhead. Source-water assessment and protection programs and wellhead protection programs aim to control or eliminate sources of contamination. Well-siting criteria that use hydrogeological information and appropriate setback distances from fecal sources can help ensure that contamination does not reach the well. Monitoring for microbial pathogens or surrogates (such as total or fecal coliform bacteria) provides direct information on contamination.

However, monitoring for pathogens at the wellhead, while desirable and useful, is inadequate by itself to ensure protection to the public. Monitoring results are useful only in a reactive mode, in that they are generally available only after exposure has occurred. Because infection may result from very limited exposure to pathogenic microorganisms, protective elements should focus on proactive measures. Monitoring results may be equivocal for other reasons: (1) if a system is positive for a pathogen or fecal indicator at a given time, uncertainties remain in the frequency and magnitude of this contamination, as well as in the types and health significance of other organisms that might co-occur; (2) if a system is found negative for indicators, it may be in fact contaminated, but the limitations of monitoring frequency, sample size, and level of quantitative analysis may not show this; (3) a system that is negative may be without contamination now but not in the future.

To supplement monitoring, assessments of source-water vulnerability may be useful. Such assessments

**Table 2** Best management practices to control microbial pathogens in groundwater

| | |
|---|---|
| Source-water protection barriers | Approved source-water protection or wellhead-protection program<br>Minimum setback distance(s) specified from microbial contamination to wells<br>Hydrogeological criteria used for well siting<br>Wellhead-monitoring data required |
| Well and water-system integrity barriers | Sanitary survey and corrections required<br>Well-construction codes |
| Operations and system-maintenance barriers | Well and pump disinfection<br>Periodic flushing of distribution system<br>Disinfection of new/repaired water mains<br>Cross-connection control programs<br>Requirements for certification of operators |
| Disinfection requirements | Specified disinfection C × T values<br>Microbial kill/reduction values<br>Specified minimum disinfectant or chlorine residual in distribution system |

generally consider land uses and sources of contamination, combined with determinations of hydrogeological sensitivity (Wireman and Job 1997, 1998). Common vulnerability factors include time of travel, presence of confining layers, soil type, depth of the unsaturated zone, nitrate levels, presence and location of contamination sources, and monitoring data. However, substantial uncertainty may exist in estimating vulnerability.

Hydrogeological criteria may indicate that a well is vulnerable to contamination, but the water may still be safe if adequate natural filtration of microbial pathogens has occurred in the subsurface. The traditional setback distance between source and well is an application, based on best professional judgment, of this concept. This is an extension of the assumption that protozoa do not contaminate true groundwaters, because their large size results in their being filtered out by the soil within a short distance from their source. Evidence exists that bacteria and viruses are similarly filtered out or absorbed by some soils under some conditions (McDowell-Boyer et al. 1986; Bales et al. 1989; Gerba et al. 1991). Hydrogeological conditions of productive aquifers and well sites vary widely across the US. Significant disagreement exists among experts in this field concerning whether this filtration can be adequately predicted or quantified to be of use for predicting risks and establishing public-health guidance on either a site-specific or national basis.

Similarly, pathogenic microorganisms may be inactivated in the subsurface over time such that, even if physically detected in groundwater, they are incapable of causing infection. The rate of this inactivation is organism-specific and highly influenced by subsurface physical and chemical conditions (Hurst et al. 1980; Hurst and Goyke 1986; Kutz and Gerba 1988; Hurst et al. 1989). As with physical removal, substantial disagreement exists about whether and how data on inactivation can be used to predict vulnerability. Setback distances and time-of-travel requirements from fecal sources used by states and communities to site wells are seldom if ever field validated.

### Source Water Assessment and Protection Programs

The 1996 Amendments to the SDWA established USEPA programs designed to support source-water protection in two ways. The Amendments mandate that states develop and implement statewide source-water assessment programs (SWAPs). Some funding for this can be obtained from set-asides to State Drinking Water Revolving Funds. States are encouraged to develop and implement voluntary source-water protection programs (SWPPs) as well.

SWAPs are to be implemented by the states for all sources of drinking water on a one-time basis over the next few years. They are to provide a consistent baseline of information on the vulnerability of sources to problematic contamination. A SWAP for groundwater sources includes three components: (1) a delineation of zones of influence around production wells; (2) an inventory of sources of contamination within these zones of influence; and (3) an assessment of well "susceptibility" (vulnerability) to contamination based on the contaminant occurrence and characteristics and hydrogeological information (USEPA 1997). States may be able to use SWAP products in their sensitivity determinations under the USEPA's proposed Groundwater Rule. Information from SWAPs can be used by local communities to create a SWPP to address current problems and prevent future threats to drinking-water quality.

SWPPs are community-based approaches to protecting sources of drinking water from contamination. With respect to providing enhanced microbial protection, SWPPs can be designed to promote a barrier to fecal contamination reaching the wellhead recharge area or zone of influence. The goal would be to eliminate or control fecal sources or ensure that adequate natural disinfection occurs in the unsaturated zone or groundwater prior to reaching the well. Management of sources is optional under the 1996 Amendments, although program guidance can provide approaches to manage existing and potential contamination problems. This approach supports collective efforts among local governments, farm and business interests, and citizen groups at the community, regional, and watershed levels. The success of these efforts depends on the involvement of all stakeholders in the implementation process. Because SWPPs are based on community and site-specific activities, the extent of the program's effectiveness cannot easily be measured and compared from one locality to the next.

SWPP activities include state and local wellhead-protection programs, state and local groundwater-protection programs and Underground Injection Control Class V programs. Local watershed-protection activities that target groundwaters or groundwater recharge areas for protection may also add to the source-water assessment and protection barrier.

### Wellhead Protection Programs

Wellhead protection is the protection of the area surrounding a well from significant potential sources of anthropogenic contamination. The USEPA has approved wellhead protection programs for 44 states and 3 territories. Some states have adopted mandatory requirements, whereas others use approaches based on voluntary activities.

The functioning unit of this program is the wellhead protection area (WHPA), which is defined as the surface and subsurface area surrounding a well or well field that supplies a public water system. WHPA boundaries are determined based on factors such as well pumping rates, time of travel of groundwater flowing to the well, aquifer boundaries, and degree of confinement. These hydrogeologic characteristics have a direct effect on the likelihood and extent of contamination.

A WHPA can be established for any type of aquifer. The extent of the areas within WHPAs varies depending upon the program goals of individual states and municipalities and the hydrogeologic settings. These programs involve forming a local team, delineating a protection area, identifying potential sources of contamination within that area, and managing these sources to protect the wellhead. By defining a WHPA and conducting an inventory of potential contaminant sources, a water supplier can gain valuable insight into the potential threats that exist to the water supply. Where possible, a public water system may help ensure the protection of existing wells from contamination through the implementation of effective management controls on these sources.

### *Possible Source Controls*

Source-control activities may be generalized to the area, such as through zoning requirements, health regulations, land acquisition, and conservation easements. They may also be site- or activity-specific, such as requirements for septic systems, sewer lines, discharges to groundwater, or feedlots. *Table 3* lists examples of source-specific control measures.

Examples of zoning controls include prohibition of certain sources, such as cesspools; limits on density of sources, such as septic tanks, through large-lot zoning; performance standards; and special permitting. Because zoning typically applies to future development and often exempts existing activities and systems, it is best used during planning.

Health regulations could include prohibition of microbial sources within a specified distance from the wellhead (e.g., setbacks). They could include performance standards for particular sources, such as design, operation, maintenance, and inspection requirements for septic tanks, sewer lines, or privately owned small sewage-treatment plants. In some cases, existing setbacks may not be large enough to protect the wellhead from microbial contaminants. The effectiveness of performance standards in preventing contamination of the wellhead by microbial contaminants may not be known.

Control by establishing requirements for land acquisition and conservation easements includes buying land in a source-water protection area and prohibition of potential sources of contamination. It includes buying or mandating conservation easements that restrict all or a portion of the property to open space or limited development. Success of this tool may depend on the public water system's or community's commitment to promote it, the presence of willing sellers, real-estate values, and the resources available to buy land or easements. Under the SDWA Amendments of 1996, states may now set aside up to 10% of the Drinking Water State Revolving Fund for loans to public water systems for purchase of land or easements.

It has proven difficult to assess the efficacy of wellhead protection programs and few such assessments have been attempted. Merkle and Reeverts (1997) report that states with approved wellhead programs had an average total coliform maximum contaminant level (MCL) violation rate of 27% (FY1991–1995) for community systems compared to 26% for states without approved programs (total coliform MCL violations indicate the presence of coliform bacteria in the drinking water system). Many assumptions were involved in this assessment For example, in this comparison they did not attempt to separate the older, established programs from the younger programs that may have had little time to make any impact upon TCR violations. However, the study does not suggest that this approach is positively affecting microbial contamination of groundwater systems in general.

### *Well-Siting Criteria*

The majority of states have well-siting requirements based either on hydrogeological criteria or on setback distances from sources of fecal contamination to the wellhead (Merkle et al. 1996; Merkle and Reeverts 1997). Twenty-four states always and five states some-

**Table 3** Examples of source-specific control measures

| | |
|---|---|
| Septic systems | Meets design standards<br>Installation provides adequate separation above groundwater<br>Adequate inspection and pumping requirements<br>Density restrictions, possibly based on nitrate loading analysis<br>Discharge is treated to kill pathogenic microbes<br>Additional requirements for new systems or systems needing repair |
| Sewer lines | Stricter standards for sewer line construction, testing, and manhole installation<br>Leak-detection system<br>Plan for corrective action if leak detected |
| Wastewater discharges to ground/injected wastewaters | Disinfect wastes before discharging<br>Alternative treatment that results in wastewater that meets a nitrate standard or other limit set by a state<br>Regular monitoring<br>Inject wastes only below aquifer used for drinking water |
| Feedlots | Divert runoff from feedlot area<br>Minimize runoff by reshaping area<br>Collect and treat runoff<br>Require lined manure pits<br>Collect and treat pit effluent<br>Establish a size threshold above which disinfection of waste materials is required |

times consider local hydrogeological criteria in the approval of the siting of a well. How carefully or with how much detail these criteria are applied in state practice is not known, nor is it known how frequently wells approved on erroneous information are required to be refitted or replaced. Without further research, the most that can be said about these programs is that they appear or do not appear in the regulations of a specific state. Most of these states give the regulatory agencies general authority to consider local hydrogeological characteristics or place the requirement to consider this feature upon the driller. Highly technical analyses, such as time-of-travel determinations or subsurface modeling, are not explicitly required. Hydrogeology is examined most commonly to determine whether to apply standardized setback distances, and to determine the depth of the well, the length of the casing, and the extent of the grouting, especially when confining layers are present. Some states, such as Louisiana, require consideration of general protective measures: "The earth formations above the water-bearing stratum shall be of such character and depth as to exclude contamination of the source of supply by seepage from the surface of the ground" (Louisiana State 1994).

The presence or absence of hydrogeological requirements can be compared with the statewide TCR MCL violation rates to determine whether these programs are associated with reduced violations at community water systems. States that do not employ hydrogeological criteria have a mean TCR MCL violation rate of 33%; states that employ such criteria have a mean TCR MCL violation rate of 23%, which represents a 30% reduction in violations. Put another way, among the 18 most successful states (i.e., those states with TCR MCL violation rates less than or equal to 20%), 72% of them use hydrogeological criteria. Of the 18 least successful states (i.e., those states with TCR MCL violation rates greater than or equal to 29%), only 28% use these criteria. Thus, the use of hydrogeological criteria in well siting appears to be associated with fewer TCR violations across a broad range of state groupings.

### Well and System Integrity Barriers

Other important means to control microbial contamination in well water focus on ensuring the integrity of wells and distribution systems. These include proper design and construction of wells, distribution lines, and storage systems according to applicable state criteria, codes, or regulations. They also include proper operations and maintenance activities.

Important examples include periodic inspections (sanitary surveys) of sources, well and system hardware, distribution lines, and storage, followed by the appropriate correction of deficiencies. Provision for a state-certified operator and implementation of an emergency response plan covering major equipment failure (e.g., well pump, transmission mains, etc.) or natural disasters help ensure successful operations.

Protection of the distribution system from fecal contamination entering via cross-connection events or siphonage is critical. A substantial portion of waterborne-disease outbreaks is associated with failures of distribution systems (Craun 1991). In urban settings, sewer lines and water mains may occupy the same trench or lack sufficient setback distances. Because sewer lines leak, pathogens can be expected external to water mains. Provision of a cross-connection control and backflow prevention program is desirable. Maintenance of an acceptable distribution system pressure at all times, water-main flushing programs, and maintenance of a disinfectant residual in the distribution system have all proved successful.

### Disinfection Barriers

Disinfection can provide a barrier at any or all points in the system, and it can provide protection to almost all of the source and system deficiencies possible in groundwater systems. At a minimum, all groundwater systems with known fecal contamination should have to disinfect, unless they immediately correct outstanding problems by some other means.

Technologies for inactivating microorganisms in groundwater are well understood, practical, and relatively inexpensive. These include the traditional use of chlorine, as gas, hypochlorite, or chlorine dioxide. They also include ultraviolet (UV) light, ozone, and ultrafiltration. The USEPA has assembled documentation on available UV, ozone, membrane filtration, chlorine, and other technologies suitable for small systems (USEPA 1996).

The degree of necessary disinfection is relevant. The SWTR (USEPA 1989a) specifies that systems must achieve a 99.99% inactivation of viruses at the first customer. This level of disinfection is considered to also ensure protection from pathogenic bacteria. This treatment level appears most appropriate to address situations with known microbial contamination. The disinfection approaches currently available are all capable of achieving this level of treatment. Another approach, frequently used for small systems, is merely to require a measurable (chlorine) disinfectant residual in the distribution system. This appears technically and economically feasible in almost all applications, yet still yields substantial disinfection credit.

Of all the groundwater protective practices studied in this work, none showed a greater state-to-state variation than disinfection. Disinfection of groundwater, defined here as the application of at least a detectable chlorine residual or its equivalent, has been addressed in some fashion by all but one state (Connecticut). Nationwide, about 55% of community water systems, 28% of non-transient non-community water systems, and 17% of transient non-community groundwater systems are disinfected. Individual state disinfection rates in these three categories range from 7%, 1%, and 1%, respectively, in Rhode Island, to 100% in these three categories in Florida, Kansas, Kentucky, and Texas.

The strikingly heterogeneous disinfection practices of the 50 states presented an opportunity to measure the relationship between statewide disinfection and statewide TCR MCL compliance rates. "Success" in this context was defined as having low TCR MCL violations. Results show that high disinfection rates are strongly associated with success. The ten highest disinfecting states have a mean TCR MCL violation rate of 18% over the 5-year period; the ten lowest disinfecting states have a mean TCR MCL violation rate of 38%. This represents a decrease in violations of more than 50% from the lowest disinfecting states to the highest. When the disinfection rates of the ten most successful states are compared with the disinfection rates of the ten least successful states, a similar result in favor of the disinfecting states is observed: the most successful states have an average disinfection rate of 72%, whereas the least successful states have an average disinfection rate of 29%. Disinfection, even at the low level of residual maintenance, is clearly associated with contaminant reduction.

## Conclusions and Recommendations

A variety of studies indicates that significant fecal contamination of groundwater wells occurs in the US. Data on waterborne-disease outbreaks in groundwater systems suggest a range of problems leading to these events. Given the apparent risks associated with groundwater systems that have not been disinfected, disinfection of all groundwater systems is a prudent public-health policy. Additionally, protection of sources from fecal contamination and maintenance of well and system integrity are likely to act as substantial barriers to contamination reaching consumers.

There remains a need for additional research on microbial contamination in groundwater and its impacts: (1) data are required to better define the public health problem. These include information on known and estimated public health risks (outbreak and endemic-disease information, pathogenicity of contaminant organisms, and microbial risk assessments) and microbial occurrence in groundwaters and distribution systems. Answers to these will help further define the nature and scope of any public health problem; (2) a better understanding is needed of the factors affecting and limiting microbial contamination of groundwater sources. Outstanding issues are the site-specific hydrogeological properties affecting vulnerability to contamination and the physical and chemical properties governing fate and transport of microbials in the subsurface.

## Disclaimer

The views expressed are those of the authors and do not necessarily represent those of the USEPA.

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