

Estimating the incidence of waterborne infectious disease related to drinking water in the United States

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Abstract The available data concerning outbreaks of waterborne infectious disease (WBID), incidence of infectious diseases and prevalence of pathogens in drinking water in the United States were used to estimate the rates of morbidity and mortality from WBID. Bacterial disease rates were estimated based on isolates reported to the Centers for Disease Control and Prevention (CDC), estimated rates for under-reporting of isolates, and cases per isolate as estimated by outbreak studies. Diseases due to parasites and viruses were estimated based upon the prevalence of specific pathogens or pathogen groups in drinking water coupled with models of infectivity. The incidence of infections from waterborne pathogens for which data were not available was estimated using expert estimates from a CDC study. Point estimates of 560 000 cases of moderate to severe cases of WBID infectious disease and 7.1 million cases of mild to moderate infections were obtained with an estimated annual mortality rate of 1200. The study also demonstrates the inadequacy of available data.

INTRODUCTION

Epidemiology, the science of public health and, for that matter, public health itself finds its roots in efforts to comprehend and prevent waterborne infectious disease. In the 1800s, England watched with fearful anticipation as the great cholera pandemics swept through Asia and finally crossed into Europe. The first cases of cholera in England provided the impetus for legislation establishing local boards of public health throughout the country.

In the early 1900s, gastrointestinal infections were the third leading cause of death in the United States. Within a few decades, the general use of drinking water chlorination coupled with improved antibiotic therapy led to dramatic reductions in mortality from waterborne infectious disease (WBID). Figure 1 shows the total number of cases WBID reported each year to the Centers for Disease Control and Prevention (CDC) and the associated case fatality rates. Mortality rates have declined dramatically as have the number of cases of WBID, but the decline in cases has reversed itself over the past thirty to forty years.

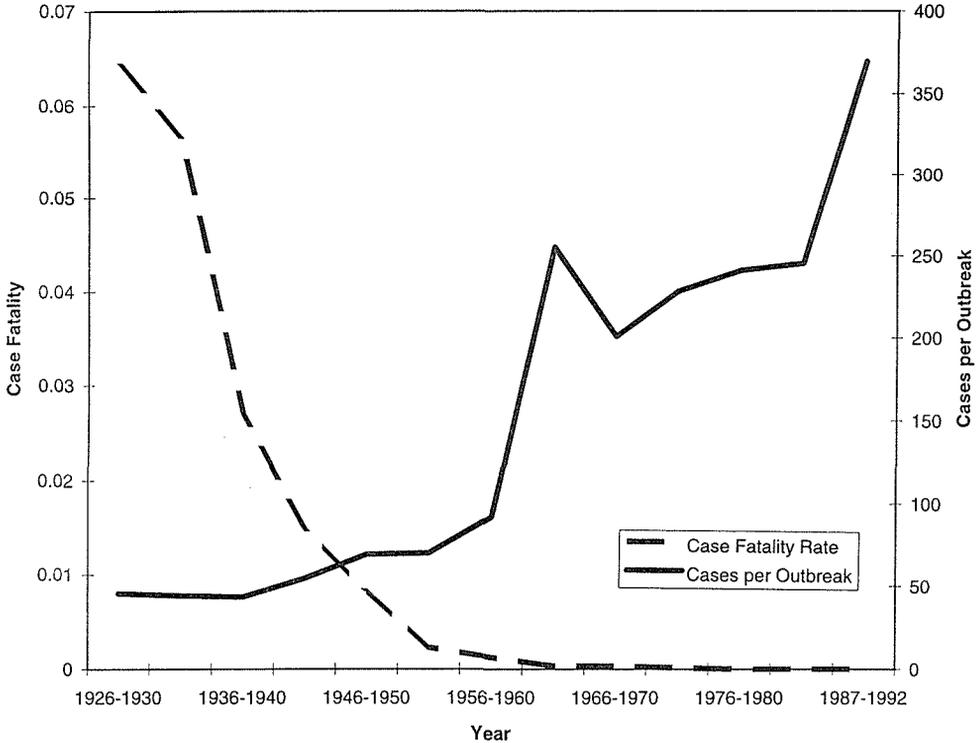


Fig. 1 Total cases of waterborne infectious disease reported to the Centers for Disease Control and Prevention together with the case-fatality rates for those outbreaks.

The problem of assessing rates of non-fatal WBID

Tracking trends in mortality rates and evaluating national mortality rates is relatively straightforward because mortality records have been centrally maintained for many years in the United States. Studying morbidity rates is a far more challenging task.

Cases of waterborne disease in the United States have been identified primarily through the reporting of outbreaks of WBID to the CDC. Outbreaks of severe disease with substantial mortality are relatively easy to detect. Less severe diseases, especially those with low case fatality rates, are more difficult to detect and have greater potential for occurring on an endemic basis. Self-limiting infections in particular are often treated without a specific diagnosis.

The goal of this study was to estimate the current annual incidence for WBID related to drinking water in the United States. The analysis was restricted to published and publicly available data. Only gastrointestinal infections were considered.

METHODS FOR ASSESSING WBID RATES

A range of approaches are available for assessing incidence rates for WBID. Passive surveillance through voluntary reporting of WBID outbreaks to CDC is the primary tool

used to track WBID in this country. Active surveillance can provide a more systematic and complete assessment of disease rates, but requires more resources than passive surveillance and has seen limited use. Surveillance of drinking water for contamination with pathogens has been more extensive and can provide information for estimating disease incidence rates. Some questions concerning the incidence of WBID cannot be answered by surveillance and require more focused epidemiological investigations.

Outbreak reporting

In the early twentieth century, the US Public Health Service introduced a system for the voluntary reporting of outbreaks of waterborne infectious disease. The CDC collect these data in cooperation with state and local health officials. Follow-up investigations of WBID outbreaks involve the collaborative effort of both the CDC and the Environmental Protection Agency (EPA).

An outbreak of drinking water related WBID is defined by CDC as, "an incident in which (a) two or more persons experience a similar illness after consumption or use of water intended for drinking and (b) epidemiologic evidence implicates the water as the source of illness". This system relies on primary care physicians recognizing such cases as potentially waterborne and conducting the follow-up activities necessary to report them. For some specific pathogens such as *Salmonella*, all individual cases are reportable. These data can be used by the CDC to identify outbreaks not recognized by individual physicians or health officials.

As illustrated in Fig. 2, there are many steps between exposure to a waterborne pathogen and the reporting of a case of WBID to CDC. Each box corresponds to a stage in the disease process with unique public health implications. Assessments of cases

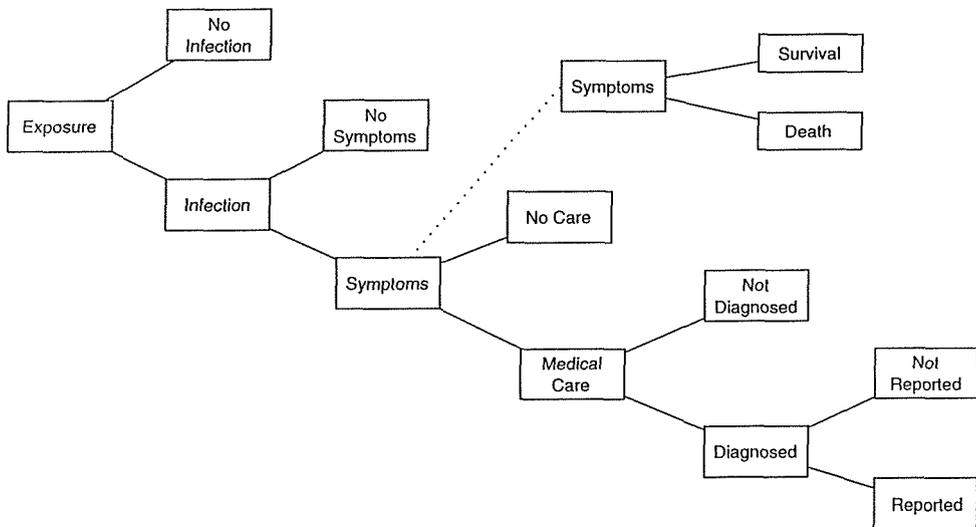


Fig. 2. Pathway from exposure to a waterborne pathogen to reporting of a case of as part of a waterborne outbreak.

based on measurements taken at each of these stages will yield substantially different estimates of disease incidence. Estimated incidence will decline as some portion of the affected population fails to proceed to the next step. Using CDC reporting data to estimate national WBID rates requires an understanding of the cumulative effect of these sequential surveillance artifacts (Rosenberg *et al.*, 1977; Chalker & Blaser, 1988).

In general, diseases that have only recently been identified as waterborne, diseases with mild symptoms of short duration and/or diseases for which simple tests have not been developed are less likely to be recognized when outbreaks are small. As evidence of this, Table 1 represents a compilation of the sizes of outbreaks reported to CDC since 1920. As further evidence of this, trends of decreasing case fatality from reported outbreaks (Fig. 1) have been accompanied by increases in the size of cause-specific, reported outbreaks (Fig. 3).

Many diseases are reportable to CDC whether or not they represent an outbreak. These include two important waterborne pathogens, *Salmonella* and *Shigella*. The CDC surveillance program calls for laboratories to report all isolates of either of these pathogens. However, like outbreak reporting, the reporting of cases is voluntary with a potential for under-reporting. It is necessary to estimate the number of cases represented by each isolate in order to estimate the total incidence of each disease.

Active disease surveillance

Active surveillance is a more costly, but more accurate tool for the direct evaluation of WBID rates. Population prevalence estimated by stool culture surveys coupled with data

Table 1 Sizes of outbreaks reported to CDC by identified pathogen for the period 1920 through 1993 (based on Craun, 1986; 1986b; St Louis, 1988; Levine & Craun, 1990; Herwaldt *et al.*, 1991; and Moore *et al.*, 1993).

Pathogen	Average number of cases per reported outbreak
Amebic dysentery	13
Typhoid fever	15
Poliomyelitis	16
Cholera	17
Hepatitis A	34
Salmonellosis	38
Giardiasis	107
Shigellosis	239
E. coli infection	243
Gastroenteritis (organism unspecified)	295
Viral	441
Campylobacteriosis	776
Cryptosporidiosis	4138

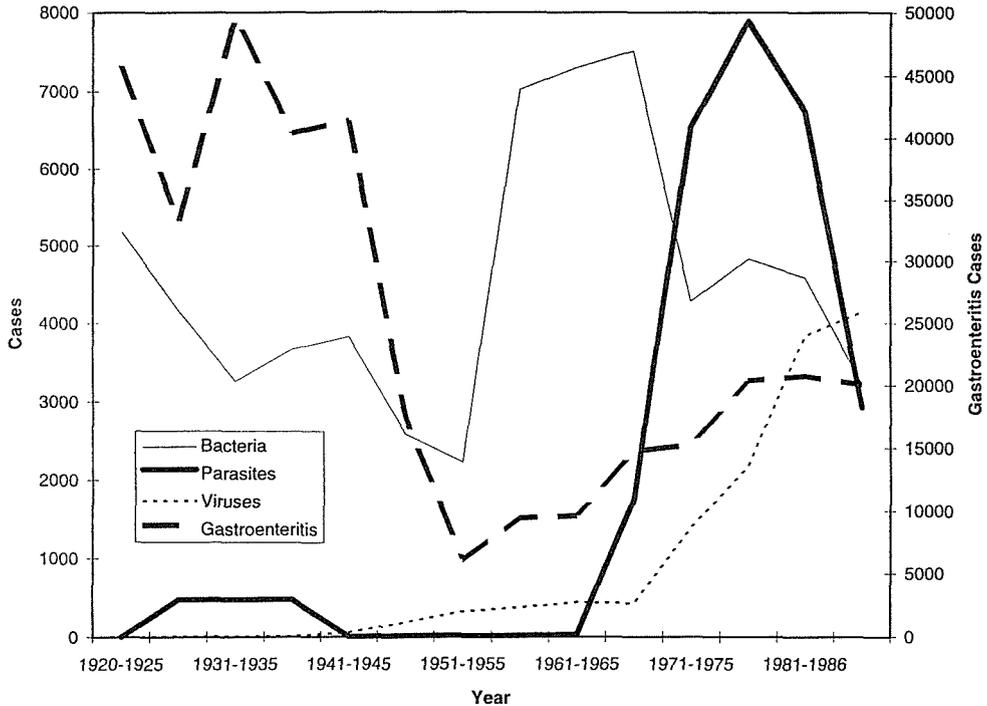


Fig. 3 Total cases in waterborne outbreaks reported to CDC by pathogen group.

on duration of excretion of pathogens can provide estimates of infection rates. Longitudinal studies of seroconversion can also provide estimates of infection rates for some diseases. Regular surveys of selected medical facilities and practitioners or analysis of data collected for other purposes such as hospital billing data and computerized records from pathology laboratories may also be adapted for disease surveillance.

Pathogen surveillance

Measuring the presence of pathogens in drinking water supplies can provide useful information for estimating disease incidence rates. An accurate estimate of disease rates for an individual water supply using this approach requires knowledge of the frequency distribution of levels of contamination and the quantitative relationship between drinking water levels and rates of symptomatic disease. Both of these elements involve substantial uncertainty, particularly the dose-response relationships for specific sub-populations such as children and the elderly.

Non-surveillance based tools

Other tools may be helpful in estimating incidence rates for gastrointestinal infections. Perhaps the most innovative approach to the evaluation of incidence rates for WBID was

an intervention study conducted by Payment *et al.* (1991) documenting that the introduction of membrane filtration in a group of test homes reduced the number of cases of mild to moderate gastrointestinal infections by 35% as compared to control homes.

In one of the most complete assessments of infectious disease rates in the United States, Bennett *et al.* (1987) relied on expert opinions provided by staff scientists at CDC to estimate the pathogen specific incidence of infectious diseases. For each pathogen, the per cent of cases attributable to various sources is estimated. The proportion given for waterborne disease does not distinguish between drinking water and recreational water use. Given the CDC data suggesting that approximately 90% of outbreak related cases of WBID are associated with drinking water, we assumed a drinking water pathway for all of Bennett's numbers. These estimates were based upon the 1980 US population, which has grown by approximately 10% during this period, so the assumption probably does not introduce substantial inaccuracy.

ESTIMATING RATES OF WBID

All of these approaches have limitations, and none provides a complete picture of the incidence of WBID in the United States. The complexity of estimating rates of WBID demands the use of all available information. The characteristics of each pathogen and its associated disease make it more or less suited to estimation by a specific method. It is reasonable, however, to group these agents according to the major categories of pathogens: bacteria, parasites, and viruses.

Bacterial diseases

Bacterial infections are the best understood and most easily diagnosed waterborne diseases. In addition, bacteria are generally more susceptible to conventional drinking water treatment technologies, especially chlorination. Endemic rates of these bacterial infections are likely to be extremely low. It is unlikely that outbreaks of these infections would escape identification in the CDC reporting system. Other, less severe, infections may occur in substantial numbers.

Salmonella* and *Shigella Although typhoid infections are rare in the United States, less virulent species of *Salmonella* cause many cases of gastroenteritis each year in this country. As noted above, isolates of *Salmonella* and *Shigella*, another major cause of gastrointestinal morbidity, are reported to the CDC. In 1993, 42 000 isolates of *Salmonella* and 32 000 isolates of *Shigella* were reported to CDC (1994). It is likely that reported cases account for only a fraction of the actual cases. Twenty years ago, a committee of the National Academy of Sciences estimated that two million cases of salmonellosis occur each year in the United States (NAS, 1969).

In a more recent study looking at under-reporting of isolates, Hauschild & Bryan (1980) evaluated the reporting of food and waterborne outbreaks. They evaluated the ratio of the total number of cases estimated by follow-up investigations of the outbreak to the number of isolates initially identified. The median estimate from a total of 26 studies of salmonellosis outbreaks was 29.5 cases per isolate. Chalker & Blaser (1988)

reduced this estimate to 19.2 cases per isolate by eliminating several weaker outbreak investigations. Alternatively, using an approach based upon sequential surveillance artifacts, they estimated this figure to be 17.7 cases per isolate. (The figure listed in their paper is 39.0, but this refers to infected persons and includes a multiplier of 2.2 for the rate of symptoms among infected persons. The current study was limited to symptomatic disease.) We multiplied the lower figure of 17.7 cases per reported isolate by the 1993 CDC data for numbers of *Salmonella* isolates to provide a low estimate of 740 000 cases per year for the incidence rate of salmonellosis. Based on carriage rates, Chalker & Blaser estimated 3.7 million infections per year, but this figure includes all infections. Adjusting for the ratio of infections to symptomatic cases, this becomes 1.7 million. This served as the high estimate for the number of cases. Hauschild & Bryan's estimate of the proportion of these cases that were waterborne was 10%. Bennett (1987) estimated this number at 3%. This range, 3-10%, was used as to estimate the extremes for the number of cases of waterborne salmonellosis.

The data for *Shigella* are less extensive. Rosenberg *et al.* (1977) estimate that each isolate of *Shigella* reported to CDC represents 15.2 cases of symptomatic disease. This ratio was applied to the 32 000 isolates reported to CDC in 1993 to give a high estimate of 490 000 cases per year. The estimate by Bennett *et al.* (1987) of 300 000 cases per year served as the low estimate. Of the estimated cases, 10% were assumed to be waterborne (Bennett *et al.*, 1987).

The estimation of incidence for WBID from these two bacteria is summarized in Table 2.

Campylobacter* and *E. coli *Campylobacter* is among the most common forms of infectious diarrhea among developed countries (Skirrow, 1991). Enterotoxigenic *E. coli* is a major cause of travelers' diarrhea. *E. coli* will be detected directly by the coliform counts used as the standard indicator for bacterial contamination of drinking water. Nonetheless, treatment failure or consumption of contaminated, untreated water can lead to exposure to this agent. Neither *Campylobacter* nor *E. coli* infections are routinely reported to the CDC and their incidence is less well studied than either *Salmonella* or *Shigella*.

Skirrow (1991) estimated that, in Britain, the annual infection rate with *Campylobacter* may be as high as 11/1000. This would correspond to approximately 2.8 million cases per year in the United States. Bennett *et al.* (1987) arrived at a somewhat lower rate of 2.1 million total cases of *Campylobacter* infections per year in the United States, of which 15% were estimated to have been waterborne.

The only estimate of the annual incidence of *E. coli* infections that could be identified by the authors was generated by Bennett *et al.* (1987). Of these 75% of occurrences were estimated to have been waterborne.

These data are summarized in Table 3.

Other Although other bacterial infections, such as tularemia, leptospirosis and cholera may be waterborne, they occur rarely in the United States. They were not included in this study.

Parasitic diseases

The three major parasitic diseases associated with contaminated drinking water in the

Table 2 Estimates of annual disease incidence and mortality from *Salmonella* and *Shigella* in drinking water in the United States.

	Low estimate	Point estimate	High estimate
<i>Salmonella</i>			
Isolates year ⁻¹		42 000 ¹	
Median cases per isolate	17.7 ²		
Range of total cases	740 000		1 700 000 ³
Per cent waterborne	3% ⁴		10% ⁵
Cases of WBID (range)	22 000		170 000
Cases of WBID (point estimate)		59 000 ⁶	
Case fatality rate		0.1% ⁴	
Deaths		59	
<i>Shigella</i>			
Isolates year ⁻¹			32 000 ¹
Median cases per isolate			15.2 ⁷
Range of total cases	300 000 ⁴		490 000 ⁴
Per cent waterborne		10% ⁴	
Cases of WBID (range)	30 000		49 000
Cases of WBID (point estimate)		35 000	
Case fatality rate		0.2% ⁴	
Deaths		70	

¹: CDC, 1994; ²: Chalker & Blaser, 1988; ³: based on high estimate for incidence of 3 700 000 cases of infection from Chalker & Blaser (1988), as derived from carriage rates. This was divided by the ratio of infections:symptomatic cases (2.2); ⁴: Bennett *et al.* (1987); ⁵: Hauschild & Bryan (1980); ⁶: $3/4 \times \text{low} + 1/4 \text{ high}$; ⁷: Rosenberg *et al.* (1977).

Table 3 Estimates of annual disease incidence and mortality from *E. coli* and *Campylobacter* in drinking water in the United States (Bennett *et al.*, 1987).

	<i>E. coli</i> (point estimates)	<i>Campylobacter</i> (point estimates)
Total annual incidence	200 000	2 100 000
Per cent waterborne	75%	15%
Cases of WBID	150 000	320 000
Case fatality rate	0.2%	0.1%
Deaths	300	320

United States are amebiasis, giardiasis, and cryptosporidiosis. Giardiasis and cryptosporidiosis have only recently been widely recognized as human diseases and tools for their diagnosis are less fully developed than those for bacterial pathogens. Perhaps even more important, physicians do not routinely test for these pathogens. As a consequence, both diagnosis and reporting are likely to be sporadic. At present, sampling of treated surface water from drinking water supply systems probably provide better data for estimating the incidence of WBID than disease reporting.

Giardia Grubbs *et al.* (1992) conducted simulations based on the distribution of pathogens in surface water and modeled the dose-response relationship using data from Le Chevallier *et al.* (1991) and Rose *et al.* (1991). The model estimated that 400 000 to 1 000 000 *Giardia* infections occur each year in the United States. Grubbs *et al.* assumed that 10% of infected individuals become symptomatic. Other published estimates of the rates of symptomatic disease among infected individuals are 25% (Wolf, 1979) and 91% (Veazie, 1979). Applying the high and low rates of symptomatic disease to the infection rates estimated by Grubbs gives a range of 40 000 to 910 000 cases per year of symptomatic giardiasis. Mortality rates for giardiasis are not well established. Bennett estimated a case fatality rate for *Giardia* of 0.0001%, but this may not accurately reflect the mortality in susceptible populations.

Cryptosporidium Estimates for cryptosporidiosis are extremely limited. Bennett (1987) estimated that 50 cases of cryptosporidiosis occur each year and that none of these was waterborne. A 1986 book on waterborne diseases did not even mention cryptosporidiosis (Harris, 1986). Recent events in Milwaukee suggest an entirely different reality. In a generally well run water supply serving more than 800 000 people with chlorinated, filtered water, an outbreak of cryptosporidiosis resulted in an estimated 403 000 illnesses, 4000 hospitalizations and more than 100 deaths (MacKenzie *et al.*, 1994; Davis, 1993). This became the largest recorded outbreak of WBID in United States history by surpassing an outbreak involving 13 000 cases of cryptosporidiosis in Georgia in 1987 (Hayes, 1989).

Again, studies of surface water contamination provide useful data. Le Chevallier *et al.* (1991) tested treated water from a group of drinking water supplies and found *Cryptosporidium* in 27% of them. Although models for *Cryptosporidium* comparable to those for *Giardia* have not been developed yet, data from the *Giardia* studies can be used to provide some preliminary estimates of incidence for *Cryptosporidium*. A recent study suggests that the infectivity of *Cryptosporidium* is similar to the infectivity of *Giardia* (DuPont, 1994). Therefore, as a first approximation, we used the ratio of contamination rates for *Cryptosporidium:Giardia* (1.6) as determined by LeChevallier. We then multiplied the disease rates for *Cryptosporidium* by this ratio.

This is somewhat simplistic and probably underestimates actual incidence for two reasons. First, the greater prevalence of *Cryptosporidium* than *Giardia* will change the shape of the pathogen frequency distribution and not simply shift it to the right on the *x*-axis as simple multiplication suggests. Second, the dose-response relationship is supra-linear in the region of the most common levels of exposure (DuPont, 1994). A multiplicative increase in exposure would again have a greater than multiplicative increase in infection rates. However, no other data were identified.

As Table 4 shows, the range of estimates for the incidence of cryptosporidiosis was

Table 4 Estimates of annual disease incidence and mortality from *Giardia* and *Cryptosporidium* in drinking water in the United States.

	Low estimate	Point estimate	High estimate
<i>Giardia</i>			
Infections	400 000 ¹		1 000 000 ¹
Symptomatic cases/infected cases	0.10 ¹		0.91 ²
Cases of WBID (range)	40 000		910 000
Cases of WBID (point estimate)		260 000 ³	
Case fatality rate		0.0001 % ⁴	
Deaths		1	
<i>Cryptosporidium</i> ⁵			
<i>Cryptosporidium</i> / <i>Giardia</i> in drinking water		1.6 ⁶	
Cases of WBID (range)	64 000 ⁷		1 500 000 ⁷
Cases of WBID (point estimate)		420 000 ³	
Case fatality rate		0.03 % ⁸	
Deaths		130	

¹: Grubbs *et al.* (1992); ²: Veazie *et al.* (1979); ³: $3/4 \times \text{low} + 1/4 \text{ high}$; ⁴: Bennett *et al.* (1987); ⁵: these numbers do not account for outbreaks the size of the 1993 Milwaukee outbreak; ⁶: Le Chevallier *et al.* (1991); ⁷: applied multiplier for *Crypto*/*Giardia* ratio to *Giardia* data based on apparent similarities in dose-response between the two pathogens (DuPont *et al.*, 1994); ⁸: Davis (1993).

64 000 to 1 500 000 cases per year and, using the case fatality rates from the Milwaukee outbreak, 92 deaths per year were estimated to be associated with this pathogen. These estimates would not include an outbreak of the magnitude of the 1993 incident.

Amebiasis The incidence of amebic dysentery is low in the United States. Nonetheless, this is a severe disease that is frequently waterborne. The only estimate that could be identified, from the expert opinions compiled by Bennett *et al.* (1987), is 12 000 cases per year with 36 deaths. None of these was considered to be waterborne. This is somewhat surprising in light of the fact that drinking water has played an important role in the transmission of this condition. Nonetheless, it was not included in the current study.

Viral diseases

The vast majority of viral gastrointestinal infections in the US involve rota-viruses and parvo-viruses and are relatively mild and self-limiting. Symptoms from these viruses are far shorter in duration than those from parasitic infections. Because of the paucity of effective anti-viral agents, specific diagnoses of viruses that cause diarrhea are generally of limited clinical value except for diagnostic exclusion. Together these factors can substantially reduce the likelihood of detection for viral outbreaks. Consequently,

reporting data from outbreaks provide a poor indication of rates of viral WBID. Viral prevalence data combined with models of infectivity similar to the approach used for parasitic diseases, are likely to be more useful.

Hurst (1991) compiled data on viral contamination of drinking water, both before and after treatment. The data indicate that almost half of the fresh water used for drinking water is contaminated with human enteric viruses, an estimate that the author considered to be low. Studies of treated water found positive sample in four of nine studies which the author again suggested may underestimate actual contamination levels due to insensitive detection procedures and other limitations.

Payment (1985) estimated the prevalence of viruses in treated surface waters in Quebec. Haas (1993) combined these data with dose-response models of viral infectivity to estimate the annual incidence of waterborne viral infections in the United States. He estimated 25 million viral infections per year. Bennett *et al.* (1987) estimated only 300 000 cases, but assumed that Norwalk virus (a type of parvo-virus) is the only viral agent causing WBID. This provides a conservative low estimate. Bennett estimated case-fatality for rota-virus (0.01%) and Norwalk virus (0.0001%). To estimate case fatality from viral disease, we used the midpoint of these two rates. Incidence estimates of waterborne viral diseases are summarized in Table 5.

Disease groupings and determination of point estimates

The pathogens were grouped according to severity. Severe disease was defined as conditions with a case-fatality rate greater than or equal to 0.1%. *Shigella*, *Campylobacter*, *Salmonella*, and *E. coli* all meet this criterion. Recognizing that these pathogens can cause a range of symptoms, this group was classified as moderate to severe disease. The

Table 5 Estimates of annual disease incidence and mortality from viruses in drinking water in the United States.

	Low estimate	Point estimate	High estimate
Annual risk per person			0.175 ¹
Population served by surface water			140 000 000
Annual incidence			25 000 000
Annual incidence ²			
Norwalk (5% of 6 000 000)	300 000		
Rota (0% of 8 000 000)	0		
Hepatitis A (0% of 48 000)	0		
Cases of WBID (range)	300 000		25 000 000
Cases of WBID (point estimate)		6 500 000 ³	
Case fatality rate		0.005% ²	
Deaths		330	

¹: Haas (1993); ²: Bennett *et al.* (1987); ³: $3/4 \times \text{low} + 1/4 \text{ high}$.

second group, mild to moderate disease, included *Cryptosporidium*, *Giardia* and the viruses. Hepatitis A infections have symptoms that are certainly moderate to severe, but, because we were unable to find virus specific estimates, all viral infections were grouped as mild to moderate. *Cryptosporidium* can cause severe disease in immuno-compromised individuals, but the severity categorizations in the current study are based on the general population.

Estimated pathogen specific disease estimates varied by as much as two orders of magnitude. The derivation of a point estimate is somewhat arbitrary. In order to be conservative, point estimates were calculated as 3/4 of the lower bound plus 1/4 of the upper bound of the range. This approach should also account for any skewness in the distribution of disease rates.

The summary estimates are listed in Table 6. The point estimate for moderate to severe infections was 560 000 with a range of 520 000 to 690 000. The corresponding figures for mild to moderate infections were 7 100 000 with a range of 400 000 to 27 000 000. Estimated mortality is over 1200 cases per year.

DISCUSSION

The primary goal of water treatment over the past century has been the elimination of mortality from infectious disease and this goal has been largely achieved. The most devastating waterborne pathogens, typhoid and cholera, do not even appear on the list of agents considered here. However, the estimates of incidence in this paper suggest that less severe WBID continues to be a public health problem in the United States. The

Table 6 Summary estimates of the incidence of and mortality from waterborne infectious disease.

	Estimated incidence (low – high)	Estimated incidence	Estimated mortality
Moderate to severe infections			
<i>Salmonella</i>	22 000 – 170 000	59 000	59
<i>Shigella</i>	30 000 – 49 000	35 000	70
<i>E. Coli</i>	not available	150 000	300
<i>Campylobacter</i>	not available	320 000	320
Total	520 000 – 690 000 ¹	560 000	750
Mild to moderate infections			
<i>Giardia</i>	40 000 – 910 000	260 000	1
<i>Cryptosporidium</i>	64 000 – 1 500 000	420 000	130
Viruses	300 000 – 25 000 000	6 500 000	330
Total	400 000 – 27 000 000	7 100 000	460

¹: This range uses the point estimates of illness related to *E. Coli* and *Campylobacter* to calculate both the high and low values.

range of likely estimates is wide, but even the low estimates of 520 000 cases year⁻¹ of moderate to severe disease and 400 000 cases year⁻¹ of mild to moderate disease are cause for concern.

The size of the range between the high and low estimates indicates serious limitations in the available data for estimating national incidence rates of WBID. Addressing concerns about WBID in the United States will require more reliable data. The greatest uncertainties in the current data base involve viral diseases and the newly emerging parasitic diseases such as cryptosporidiosis.

Recent events in Milwaukee have sharpened our appreciation of the vulnerability of our drinking water supplies to microbial contamination and the intractability of the problem. Both of the two largest outbreaks reported here [Georgia (Hayes, 1987) and Milwaukee (McKenzie, 1994)] occurred in filtered and disinfected water meeting all federal drinking water standards. WBID is not simply the concern of past generations, but must remain on the current public health agenda.

Disclaimer The views expressed in this paper are those of the authors and do not necessarily represent the policy of the US Environmental Protection Agency.

REFERENCES

- Bennett, J. V., Holmberg, S. D., Rogers, M. F. & Solomon, S. L. (1987) Infections and parasitic diseases. In: *Closing the Gap: The Burden of Unnecessary Illness* (ed. by Amler & Dull). Oxford University Press, New York.
- CDC (1994) Final 1993 reports of notifiable diseases. *MMWR* **42**, 597-603.
- Chalker, R. B. & Blaser, M. J. (1988) A review of human salmonellosis: III. Magnitude of salmonella infection in the United States. *Rev. Infectious Diseases* **10**, 111-124.
- Craun, G. F. (1986) Recent statistics of waterborne disease outbreaks (1981-1983). In: *Waterborne Diseases in the United States* (ed. by G. F. Craun), 161-168. CRC Press, Boca Raton, Florida.
- Craun G. F. (1986b) Statistics of waterborne outbreaks in the US (1920-1980). In: *Waterborne Diseases in the United States* (ed. by G. F. Craun), 73-159. CRC Press, Boca Raton, Florida.
- Davis, J. (1993) A massive outbreak of *Cryptosporidium* infection associated with a filtered public water supply. *American Water Works Association Annual Meeting*, Miami, Florida, 10 November 1993.
- Dupont, H. L., Chappell, C. L., Sterling, C. R., Okhuysen, P. C., Rose, J. B. & Jakubowski, W. (1994) Infectivity of *Cryptosporidium* Parvum for adult humans. Presented at the *Joint Meeting of the Association of American Physicians, the American Society for Clinical Investigations and the Federation for Clinical Research*, Baltimore, Maryland, USA.
- Grubbs, W. D., Macler, B. A. & Regli, S. (1992) *Simulation of microbial occurrence, exposure and health risks after drinking water treatment processes*. EPA Report 811-B-92-005; prepared for the EPA Office of Drinking Water.
- Haas, C. N. (1993) Quantifying microbiological risks. In: *Safety of Water Disinfection: Balancing Chemical and Microbial Risks* (ed. by G. F. Craun). ILSI Press, Washington, DC.
- Harris, J. R. (1986) Clinical and epidemiological characteristics of common infectious diseases and chemical poisonings caused by ingestion of contaminated drinking water. In: *Waterborne diseases in the United States* (ed. by G. F. Craun), 11-21. CRC Press, Boca Raton, Florida.
- Hauschild, A. H. W. & Bryan, F. L. (1980) Estimate of cases of food and waterborne illness in Canada and the United States. *J. Food Prot.* **43**, 435-440.
- Hayes, E. B. et al. (1989) Large community outbreak of cryptosporidiosis due to contamination of a filtered public water supply. *New Eng. J. Med.* **320**, 1372-1376.
- Herwaldt, B. L., Craun, G. F., Stokes, S. L. & Juranek, D. D. (1991) Waterborne-disease outbreaks, 1989-1990. *MMWR* **40**(SS-3), 1-22.
- Hurst, C. J. (1991) Presence of enteric viruses in freshwater and their removal by the conventional water treatment process. *Bull. WHO* **69**, 113-119.
- Le Chevallier, M. W., Norton, W. D. & Lee, R. G. (1991) Occurrence of *Giardia* and *Cryptosporidium* spp. in surface water supplies. *Appl. Environ. Microbiol.* **57**, 2610-2616.
- Levine, W. C. & Craun, G. F. (1990) Waterborne disease outbreaks, 1986-1988. *MMWR* **39**(SS-1), 1-14.
- MacKenzie, W. R., Hoxie, N. J., Proctor, M. E. et al. (1994) A massive outbreak in Milwaukee of *Cryptosporidium* infection transmitted through the public water supply. *New Eng. J. Med.* **331**, 161-167.

- Moore, A. C., Herwaldt, B. L., Craun, G. F., Calderon, R. L., Highsmith, A. K. & Juranek, D. D. (1993) Surveillance for waterborne disease outbreaks - United States, 1991-1992. *MMWR* 42(SS-5), 1-22.
- NAS (1969) *An Evaluation of the Salmonella Problem*. National Research Council, Committee on Salmonella. National Academy of Sciences, Washington, DC.
- Payment, P., Richardson, L., Siemiatycki, J., *et al.* (1991) A randomized trial to evaluate the risk of gastrointestinal disease due to consumption of drinking water meeting current microbiological standards. *Am. J. Public Health* 81, 703-708.
- Payment, P., Trudel, M. & Plante R. (1985) Elimination of viruses and indicator bacteria at each step of treatment during preparation of drinking water at seven water treatment plants. *Appl. Environ. Microbiol.* 49, 1418.
- Rose, J. B., Haas, C. N. & Regli, S. (1991) Risk assessment and control of waterborne Giardiasis. *Am. J. Public Health* 81, 709-713.
- Rosenberg, M. L., Gangarosa, E. J., Pollard, R. A., Wallace, M. & Brolnitsky, O. (1977) Shigella surveillance in the United States, 1975. *J. Infectious Diseases* 136, 458-460.
- Skirrow, M. B. (1991) Epidemiology of Campylobacter enteritis. *Internat. J. Food Microbiol.* 12, 9-16.
- St Louis, M. E. (1988) Water-related disease outbreaks, 1985. *MMWR* 37(SS-2), 15-24.
- Veazie, L., Brownlee, I. & Sears, H. J. (1979) An outbreak of gastroenteritis associated with *Giardia lamblia*. In: *Waterborne Transmission of Giardiasis* (ed. by W. Jakubowski & J. J. Hoff). EPA, Cincinnati, Ohio.
- Wolf, M. S. (1979) Managing the patient with Giardiasis: Clinical, diagnostic and therapeutic aspects. In: *Waterborne Transmission of Giardiasis* (ed. by W. Jakubowski & J. J. Hoff). EPA, Cincinnati, Ohio.