Drinking-water safety – challenges for community-managed systems

S. Rizak and Steve E. Hrudey

ABSTRACT

A targeted review of documented waterborne disease outbreaks over the past decades reveals some recurring themes that should be understood by drinking-water suppliers. Evidence indicates the outbreaks are often linked to some significant change in conditions that provides a sudden challenge to a water system. Severe weather events, such as heavy rainfall or runoff from snow melt, as well as treatment process and system changes, are common risk factors for drinking-water outbreaks. Failure to recognise warning signs and complacency are important contributors to drinking water becoming unsafe. Drinking-water suppliers must focus on competence and vigilance in maintaining effective multiple barriers appropriate to the challenges facing the drinking-water system. Understanding the risk factors and failure modes of waterborne disease outbreaks is an essential component for effective management of community drinking-water supplies and ensuring the delivery of safe drinking-water to consumers.

Key words | drinking-water safety, outbreaks, risk factors

S. Rizak (corresponding author)
Department of Epidemiology and Preventive Medicine and Cooperative Research Centre for Water Quality and Treatment,
Monash University,
Central and Eastern Clinical School,
Alfred Hospital, Commercial Road,
Melbourne Victoria 3004
Australia
Tel.: +613 9903 0140
E-mail: *Samantha.Rizak@med.monash.edu.au*

Steve E. Hrudey
Environmental Health Sciences,
School of Public Health,
University of Alberta,
Edmonton Alberta T6G 2G3
Canada

INTRODUCTION

Protection of public health by ensuring the safety of drinking-water is the primary objective of drinking-water quality management and treatment. Although in the developed world the systems and knowledge capable of ensuring the safety of drinking-water are widely held, waterborne disease outbreaks continue to occur. Fortunately such outbreaks are relatively infrequent in affluent countries. However, when they do occur they can result in very serious public health consequences and have significant social and economic costs. Understanding the risk factors and failure modes of waterborne disease outbreaks is an essential component for effective management of community drinking-water supplies and ensuring the delivery of safe drinking-water to consumers.

doi: 10.2166/wh.2008.033

METHODS

This paper undertakes a targeted review and analysis of some common risk factors contributing to drinking-water disease outbreaks by searching the published English language literature over the past decades. Papers were screened for those that discussed specific drinking waterborne disease outbreaks and that described some of the failure modes contributing to the outbreak. Details on both were required for inclusion in this review. This was not an attempt to exhaustively review all drinking-water outbreaks. Rather, this paper is intentionally limited to a selective description of the relevant literature for the purposes of identifying some obvious recurring themes that should be understood by drinking-water providers.

Larger organisations serving multiple communities may have the capacity to capture lessons within their own experience, but smaller community-managed systems in particular are often limited in resources and require opportunities to learn from the experience of others.

RESULTS

Outbreak risk factors associated with weather events

Reviews of historical drinking-water outbreaks frequently reveal that a key risk factor for outbreaks is a change in environmental conditions, typically heavy rainfall or runoff from heavy snow melt (Curriero *et al.* 2001; Craun *et al.* 2003; Hrudey & Hrudey 2004).

In a study of waterborne disease outbreaks in the United States over nearly 50 years from 1948 to 1994 it was found that over half were associated with extreme rainfall events prior to the outbreak. Of 548 outbreaks that occurred between 1948 and 1994, 51% were preceded by precipitation events at the 90th percentile of intensity ($P = 0.002$) and 68% were by events above the 80th percentile ($P = 0.001$) (Curriero *et al.* 2001). This analysis indicated that for surface water outbreaks the association was most significant for extreme precipitation during the month of the outbreak while for groundwater supplies the strongest association was found two months prior to the outbreak. This can be explained by the more immediate effects of contaminated runoff on surface water supplies, as opposed to the slower and more complex routes by which surface water contaminants may reach underground water tables (Curriero *et al.* 2001).

Rose *et al.* (2000) also conducted a review of waterborne disease outbreaks and climate in the United States for the years 1971–1994. Outbreak occurrence was associated with months having total precipitation ranked in the highest 10%, highest 5% and highest 2.5% of monthly totals, or the months following those with high precipitation (Logsdon *et al.* 2004). For surface water sources, the percentage of outbreaks occurring during the months in the highest 10% of precipitation totals, according to season, ranged from 25% in winter to 40% in spring and autumn.

There are also numerous examples of individual outbreaks documented on the vulnerability of municipal water systems under conditions of rainfall and/or spring thaw (Hrudey & Hrudey 2004). Walkerton, Canada is a recent example where contamination and the subsequent outbreak followed periods of heavy rainfall and associated flooding. The Walkerton community is a town of approximately 5,000 people and was served by a shallow groundwater supply drawn from three wells in and around the district; the groundwater was treated with chlorine before entering the distribution system. In May 2000, a waterborne outbreak occurred causing 7 deaths, 65 hospitalisations and more than 2,300 cases of gastrointestinal illness. These included 27 cases of haemolytic uremic syndrome, a serious kidney ailment with potential lifelong implications. The microbial pathogens *Escherichia coli* O157:H7 and *Campylobacter jejuni* causing this outbreak were attributed to contamination of the shallow groundwater supply arising from cattle manure from a local farm. The outbreak occurred following an unusually heavy spring rainfall, approximately 134 mm of rainfall over 5 d, with 70 mm falling on the last day. Such rainfall over a 5-d period was estimated to happen approximately once in 60 years (on average) for this region in May (O'Connor 2002).

The cryptosporidiosis outbreak at Milwaukee in 1993 was also preceded by periods of severe winter storms and heavy runoff from snow melt (MacKenzie *et al.* 1994; Fox & Lytle 1996). This outbreak was attributed to microbial contamination of its surface water supply and poor treatment performance at one of the city's treatment plants. During this period, the raw water conditions at this time were cold and unusually turbid and poor coagulation and filtration performance allowed for the passage of *Cryptosporidium* oocysts into the treated water, ultimately affecting an estimated 400 000 people. Speculation of the source of contamination initially included cattle along the rivers, slaughterhouses and human sewage (MacKenzie *et al.* 1994). However, subsequent advances in biological techniques allowing genotyping of oocysts suggest the infections were the human genotype and thus human sewage contamination as the cause of the outbreak (Peng *et al.* 1997; Sulaiman *et al.* 1998).

Similarly, a waterborne disease outbreak of giardiasis in Montana, USA occurred following a volcanic eruption of Mount St. Helen's which triggered heavy runoff from melting snow. The surface water supply was highly vulnerable to contamination and treatment consisted of only marginal chlorination and no filtration. The watershed contained camping grounds and hiking trails, wildlife including beavers, human dwellings and septic systems as well as cattle grazing upstream (Weniger *et al.* 1983). These examples are just a few of the numerous other documented outbreaks in which heavy rainfall and/or runoff was a major contributing factor to the contamination episode and resulting illnesses (Table 1).

Impact of weather events

The risk of heavy rainfall or snowmelt, and the associated runoff, is that they are key factors in the transportation of pathogenic microorganisms and can lead to a marked decline in water quality (Hunter 2003; Logsdon *et al.* 2004). Studies of the occurrence of pathogens in water have found a positive correlation between rainfall and concentrations of *Giardia* and *Cryptosporidium* (Atherholt *et al.* 1998) and also with viruses (Miossec *et al.* 2000). A Florida survey following the heavy rainfall that accompanied El Nino of 1997 and 1998 also found higher concentrations of faecal indicator organisms than occurred during the rest of the year (Curriero *et al.* 2001).

For surface water systems, heavy rainfall may lead to changes in the direction of flow of water systems and flow through channels that would not normally occur, and can also cause overflow of storm sewers and contaminated runoff into surface water sources. Particularly where the sewage system is combined with stormwater, this can allow substantial faecal contamination of surface water (Curriero *et al.* 2001; Hunter 2003). Heavy rainfall and runoff/flooding can also lead to flows of contaminated water or agricultural runoff into groundwater sources, causing outbreaks particularly where treatment is inadequate for these sources.

Most water treatment processes function best under steady-state conditions and performance seriously deteriorates as major fluctuations in water quality or flow occur. Runoff from heavy rainfall or snowmelt can dramatically increase flow and turbidity as well as the concentration of natural organic matter (Hunter 2003; Logsdon *et al.* 2004). Runoff can also potentially alter the pH and alkalinity of source waters (Logsdon *et al.* 2004). These fluctuations in flow or quality cause additional stress on water treatment systems and can interfere with the effectiveness of water treatment. The failure of treatment processes to cope with the impacts of heavy rainfall and runoff events is a common theme in many waterborne disease outbreaks.

Climate change may also make these problems more prominent in the future. Climate changes will likely include increases in temperature, precipitation, evaporation and intensity of rainfall events and runoff; thus potentially resulting in episodes of greater concentrations of pathogens in surface waters (Curriero *et al.* 2001; Hunter 2003; Schijven & Husman 2005). Drought conditions have also been a factor in several waterborne disease outbreaks. Brushy Creek, Texas is one such case that experienced an outbreak of cryptosporidiosis in 1998 during extended drought conditions. The Brushy Creek drinking water supply was derived from two sources. Chlorinated groundwater was the primary supply serving approximately 60% of the demand, and a surface water supply with conventional treatment provided by a neighbouring city supplementing this (Bergmire-Sweat *et al.* 1999). Following a lightning strike, sewage contaminated the deep groundwater source through fractures in the bedrock following a period of drought and extreme heat in which heavy water demand and no rainfall was present to recharge the aquifer (Bergmire-Sweat *et al.* 1999).

Another waterborne disease outbreak of cryptosporidiosis occurred in Northwest London and West Hertfordshire, UK in 1997 under similar conditions. Evidence from the outbreak suggested that a role in contributing to the contamination was the longest period of drought recorded preceding the outbreak, then followed by rainfall that was 162% above average for the month (Willocks *et al.* 1998). Unusually cold temperatures and drought conditions followed by heavy rain was likely to create the opportunity for contamination of the groundwater supply; however, no specific pathway was identified (Willocks *et al.* 1998). Other documented outbreaks where drought followed by heavy rains was a contributing factor include Jackson County, Oregon, USA, Isle of Thanet, Kent, UK and Ogose Town, Saitama Prefecture, Japan (Table 1).

Increasing and severe temperatures can cause serious problems, particularly when accompanied by increased nutrient load from heavy rainfall and runoff, in that they can also lead to an increase in cyanobacteria blooms and

Table 1 | Occurrence of waterborne disease outbreaks following weather events

Year	Location	Pathogen	Outbreak characteristics/contributing factors	Reference
2000/2001	Asikkala, Finland	*Campylobacter jejuni*	Heavy rainfall, unknown source of contamination	Hanninen *et al.* (2003)
2000	Walkerton, Ontario, Canada	*Escherichia coli* O157:H7, *Campylobacter* spp.	Heavy rainfall, manure contamination	O'Connor (2002)
2000	Clitheroe, Lancashire, England	*Cryptosporidium parvum*	Heavy rainfall and flooding, manure contamination	Howe *et al.* (2002)
1999	Washington County Fair, NewYork, USA	*Escherichia coli* O157:H7, *Campylobacter jejuni*	Drought conditions followed by heavy rainfall, sewage contamination	Novello (2000)
1998	Brushy Creek, Texas, USA	*Cryptosporidium parvum*	Drought conditions, extreme high temperatures, sewage contamination	Bergmire-Sweat *et al.* (1999)
1998	Alpine, Wyoming, USA	*Escherichia coli* O157:H7	Heavy rainfall, potential contamination from wildlife	Olsen *et al.* (2002)
1997	Northwest London & West Herfordshire, England	*Cryptosporidium parvum*	Drought conditions followed by heavy rainfall, potential sewage and livestock contamination	Willocks *et al.* (1998)
1996	Cranbrook, BC, Canada	*Cryptosporidium parvum*	Spring runoff, livestock contamination	Ong *et al.* (1997)
1996	Ogose Town, Saitama Prefect., Japan	*Cryptosporidium parvum*	Drought conditions followed by heavy rainfall, sewage contamination	Yamamoto *et al.* (2000)
1995	South Devon, England	*Cryptosporidium parvum*	Heavy runoff and flooding, lightning, sewage contamination	OCT (1996); Harrison *et al.* (2002)
1994	Temagami, Ontario, Canada	*Giardia lamblia*	Spring runoff, sewage contamination	Wallis *et al.* (1998)
1994	Noormarkku, Finland	likely Norwalk or other virus	Heavy runoff and flooding, sewage contamination	Kukkula *et al.* (1997)
1993	Gideon, Missouri, USA	*Salmonella typhimirium*	Extreme cold temperatures, contamination of storage facilities	Clark *et al.* (1996); Angulo *et al.* (1997)
1993	Milwaukee, Wisconsin, USA	*Cryptosporidium parvum*	Severe winter storms and heavy runoff, sewage contamination	MacKenzie *et al.* (1994); Fox & Lytle (1996)
1992/1993	Warrington, Cheshire, England	*Cryptosporidium parvum*	Heavy rainfall, sewage contamination	Bridgman *et al.* (1995)
199	Bradford, W.Yorkshire, England	*Cryptosporidium parvum*	Heavy rainfall	Atherton *et al.* (1995)
1992	Jackson County, Oregon, USA	*Cryptosporidium parvum*	Drought conditions, sewage contamination	Leland *et al.* (1993)
1991/1992	Uggelose, Denmark	not identified	Heavy rainfall, sewage contamination	Laursen *et al.* (1994)
1990/1991	Isle of Thanet, Kent, England	*Cryptosporidium parvum*	Drought conditions followed by heavy rainfall, abnormal operations	Joseph *et al.* (1991)
1989/1990	Cabool, Missouri, USA	*Escherichia coli* O157:H7	Extreme cold temperatures, sewage contamination	Swerdlow *et al.* (1992); Geldreich *et al.* (1992)
1988/1989	Swindon & Oxfordshire, England	*Cryptosporidium parvum*	Heavy rainfall, poor operational performance	Richardson *et al.* (1991)
1988	Saltcoats & Stevenston, Scotland	*Cryptosporidium parvum*	Heavy rainfall, contaminated runoff, cattle manure	Smith *et al.* (1988), 1989)
1988	Sunbury, Victoria, Australia	not identified	Heavy rainfall, fecal contamination	Kirk *et al.* (1999)
1987	Carrollton, Georgia, USA	*Cryptosporidium parvum*	Heavy rainfall, likely sewage contamination	Hayes *et al.* (1989)
1986	Penticton, BC, Canada	*Giardia lamblia*	Spring runoff, likely contamination from infected beavers	Moorehead *et al.* (1990)

Table 1 | *(continued)*

Year	Location	Pathogen	Outbreak characteristics/contributing factors	Reference
1985	Orangeville, Ontario, Canada	*Campylobacter jejuni*	Heavy rainfall and runoff, livestock contamination	Millson *et al.* (1991)
1984	Alsvåg, Norway	*Campylobacter jejuni*	Heavy rainfall, livestock contamination	Melby *et al.* (1990, 1991)
1980	Red Lodge, Montana, USA	*Giardia lamblia*	Heavy runoff, volcanic ashfall	Weniger *et al.* (1983)
1980	Georgetown, Texas, USA	Coxsackievirus B3; hepatitis A	Heavy rainfall, sewage contamination	Hejkal *et al.* (1982)
1979	Bradford, Pennsylvania, USA	*Giardia lamblia*	Heavy rainfall, inappropriate treatment	Lippy (1981)
1978	Bennington, Vermont, USA	*Campylobacter jejuni*	Heavy rainfall, potential sewage contamination	Vogt *et al.* (1982)

other planktonic species that are directly or indirectly human health risks (Hunter 2003). Even extreme cold has been attributed to various waterborne disease outbreaks. In 1990, Cabool, Missouri experienced distribution contamination of *E. coli* 0157:H7 during cold temperatures, causing an outbreak of at least 243 cases of gastrointestinal disease with four people dying (Swerdlow *et al.* 1992). The cold temperatures caused failures of two large water mains and failure of 45 in-ground water meters. The occurrence of these repairs in the period immediately before the outbreak strongly implicated contamination arising during these incidents as the likely cause of the contamination. There was visual evidence of several sewage overflows, which happened regularly in this system, suggesting that the most plausible explanation was direct cross-connection (Geldreich *et al.* 1992). Low temperatures also caused a thermally induced turnover in a storage tank which triggered an outbreak of *salmonellosis* in Gideon, Missouri in 1993 ultimately affecting more than 650 people including seven deaths (Clark *et al.* 1996; Angulo *et al.* 1997).

Outbreak risk factors associated with process or system changes

In addition to changing environmental conditions and their impacts on source water, any changes in conditions from the normal operation of a water treatment system can also pose a significant risk of waterborne disease outbreaks occurring. Reviews of waterborne disease outbreaks have frequently revealed contamination potential occurring during periods of maintenance of the water treatment plant and storage facilities, plant upgrades, changes to water treatment processes, as well as during construction or repair of water mains (Kramer *et al.* 1996; Logsdon *et al.* 1996; Craun *et al.* 2003; Hrudey & Hrudey 2004).

North Battleford, Canada in 2001 was a case where poor maintenance and changes in water treatment processes played a key role in contributing to a waterborne disease outbreak of cryptosporidiosis (Laing 2002). Due to a crack in the floor, maintenance was performed on the solids contact unit (SCU), the upflow clarifier following coagulation and preceding filtration. At this time, the SCU was completely drained and repaired, and in this instance, no coagulant sludge was retained to aid in re-establishing a floc blanket while bringing the SCU back online as was normal practice. The SCU was then refilled with water with an elevated coagulant dose and water was run to waste for 3.5 h. However, negligible settling and minimal clarification was observed for several weeks thereafter due to difficulties in re-establishing an effective floc blanket which is essential for effective operation of the SCU. During this period, dosages of coagulant chemicals were changed in an attempt to improve settling but this resulted in increased turbidities. Consequently, the filters required more frequent backwashing and filtered water was not run to waste immediately after backwashing, so the filters were not allowed to ripen to optimise performance. At various times, filtered water turbidities exceeded raw water turbidities. The river water source was susceptible to *Cryptosporidium parvum* contamination, particularly during spring runoff, and the treatment plant was located 3.5 km downstream of the city's sewage effluent outfall. Operation during this period was also in a start–stop mode due to low demand, thus exacerbating the poor treatment performance that allowed *Cryptosporidium* to break through the treatment plant for a prolonged period, ultimately infecting between 5800 and 7100 people (Laing 2002).

An outbreak of gastrointestinal disease was also experienced in Boden, Sweden in 1988 following an upgrade to the drinking-water system affecting 41% of the community (Andersson 1991). The drinking-water supply for the city was from a river water source and was treated with sand filtration and chlorination. Following the upgrade of an electronic control system for water treatment, the chlorination process and its monitoring system were not functional. The raw water intake was upstream from the city's sewage treatment plant; however, two sewer overflow sites were upstream of the water intake. No causative agent was identified but may have included viral or bacterial pathogens, rotavirus, *E.coli* and *Klebseilla*, which are readily killed with effective chlorination practices. There was no evidence reported that sewer overflows upstream of the drinking-water intake were the source of contamination but high runoff from warm weather following winter, causing snow melt, was a possible risk factor that may have contributed (Andersson 1991). Other documented outbreaks which occurred during periods of process changes, maintenance and repairs are listed in Table 2.

Table 2 | Occurrence of waterborne disease outbreaks following process or system changes

Year	Location	Pathogen	Outbreak characteristics/contributing factors	References
2001	North Battleford, Saskatchewan, Canada	*Cryptosporidium parvum*	Maintenance to upflow clarifier, poor operational performance, sewage contamination	Laing (2002)
2001	Hawkes Bay, New Zealand	*Campylobacter jejuni*	Failure of UV system and inadequate repair and maintenance, poor operational performance, contamination of cattle manure	McElnay & Inkson (2001)
1995	South Devon, England	*Cryptosporidium parvum*	Treatment process changes, poor operational performance, likely sewage contamination	Waite (1997)
1990/1991	Isle of Thanet, Kent, England	*Cryptosporidium parvum*	Repair of dosing equipment at treatment plant, abnormal operations	Joseph *et al.* (1991)
1989/1990	Cabool, Missouri, USA	*Escherichia coli* O157:H7	Repair of mains and water meter replacement, sewage contamination	Swerdlow *et al.* (1992); Geldreich *et al.* (1992)
1988	Boden, Sweden	Possible rotavirus, *Escherichia coli, Klebsiella*	Plant upgrade – installation of electronic control system, sewage contamination	Andersson (1991)
1988	Skjervøy, Norway	*Campylobacter jejuni/coli*	Repair of chlorinator system, unknown source of contamination	Melby *et al.* (2000)
1985/1986	Pittsfield, Massachusetts, USA	*Giardia lamblia*	Plant upgrade – construction of filtration system, change in water source, potential contamination from wildlife	Kent *et al.* (1988)

Summary of outbreak risk factors associated with change

Evidence from documented drinking-water outbreaks indicates that waterborne disease outbreaks are often linked to some significant change in conditions, environmental or otherwise, that provides a sudden challenge to a water system (Logsdon *et al.* 1996; Curriero *et al.* 2001; Craun *et al.* 2003; Hrudey & Hrudey 2004). Furthermore, reported waterborne disease outbreaks frequently reveal systems are at most risk when a combination of risk factors coincide, e.g. heavy rainfall during plant maintenance and repairs, increased demand for water and inadequate treatment performance, coupled with old facilities (Tables 1 and 2). The frequency of waterborne disease outbreaks in with which raw water or drinking-water sources become contaminated from sewage systems, septic tanks and agricultural activities is also noteworthy (Table 1). Failing to protect source water quality and poor knowledge of the catchment area and water system are common risk factors in numerous outbreaks.

CONCLUSIONS

Failing to recognise warning signs and complacency are key factors for drinking-water becoming unsafe. Drinking-water suppliers must focus on competence and vigilance in maintaining effective multiple barriers appropriate to the challenges facing the drinking-water system. This requires a thorough understanding of the entire water supply system from catchment to consumer, particularly with regard to the hazards and events that can ultimately compromise the safety of drinking water.

Waterborne disease threats and outbreaks have serious implications and typically serve to undermine consumer confidence in the safety of public drinking-water. Many people, distrustful of their community systems, seek to implement individual home treatment systems or, more frequently, buy and consume bottled water, both of which are far more expensive per unit volume of water consumed than any conceivable cost for advanced treatment of community systems. Ultimately drinking-water suppliers are accountable for drinking-water quality and safety; however, they cannot be expected to do this effectively in isolation. Consumers must value the benefits of having safe drinking-water delivered to their taps and become engaged and interested in the safety of their drinking water to ensure that the highest reasonable standards are being achieved.

ACKNOWLEDGEMENTS

Financial support from the Australian Cooperative Research Centre for Water Quality and Treatment, the Canadian Water Network, Alberta Health and Wellness, and the Natural Sciences and Engineering Research Council of Canada are gratefully noted.

REFERENCES

Andersson, Y. 1991 A waterborne disease outbreak. *Wat. Sci. Technol.* **24**(2), 13–15.

Angulo, F. J., Tippen, S., Sharp, D. J., Payne, B. J., Collier, C., Hill, J. E., Barrett, T. J., Clark, R. M., Geldreich, E. E., Donnell, H. D. & Swerdlow, D. L. 1997 A community waterborne outbreak of *salmonellosis* and the effectiveness of a boil water order. *Am. J. Public Health* **87**(4), 580–584.

Atherholt, T. B., LeChevallier, M. W., Norton, W. D. & Rosen, J. S. 1998 Effect of rainfall on Giardia and crypto. *J. AWWA* **90**(9), 66–79.

Atherton, F., Newman, C. P. S. & Casemore, D. P. 1995 An outbreak of waterborne cryptosporidiosis associated with a public water supply in the UK. *Epidemiol. Infect.* **115**, 123–131.

Bergmire-Sweat, D., Morgan, J., Wilson, K., VonAlt, K., Marengo, L., Bennett, T., Lee, Y. M., Tsang, V. C. W., MacKenzie, W. R. & Furness, B. 1999 *Cryptosporidiosis at Brushy Creek: Describing the Epidemiology and Causes of a Large Outbreak in Texas, 1998. International Symposium on Waterborne Pathogens*, WI. American Water Works Association, Milwaukee, WI.

Bridgman, S. A., Robertson, R. M. P., Syed, Q., Speed, N., Andrews, N. & Hunter, P. R. 1995 Outbreak of cryptosporidiosis associated with a disinfected groundwater supply. *Epidemiol. Infect.* **115**, 555–566.

Clark, R. M., Geldreich, E. F., Fox, K. R., Rice, E. W., Johnson, C. H., Goodrich, J. A., Barnick, J. A. & Abdesaken, F. 1996 Tracking a *Salmonella serovar typhimurium* outbreak in Gideon Missouri: role of contaminant propagation modelling. *J. Wat. Supply Res. Technol. – Aqua* **45**(4), 171–183.

Craun, G. F., Calderon, R. L. & Nwachuku, N. 2003 Causes of waterborne disease outbreaks reported in the United States, 1991-1998. In *Drinking Water and Infectious Disease:*

Establishing the Link (ed. P. R. Hunter, M. Waite & E. Ronchi), pp. 105–118. CRC Press, Boca Raton, FL.

Curriero, F. C., Patz, J. A., Rose, J. B. & Lele, S. 2001 The association between extreme precipitation and waterborne disease outbreaks in the United States 1948–1994. *Am. J. Public Health* **91**(8), 1194–1199.

Fox, K. R. & Lytle, D. A. 1996 Milwaukee's crypto outbreak: investigation and recommendations. *J. AWWA* **88**(9), 87–94.

Geldreich, E. E., Fox, K. R., Goodrich, J. A., Rice, E. W., Clark, R. M. & Swerdlow, D. L. 1992 Searching for a water supply connection in the Cabool Missouri disease outbreak of *Escherichia coli* O157:H7. *Wat. Res.* **26**, 1127–1137.

Hanninen, M.-L., Haajanen, H., Pummi, T., Wermundsen, K., Katila, M.-L., Sarkkinen, H., Miettinen, I. & Rautelin, H. 2003 Detection and typing of *Campylobacter jejuni* and *Campylobacter coli* and analysis of indicator organisms in three waterborne outbreaks in Finland. *Appl. Environ. Microbiol.* **69**, 1391–1396.

Harrison, S. L., Nelder, R., Hayek, L., Mackenzie, I. F., Casemore, D. P. & Dance, D. 2002 Managing a large outbreak of cryptosporidiosis: how to investigate and when to decide to lift a 'boil water' notice. *Commun. Dis. Public Health* **5**(3), 230–239.

Hayes, E. B., Matte, T. D., O'Brien, T. R., McKinley, T. W., Logsden, G. S., Rose, J. B., Ungar, B. L. P., Word, D. M., Pinsky, P. F., Cummings, M. L., Wilson, M. A., Lang, E. G., Hurnitz, E. S. & Juranek, D. D. 1989 Large community outbreak of cryptosporidosis due to contamination of a filtered public water supply. *New Engl. J. Med.* **320**, 1372–1376.

Hejkal, T. W., Keswick, B., LaBelle, R. L., Gerba, C. P., Sanchez, Y., Dreesman, G., Hafkin, B. & Melnick, J. L. 1982 Viruses in community water supply associated with an outbreak of gastroenteritis and infectious hepatitis. *J. AWWA* **74**(6), 318–321.

Howe, A. D., Forster, S., Morton, S., Marshall, R., Osborn, K. S., Wright, K. S., Wright, P. & Hunter, P. R. 2002 Cryptosporidium oocysts in a water supply associated with a cryptosporidiosis outbreak. *Emerg. Infect. Dis.* **8**, 619–624.

Hrudey, S. E. & Hrudey, E. J. 2004 *Safe Drinking Water - Lessons from Recent Outbreaks in Affluent Nations*. IWA Publishing, London.

Hunter, P. R. 2003 Climate change and waterborne and vector-borne disease. *J. Appl. Microbiol.* **94**(S), 37S–46S.

Joseph, C., Hamilton, G., O'Connor, M., Nicholas, S., Marshall, R., Stanwell-Smith, R., Sims, R., Ndawula, E., Casemore, D., Gallagher, P. & Harnett, P. 1991 Cryptosporidiosis in the Isle of Thanet: an outbreak associated with local drinking water. *Epidemiol. Infect.* **107**, 509–519.

Kent, G. P., Greenspan, J. R., Herndon, J. L., Mofenson, L. M., Harris, J. S., Eng, T. R. & Waskin, H. A. 1988 Epidemic giardiasis caused by a contaminated public water supply. *Am. J. Public Health* **78**, 139–143.

Kirk, M., Rouch, G. & Veitch, M. 1999 What happens in an outbreak of waterborne disease? An historical look at the Sunbury gastroenteritis outbreak. In *18th Federal Convention of the Australian Water and Wastewater Association*. Australian Water and Wastewater Association, Adelaide, SA, CD ROM.

Kramer, M. H., Herwaldt, B. L., Craun, G. F., Calderon, R. L. & Juranek, D. D. 1996 Waterborne disease: 1993 and 1994. *J. AWWA* **88**(9), 66–80.

Kukkula, M., Arstila, P., Klossner, M.-L., Maunula, L., von Bonsdorff, C.-H. & Jaatinen, P. 1997 Waterborne outbreak of viral gastroenteritis. *Scand. J. Infect. Dis.* **29**, 415–418.

Laing, R. D. 2002 *Report of the Commission of Inquiry into Matters Relating to the Safety of the Public Drinking Water in the City of North Battleford Saskatchewan*. Department of Justice, Government of Saskatchewan, Available at: http://www.northbattlefordwaterinquiry.ca [accessed Jan 14 2006].

Laursen, E., Mygind, O., Rasmussen, B. & Ronne, T. 1994 Gastroenteritis: a waterborne outbreak affecting 1,600 people in a small Danish town. *J. Epidemiol. Commun. Health* **48**, 453–458.

Leland, D., McAnulty, J., Keene, W. & Stevens, G. 1993 A cryptosporidiosis outbreak in a filtered water supply. *J. AWWA* **85**(6), 34–42.

Lippy, E. C. 1981 Waterborne disease: occurrence is on the upswing. *J. AWWA* **73**, 57–62.

Logsdon, G. S., Budd, G. C. & Long, B. W. 1996 Waterborne outbreaks – can we control them? *Proceedings of the 1996 AWWA Annual Conference*. AWWA, Denver, CO, Toronto, Canada, p 899.

Logsdon, G. S., Schneider, O. D. & Budd, G. C. 2004 Hindsight is 20/20: using history to avoid waterborne disease outbreaks. *J. AWWA* **96**(7), 66–74.

MacKenzie, W. R., Hoxie, N. J., Proctor, M. E., Gradus, M. S., Blair, K. A., Peterson, D. E., Kazmierczak, J. J., Addiss, D. G., Fox, K. R., Rose, J. B. & Davis, J. P. 1994 A massive outbreak in Milwaukee of cryptosporidium infection transmitted through the public water supply. *New Engl. J. Med.* **331**, 161–167.

McElnay, C. & Inkson, I. 2001 *Outbreak of Campylobacteriosis Traced to a School Water Supply*. Hawke's Bay District Health Board, Hawke's Bay, New Zealand.

Melby, K. K., Dahl, O. P., Crisp, L. & Penner, J. L. 1990 Clinical and serological manifestations in patients during a waterborne epidemic due to *Campylobacter jejuni*. *J. Infect.* **21**, 309–316.

Melby, K. K., Gondrosen, B., Gregusson, S., Ribe, H. & Dahl, O. P. 1991 Waterborne *campylobacteriosis* in northern Norway. *Int. J. Food Microbiol.* **12**, 151–156.

Melby, K. K., Svendby, J. G., Eggebo, T., Holmen, L. A., Andersen, B. M., Lind, L., Sjogren, E. & Kaijser, B. 2000 Outbreak of *Campylobacter* infection in a subarctic community. *Eur. J. Clin. Microbiol. Infect. Dis.* **19**, 542–544.

Millson, M., Bokhout, M., Carlson, J., Spielberg, L., Aldis, R., Borczyk, A. & Lior, H. 1991 An outbreak of *Campylobacter jejuni* gastroenteritis linked to meltwater contamination of a municipal well. *Can. J. Public Health* **82**, 27–31.

Miossec, L., Le Guyader, F., Haugarreau, L. & Pommepuy, M. 2000 Magnitude of rainfall on viral contamination of the marine environment during gastroenteritis epidemics in human coastal population. *Revuee d Epidemiologie et de Sante Publique* **48**(Suppl. 2), 2S62–2S71.

Moorehead, W. P., Guasparini, R., Donovan, C. A., Mathias, R. G., Cottle, R. & Baytalan, G. 1990 Giadiasis outbreak from a chlorinated community water supply. *Can. J. Public Health* **81**, 358–362.

Novello, A. 2000 *The Washington County Fair Outbreak Report*. Department of Health, Albany, NY.

O'Connor, D. R. 2002 *Report of the Walkerton Inquiry. Part 1. The Events of May 2000 and Related Issues*. The Walkerton Inquiry, Toronto. Available at: http://www.attorneygeneral.jus.gov.on.ca/english/about/pubs/walkerton [accessed Jan 14 2006].

OCT 1996 *Outbreak of Cryptosporidiosis South and West Devon August to September 1995*. Outbreak Control Team, South and West Devon Health Authority, Dartington, Devon, UK.

Olsen, S. J., Miller, G., Breuer, T., Kennedy, M., Higgins, C., Walford, J., McKee, G., Fox, K., Bibb, W. & Mead, P. 2002 A waterborne outbreak of *Escherichia coli* O157:H7 infections and hemolytic uremic syndrome: implications for rural water systems. *Emerg. Infect. Dis.* **8**, 370–375.

Ong, C., Pearce, M., Eisler, D., Goh, S. H., King, A. S., Bowie, W. R., Issac-Renton, J. L. & Beard, C. B. 1997 An outbreak of cryptosporidiosis in southeastern British Columbia, Canada. In *International Symposium on Waterborne Cryptosporidium*. AWWA, Denver, CO, pp. 355–366.

Peng, M. M., Xiao, L., Freeman, A. R., Arrowood, M. J., Escalante, A. A., Weltman, A. C., Ong, C. S. L., Mackenzie, W. R., Lal, A. A. & Beard, C. B. 1997 Genetic polymorphism among Cryptosporidium parvum isolates: evidence of two distinct human transmission cycles. *Emerg. Infect. Dis.* **3**, 567–573.

Richardson, A. J., Frankenberg, R. A., Buck, A. C., Selkon, J. B., Colbourne, J. S., Parsons, J. W. & Mayon-White, R. T. 1991 An outbreak of waterborne cryptosporidiosis in Swindon and Oxfordshire. *Epidemiol. Infect.* **107**, 485–495.

Rose, J. B., Daeschner, S., Easterling, D. R., Curriero, F. C., Lele, S. & Patz, J. A. 2000 Climate and waterborne disease outbreaks. *J. AWWA* **92**(9), 77–87.

Schijven, J. F. & Husman, A. M. D. 2005 Effect of climate changes on waterborne disease in the Netherlands. *Wat. Sci. Technol.* **51**(5), 79–87.

Smith, H. V., Patterson, W. J., Hardie, R., Greene, L. A., Benton, C., Tulloch, W., Gilmour, R. A., Girdwood, W. A., Sharp, J. C. M. & Forbes, G. I. 1988 Waterborne outbreak of cryptosporidiosis. *Lancet* **1988**(Dec. 24/31), 1484.

Smith, H. V., Girdwood, R. W. A., Patterson, W. J., Hardie, R., Green, L. A., Benton, C., Tulloch, W., Sharp, J. C. M. & Forbes, G. I. 1989 An outbreak of waterborne cryptosporidiosis caused post-treatment contamination. *Epidemiol. Infect.* **103**, 703–715.

Sulaiman, I. M., Xiao, L., Yang, C., Escalante, L., Moore, A. C., Beard, C. B., Arrowood, M. J. & Lal, A. A. 1998 Differentiating human from animal isolates of *Cryptosporidium parvum*. *Emerg. Infect. Dis.* **4**, 681–685.

Swerdlow, D. L., Woodruff, B. A., Brady, R. C., Griffin, P. M., Tippen, S., Donnell, H. D., Geldreich, E., Payne, B. J., Meyer, A., Wells, J. G., Greene, K. D., Bright, M., Bean, N. H. & Blake, P. A. 1992 A waterborne outbreak in Missouri of *Escherichia coli* O157:H7 associated with bloody diarrhea and death. *Ann. Intern. Med.* **117**(10), 812–819.

Vogt, R. L., Sours, H. E., Barrett, T., Feldman, R. A., Dickinson, R. J. & Witherell, L. 1982 *Campylobacter* enteritis associated with contaminated water. *Ann. Intern. Med.* **96**, 292–296.

Waite, W. M. 1997 *Assessment of Water Supply and Associated Matters in Relation to the Incidence of Cryptosporidiosis in Torbay in August and September 1995*. Drinking Water Inspectorate, London.

Wallis, P. M., Primrose, B. & Robertson, W. J. 1998 Outbreak of waterborne giardiasis caused by sewage contamination of drinking water. *Environ. Health Rev.* **42**(2), 44–51.

Weniger, B. G., Blaser, M. J., Gedrose, J., Lippy, E. C. & Juranek, D. D. 1983 An outbreak of waterborne giardiasis associated with heavy water runoff due to warm weather and volcanic ashfall. *Am. J. Public Health* **73**, 868–872.

Willocks, L., Crampin, A., Milne, L., Seng, C., Susman, M., Gair, R., Moulsdale, M., Shafi, S., Wall, R., Wiggins, R. & Lightfoot, N. 1998 A large outbreak of cryptosporidiosis associated with a public water supply from a deep chalk borehole. *Commun. Dis. Public Health* **1**(4), 239–243.

Yamamoto, N., Urabe, K., Takaoka, M., Nakazawa, K., Gotoh, A., Haga, M., Fuchigami, H., Kimata, I. & Iseki, M. 2000 Outbreak of cryptosporidiosis after contamination of the public water supply in Saitama Prefecture, Japan in 1996. *Kansenshogaku Zasshi – J. Japan. Assoc. Infect. Dis.* **74**(6), 518–526.

First received 2 April 2007; accepted in revised form 19 July 2007.