Waterborne transmission of protozoan parasites: A worldwide review of outbreaks and lessons learnt

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ABSTRACT

At least 325 water-associated outbreaks of parasitic protozoan disease have been reported. North American and European outbreaks accounted for 93% of all reports and nearly two-thirds of outbreaks occurred in North America. Over 30% of all outbreaks were documented from Europe, with the UK accounting for 24% of outbreaks, worldwide. *Giardia duodenalis* and *Cryptosporidium parvum* account for the majority of outbreaks (132; 40.6% and 165; 50.8%, respectively), *Entamoeba histolytica* and *Cyclospora cayetanensis* have been the aetiological agents in nine (2.8%) and six (1.8%) outbreaks, respectively, while *Toxoplasma gondii* and *Isospora belli* have been responsible for three outbreaks each (0.9%) and *Blastocystis hominis* for two outbreaks (0.6%). *Balantidium coli*, the microsporidia, *Acanthamoeba* and *Naegleria fowleri* were responsible for one outbreak, each (0.3%). Their presence in aquatic ecosystems makes it imperative to develop prevention strategies for water and food safety. Human incidence and prevalence-based studies provide baseline data against which risk factors associated with waterborne and foodborne transmission can be identified. Standardized methods are required to maximize public health surveillance, while reporting lessons learned from outbreaks will provide better insight into the public health impact of waterborne pathogenic protozoa.

Key words | method standardisation, molecular methods, protozoan parasites, validation, waterborne outbreaks, worldwide

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INTRODUCTION

Waterborne diseases occur worldwide, and outbreaks caused by the contamination of community water systems have the potential to cause disease in large numbers of consumers. Waterborne outbreaks have economic consequences beyond the cost of health care for affected patients, their families and contacts, and the economic costs of illness and disease, as they also create a lack of confidence in potable water quality and in the water industry in general. In addition to outbreaks caused by contaminated potable water, there are outbreaks caused following the accidental ingestion of recreational (or other) waters.

National statistics on outbreaks linked to contaminated water have been available in the USA since 1920 (Craun 1986), and since 1971, the Centers for Disease Control (CDC), the US Environmental Protection Agency (USEPA), and the Council of State and Territorial Epidemiologists have maintained a collaborative surveillance system for collecting data pertaining to the occurrence and causes of outbreaks of waterborne disease (Barwick *et al.* 2000; Lee *et al.* 2002). In Europe during 1986–96, 277 outbreaks associated with drinking and recreational water were reported from 16 European countries (Kramer *et al.* 2001).

Interest in the contamination of drinking water by enteric pathogenic protozoa has increased considerably during the past three decades and a number of protozoan parasitic infections of humans are transmitted by the waterborne route

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Table 1 | Some parasitic protozoa and the waterborne route of transmission (modified from Smith & Lloyd 1997)

Organism	Disease/symptoms	Geographic distribution	Transmissive stage (size range) and route of infection
Entamoeba histolytica	Dysentery, liver abscess	Cosmopolitan	Cyst (9–14.5 μm) ingestion
Giardia duodenalis	Diarrhoea, malabsorption	Cosmopolitan	Cyst (8–12 μm) ingestion
Cryptosporidium spp.	Diarrhoea	Cosmopolitan	Oocyst (4–6 μm) ingestion
Balantidium coli	Diarrhoea, dysentery	Cosmopolitan	Cyst (50–60 μm) ingestion
Sarcocystis sp.	Diarrhoea, muscle weakness	Cosmopolitan	Oocyst (7.5–17 μm) ingestion
Toxoplasma gondii	Lymphadenopathy, fever, congenital infections	Cosmopolitan	Oocyst (10–12 μm) ingestion
Cyclospora sp.	Protracted diarrhoea	Cosmopolitan	Oocyst (8–10 μm) ingestion
Microsporidia	Enteritis, hepatitis, peritonitis, kerato-conjunctivitis	Cosmopolitan	Spore (1.8–5.0 μm) ingestion/contact with eye

(Table 1). The species names *lamblia*, *intestinalis* and *duodenalis* have all been used to describe those *Giardia* parasites that infect humans. Although there is increasing agreement that the use of these species names causes confusion, there is no clear consensus as to which species name should be adopted to describe those *Giardia* that infect humans. We have chosen to use *Giardia duodenalis* (from the type species) to describe those *Giardia* that infect humans. In industrialized countries, *Giardia duodenalis* and *Cryptosporidium* spp. are of major concern as waterborne pathogens. Three features of the life-cycles of *Giardia* and *Cryptosporidium* enhance the likelihood of waterborne transmission. First, *Giardia* and *Cryptosporidium* are monoxenous, completing their life-cycles within a single host that excretes large numbers of infective transmissive stages (*Giardia* cysts and *Cryptosporidium* oocysts [(oo)cysts]) in faeces. Second, zoonotic transmission can occur, enhancing both the reservoir of infection and environmental contamination, thus enhancing the likelihood of waterborne transmission. Third, infective (oo)cysts are environmentally robust, are sufficiently small to penetrate the physical barriers of water treatment (Table 1) and are insensitive to many disinfectants used in the water industry. The chlorine insensitivity of (oo)cysts has enhanced good operational practice in treatment works and distribution systems and has driven research into alternative technologies for (oo)cyst removal in the both the physical and chemical processes of water treatment (Smith & Grimason 2003).

A variety of features, particularly the size of the transmissive stage (with the exception of *Balantidium coli*), their environmental abundance and robustness, augment the potential for waterborne transmission. More is known of the features of *Cryptosporidium parvum* and *Giardia duodenalis* (oo)cysts that enhance survival in the environment and facilitate waterborne transmission (Table 1) than the others listed in Table 2, but many of these features are also applicable to the others identified. *Cyclospora cayetanensis* is a recently recognized waterborne parasite, which also has small oocysts (Table 1) that are environmentally robust, but no validated methods, currently used to assure the safety of drinking water supplies, are available for its detection (Herwaldt *et al.* 1997). Information on the waterborne transmission of *Entamoeba histolytica*, *Blastocystis hominis*, *B. coli*, *Isospora belli*, *Toxoplasma gondii*, the microsporidia, *Naegleria*, *Acanthamoeba*, *Balamuthia*, etc. is even scarcer.

METHOD

This review of waterborne outbreaks caused by protozoan pathogens is based on literature and data collected from a variety of sources including MEDLINE, electronic data from Eurosurveillance, Communicable Disease Report (CDR), Morbidity and Mortality Weekly Report (MMWR), Canada Communicable Disease Report (CCDR) and published, original articles. All data are summarised in Tables 3–8. Table 3 documents waterborne giardiasis outbreaks worldwide and, for each outbreak, the parameters of time, place, estimated cases and suspected cause, as well as additional comments, are provided if available. Table 4 documents waterborne cryptosporidiosis outbreaks

Table 2 | Some features of *C. parvum* and *G. intestinalis* which enhance survival in the environment and facilitate waterborne transmission (adapted from: Smith *et al.* 1995)

Feature	*Cryptosporidium*	*Giardia*
Large numbers of oocysts and cysts excreted by infected hosts	Approximately 10^{10} oocysts excreted during symptomatic infection	Up to 1.44×10^9 cysts per day can be excreted by an infected human
Low host specificity increases the potential for environmental spread and contamination	*C. parvum* infections reported from a variety of mammals including human beings, domestic livestock, pets and feral animals	*Giardia duodenalis* infections reported from a variety of animals including human beings, domestic livestock and wild animals
Robust nature of oocysts and cysts enhances their survival for long periods of time in favourable environments	Oocyst survival is enhanced in moist, cold environments. A proportion of oocysts can survive for >6 months suspended in water	Cyst survival is enhanced in moist, cold environments. A proportion of cysts can survive for 1–2 months suspended in water
Environmental robustness of oocysts and cysts enables them to survive some water treatment processes	Waterborne outbreaks indicate that oocysts can survive physical treatment and disinfection. Oocysts are resistant to disinfectants commonly used in water treatment	Waterborne outbreaks indicate that cysts can survive some water treatment processes. Cysts are sensitive to some disinfectants commonly used in water treatment
Small size of oocysts and cysts aid their penetration through sand filters	4–6 μm	8–12 × 7–10 μm (length × width)
Few infectious oocysts and cysts need to be ingested for infection to establish in susceptible hosts	Nine oocysts can cause infection in humans; five oocysts can cause infection in gnotobiotic lambs	Median infectious dose in humans is 25–100 cysts
Excretion of oocysts and cysts in faeces facilitate spread to water by water-roosting birds	Viable oocysts excreted by transport hosts such as seagulls and other sewage/carrion feeders	Water-roosting, sewage/carrion feeders may transport viable cysts

worldwide, while Table 5 documents waterborne outbreaks caused by *Entamoeba*, *Balantidium*, *Isospora*, *Toxoplasma*, *Blastocystis*, *Cyclospora*, *Acanthamoeba* and the microsporidia. Table 6 documents waterborne protozoan outbreaks associated with recreational water and Table 7 documents waterborne outbreaks associated with foreign travel or residence in endemic settings. The summary Table (Table 8) categorizes all outbreaks by aetiological agent and suspected cause, while Figure 1 illustrates their worldwide distribution.

RESULTS

The distribution of waterborne protozoan parasite outbreaks worldwide is presented in Figure 1. At least 325 outbreaks associated with waterborne transmission of one or more and rarely two pathogenic protozoa have been documented. Outbreaks reported from North America and Europe accounted for 93% of all reports, while Japan, Australia and New Zealand, and other countries accounted for 1, 2 and 4%, respectively, of documented outbreaks (Figure 1). Nearly two-thirds of outbreaks (60%) occurred in North America, with the majority (52.6%, $n=171$) recorded from the USA. There were 7.5 times as many outbreaks recorded from the USA compared with Canada. Approximately one-third (32.6%, $n = 106$) of all outbreaks were documented from Europe, with the UK accounting for 24% of outbreaks, worldwide. Seventy-eight (73.6%) of the European outbreaks occurred in the UK, which is 2.6 times as many as recorded from mainland Europe.

Thirty-two per cent (104) of reported outbreaks were associated with drinking water systems contaminated or presumably contaminated with *Giardia lamblia*, while 23.7% (77) of reported outbreaks were caused by *C. parvum* or *Cryptosporidium* sp. which passed through filtered or unfiltered drinking water systems supplied by both small and large community water systems.

At least 8.6% (28) of reported outbreaks associated with potable water systems were due to protozoa other than *Giardia* and *Cryptosporidium*, including *E. histolytica*, *C. cayetanensis*, *T. gondii*, *B. hominis*, *B. coli*, microsporidia and *Acanthamoeba* sp. (Table 5). *Naegleria fowleri* was

Table 3 | Outbreaks of giardiasis associated with contaminated drinking water worldwide

Month/year	Location/country	Est. cases	Suspected cause(s) (comments)	Key references
Oct 1954–Mar 1955	Portland, Oregon, USA	50,000	Mixed aetiology (surface water source with chlorination as only treatment)	Veazie 1969; Meyer 1973
Dec 1965–Jan 1966	Aspen, Colorado, USA	123	Sewage contamination of two wells serving the eastern side of the city (leaking sewer mains near the wells. Possible contamination of a mountain creek served as additional water source)	Barwick *et al.* 2000; CDR 1997
Aug 1969	Lookout Mt., Colorado, USA	19	Contaminated private water system.	Moore *et al.* 1969; Taylor *et al.* 1972
May–Jun 1970	Idyllwild, California, USA	34	Treatment deficiencies of surface water (surface water source with filtration and disinfection. Filters used intermittently)	Craun 1979
May 1972	Campground, Boulder, Colorado, USA	28	Surface water with disinfection only. Defective chlorinator.	Craun 1979
May 1972	Resort, High, Colorado, USA	24	Surface water with disinfection only. Defective chlorinator.	Craun 1979
Jun–Aug 1972	Boulder, Colorado, USA	297	Treatment deficiencies (surface water from one source bypassed the filtration system; alum use prior to filtration ceased prior to the outbreak)	Vernon 1973
Sep 1972	Camp, San Juan Area, Utah, USA	60	Use of untreated surface water	Craun 1979
Dec 1972–Jan 1973	Subdivision, Park, Colorado, USA	12	Septic tank seepage into wells. No treatment of well water.	Craun 1979
Jul 1973	Lodge, Grand, Colorado, USA	16	Use of untreated surface water	Craun 1979
Aug 1973	Farm, Tennessee, USA	5	Contaminated underground water supply. No treatment (storage of untreated water in a cistern inadequately sealed to prevent seepage and surface contamination. A nearby outhouse a possible source of contamination. Doubts regarding the reported findings of *Giardia* in water samples taken from the cistern)	Brady & Wolfe 1974
Nov 1973–Apr 1974	Essex, Vermont, USA	32	Surface water with disinfection only	Craun 1979
Dec 1973–Apr 1974	Danville Green, Vermont, USA	20	Surface water with disinfection only	Craun 1979
Jun 1974	Lodge, Grand, Colorado, USA	18	Surface water with disinfection only	Craun 1979
Jun–Aug 1974	Meriden, New York, USA	78	Surface water with disinfection only	Craun 1979
Sep 1974	Uinta Mts, Utah, USA	34	Use of untreated surface water (remote mountain stream) (several active beaver ponds, grazing sheep and a shepherd in the area)	Barbour *et al.* 1976
Nov 1974–Jun 1975	Rome, New York, USA	4,800–5,300	Mixed aetiology (first outbreak where a *G. lamblia* cyst was detected in the municipal water supply. Surface water source with chlorination as only treatment. Human settlements within the watershed area. Use of chloramines for disinfection)	CDC 1975; Shaw *et al.* 1977
Sep 1975	Idaho, USA	9	Use of untreated surface water	Craun 1979
1976–1979	Craeagle, Plumas County, California, USA	42	Basically unknown (2 of 3 beavers trapped in the watershed were *Giardia*-positive)	Keifer *et al.* 1980
Feb 1976	Office and residence, Grand, Colorado, USA	12	Use of untreated surface water	Craun 1979

Table 3 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause(s) (comments)	Key references
May 1976	Camas, Washington, USA	600	Treatment deficiencies (first outbreak involving a filtered water supply. Three infected beavers within foraging distance of the water intakes. Chlorination equipment failure; numerous deficiencies in the condition and operation of the pressure filters prior to the outbreak; ineffective chemical pretreatment)	CDC 1977*c*; Kirner *et al.* 1978
Jun 1976	Camp, Rocky Mt. Nat. Park, Estes Park, Colorado, USA	27	Mixed aetiology (surface water source with disinfection only. *Giardia* cysts in a water sample from a beaver pond located upstream from the water reservoir)	CDC 1977*a*, *c*
Apr–May 1977	Berlin, New Hampshire, USA	*c.* 7,000	Mixed aetiology (evidence for occurrence of **two simultaneous outbreaks**. Drinking water originated from two rivers and two largely independent water systems. Detection of *Giardia* cysts in raw and finished water from both water systems. A 30-year-old physical plant for one of the rivers had numerous deficiencies. For the second river, a new treatment plant just put into service; lack of experience; faulty construction of a common wall separating filtered and unfiltered water. Spring thawing in April may have caused simultaneous run-off of contaminated ground material into the rivers. Possible human faecal contamination of the streams due to recreational activities. Direct sewage discharges along the upstream portion of one of the two water systems. A *Giardia*-positive beaver)	CDC 1977*c*; Lippy 1978
Jun 1977	Campground, Utah, USA	7	Use of untreated well water influenced by surface water (stream) (a beaver dam located half a mile upstream from the well)	CDC 1977*a*
Jul 1977	Hotel, Glacier Park, Montana, USA	55	Use of untreated surface water	Craun 1979
Jul 1977	W. Sulfur Springs, Montana, USA	246	Surface water with disinfection only	Craun 1979
Mar–Apr 1978	Vail, Colorado, USA	5,000	Contaminated water source. Treatment deficiencies (sewer line obstruction and leakage of sewage into the water source. No chemical pretreatment; filter breakthrough and interruption of chlorination prior to the outbreak)	CDC 1978
Jul 1978	Utah, USA	18	Contaminated water source	Haley *et al.* 1980
Aug 1978	Washington, USA	23	Contaminated non-community water system	Haley *et al.* 1980
Nov 1978	New York, USA	130	Contaminated community water system	Haley *et al.* 1980
1979	Estes Park, Colorado, USA	53	Contaminated water source. Treatment deficiencies (alum did not provide a good floc)	CDC 1980
1979	Government camp, Oregon, USA	ND	Contaminated municipal water supply (*Giardia* cysts in beaver faeces from the watershed)	Keifer *et al.* 1980
1979	Zig Zag, Oregon, USA	ND	Contaminated municipal water supply (*Giardia* cysts in beaver faeces from the watershed)	Keifer *et al.* 1980
Sep–Dec 1979	Bradford, Pennsylvania, USA	3,500	Contaminated water source. Treatment deficiencies (infected beavers within the watershed. Interrupted and ineffective chlorination)	CDC 1980; Lippy 1981

Table 3 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause(s) (comments)	Key references
1980	Private campground, Arizona, USA	2,000	Sewage-contaminated drinking water (direct cross-connection between the potable water pipes and a pipe carrying sewage effluent for irrigation)	Starko *et al.* 1980
Jun–Aug 1980	Red Lodge, Montana, USA	780	Mixed aetiology (very heavy water runoff, resulted from warm sunny weather and snow darkened by ash fall from the Mt St Helens volcanic eruption of 18 May 1980. Unfiltered and inadequately chlorinated surface water; antiquated water system; no distribution system storage; individual service water meters or barriers)	Weniger *et al.* 1983
Aug 1981	Colorado, USA	100	Unfiltered surface water source	Hopkins *et al.* 1985
Fall 1981	100 Mile House, British Columbia, Canada	60	Contamination of the municipal water system. Surface water source with chlorination as only treatment (beavers and muskrats the suspected source of contamination)	Bryck *et al.* 1988
Sep 1981	Colorado, USA	29	Treatment deficiencies (surface water source; filter off line)	Hopkins *et al.* 1985
Nov 1981	Ski resort, Aspen Highlands, Colorado, USA	40	Contaminated raw water and water from the distribution system. Treatment deficiencies (shortened chlorine contact time due to a pump failure; inadequate filter. *Giardia* cysts in water specimens both before and after treatment)	Istre *et al.* 1984; Hopkins *et al.* 1985
Nov 1981	Colorado, USA	85	Treatment deficiencies (back up of unfiltered beaver pond water into a spring house)	Hopkins *et al.* 1985
Dec 1981	Colorado, USA	135	Treatment deficiencies (surface water source; no pretreatment before filtration)	Hopkins *et al.* 1985
Jan 1982	Colorado, USA	ND	Treatment deficiencies (underground water source, shallow well, adjacent to a river; no pretreatment before filtration)	Hopkins *et al.* 1985
Aug 1982	Reno, Nevada, USA	324	Contaminated water supply reservoir. Chlorination only (the city has been supplied in part by surface water chemically coagulated, settled and chlorinated, but not filtered. *Giardia* cysts detected in the water supply. A *Giardia*-infected beaver in one of the reservoirs)	Navin *et al.* 1985
Winter 1982	Banff, Alberta, Canada	>150	Town water supply with chlorination as only treatment. Contaminated beaver swimming in the town reservoir	McClure & McKenzie 1988
Jul 1982	Colorado, USA	28	Unfiltered surface water source. Heavy runoff	Hopkins *et al.* 1985
Sep 1982	Colorado, USA	28	Contaminated unfiltered surface water source	Hopkins *et al.* 1985
Oct 1982	Mjövik, Sweden	56	Sewage related incident. Construction deficiencies (17-year-old water distribution system damaged by tree roots. Faulty sewer construction; possibly a defective sand-filter)	Neringer *et al.* 1987
Late fall 1982–Apr 1983	Edmonton, Alberta, Canada	>895	Basically unknown (never proven to be waterborne. Deficiencies in the municipal water treatment facilities the probable cause of the outbreak)	McClure & McKenzie 1988; Harley 1988
Feb 1983	Colorado, USA	50	Treatment deficiencies (surface water source; filtration with inadequate pretreatment)	Hopkins *et al.* 1985

Table 3 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause(s) (comments)	Key references
Jul 1983	Red Lodge, Montana, USA	100	Contaminated surface water source (increased melt runoff due to volcanic eruption. Animals and human usage within the watershed)	Erlandsen & Bemrick 1988
Dec 1983–Apr 1984	McKeesport, Pennsylvania, USA	347	Mixed aetiology (numerous water line breaks due to low temperatures. Treatment deficiencies. Human sewage contamination of surface water supplies)	Erlandsen & Bemrick 1988; Sykora *et al.* 1988
Dec 1983	Pittston, Pennsylvania, USA	ND	Contaminated water source	Sykora *et al.* 1988; Rose *et al.* 1991
Mar 1984	Wilkes-Barre, Scranton, Pennsylvania, USA	ND	Unknown	Sykora *et al.* 1988
Nov 1984	Houtzale, Pennsylvania, USA	ND	Contaminated water source	Sykora *et al.* 1988; Rose *et al.* 1991
Jul 1985	Bristol, UK	108	Contaminated water system (possible contamination during engineering work on the water main serving the affected area of the city)	Jephcott *et al.* 1986; Galbraith *et al.* 1987
Nov 1985–Jan 1986	Pittsfield, Massachusetts, USA	703	Mixed aetiology (contaminated water supply reservoirs; infected animals within the watershed; signs of human recreational use; chlorination only; a community water reservoir, ceased for three years, was put into use again just prior to the outbreak)	Kent *et al.* 1988
Jan 1986	Trailer park, Vermont, USA	37	Contaminated park water. Treatment deficiencies (a stream as water source. Contact times for disinfection estimated to be only a few minutes during periods of peak water use. Two *G. lamblia* cysts in filtered water. A beaver dam and numerous homes with septic field sewage systems near the park. Recent release of a large volume of water into the stream following destruction of a beaver dam)	Birkhead *et al.* 1989
Jun–Aug 1986	Penticton, British Columbia, Canada	362	Contaminated surface water source. Chlorination as only treatment (a reservoir pond containing *Giardia*-infected beaver the suspected source of contamination)	Moorehead *et al.* 1990
Oct 1986	Penticton, British Columbia, Canada	ND	Contaminated surface water source (the second outbreak in the same area. Despite improvements on the reservoir, the second outbreak occurred when the implicated water source was re-instituted)	Moorehead *et al.* 1990
Christmas 1986	Ski resort, Sälen, Sweden	>1,400	Sewage contaminated drinking water (a simultaneous outbreak of giardiasis and amoebiasis. Overflow of sewage water into the drinking water system)	Andersson & de Yong 1989
Feb 1989	Colorado, USA	19	Treatment deficiency of river water	Herwaldt *et al.* 1992
Apr 1989	New York, USA	308	Treatment deficiency of reservoir water	Herwaldt *et al.* 1992
Jun 1989	Prison, New York, USA	152	Treatment deficiency of reservoir water	Herwaldt *et al.* 1992
Jul 1989	New York, USA	53	Treatment deficiency of lake water	Herwaldt *et al.* 1992
Mar 1990	Lodge, Alaska, USA	18	Consumption of untreated surface water (river) (use of untreated river water as the usual water source, well water, had been frozen at that time)	Herwaldt *et al.* 1992
Mar 1990	Resort, Vermont, USA	24	Treatment deficiency of lake water	Herwaldt *et al.* 1992

Table 3 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause(s) (comments)	Key references
Jun 1990	Two block of flats, Edinburgh, UK	9	Faecal contaminated water tank (probably a deliberate post-treatment contamination)	Ramsay & Marsh 1990; Bell *et al.* 1991
Aug 1990	Colorado, USA	123	Treatment deficiency of spring water (spring vulnerable to contamination above ground due to land erosion)	Herwaldt *et al.* 1992
Jul 1991	Recreation area, California, USA	15	Distribution system deficiency (a cross-connection at the water storage tanks resulted in contaminated surface water entering a distribution system using a spring water source)	Moore *et al.* 1993
Sep 1991	Park, Pennsylvania, USA	13	Contaminated water source (well and underground storage tanks). Treatment deficiency (coliforms present in a water sample. Undetermined source of contamination of either the well or the underground storage tanks)	Moore *et al.* 1993
Nov 1991	Rural community, West Midlands, UK	31	Contaminated water reservoir. Treatment deficiencies (village water abstracted originally from a ground water supply. Livestock grazing in the area the suspected source of a reservoir's contamination. Irregular chlorination of the water supply)	Furtado *et al.* 1998
Mar 1992	Trailer park, Idaho, USA	15	Consumption of chlorinated, unfiltered groundwater (well)	Moore *et al.* 1993
Mar 1992	Nevada, USA	80	Contaminated surface water source (lake). Treatment deficiency (low levels of *Giardia* cysts in unfiltered surface water. Chlorination of finished water not consistently maintained)	Moore *et al.* 1993
Jan 1993	Trailer park, Pennsylvania, USA	20	Treatment deficiency of well water (sewage contamination of filtered and chlorinated well water. *G. lamblia* and *E. coli* in tap water)	Kramer *et al.* 1996
Sep 1993	Subdivision, South Dakota, USA	7	Consumption of untreated groundwater (well) (untreated well water contaminated by a nearby creek. *Giardia* cysts in well water. Faecal coliforms in well and tap water)	Kramer *et al.* 1996
Feb–Apr 1994	Temagami, Ontario, Canada	*c.* 300	Contaminated drinking water (high concentrations of *Giardia* cysts in treated water. Two separate surface water supplies. Leakage from the storm and sanitary sewage systems aggravated by surface runoff following a winter thaw the suspected source of contamination of one of the supplies)	Wallis *et al.* 2001
Mar 1994	Correctional facility, Tennessee, USA	304	Distribution system deficiency (cross-connection between potable and wastewater lines. Potable water used to cool the seals of a wastewater pump. A fall in pressure in the potable water system probably caused wastewater to flow back into the line for potable water. High concentrations of *Giardia* cysts in tap water)	Kramer *et al.* 1996
May 1994	New Hampshire, USA	18	Contaminated reservoir. Unfiltered, chlorinated surface water. Treatment deficiencies (suspicions for inadequate chlorine contact times)	Kramer *et al.* 1996
May 1994	New Hampshire, USA	36	Unfiltered, chlorinated surface water (lake). Sewage contaminated finished water. Treatment deficiencies (suspicions for inadequate chlorine contact times)	Kramer *et al.* 1996
Jul 1995	Washington, USA	87	Distribution treatment deficiency of well water (contamination of multiple community wells due to an illegal cross-connection between a domestic water supply and an irrigation system at a plant nursery)	Lee *et al.* 2002

Table 3 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause(s) (comments)	Key references
Jul 1995	Revelstoke, British Columbia, Canada	ND	Unknown (a simultaneous outbreak of giardiasis and campylobacteriosis. Five cases of cryptosporidiosis reported as well)	Ong *et al.* 1999
Aug 1995	Alaska, USA	10	Consumption of untreated spring water	Levy *et al.* 1998
Dec 1995	New York, USA	1,449	Treatment deficiency of lake water (although no identified interruptions in chlorination at the water plant, post-filter water turbidity readings, serving as an index of the effectiveness of filtration, exceeded the regulated limit before and during the outbreak)	Levy *et al.* 1998
Jun 1997	Campground, Oregon, USA	100	Distribution treatment deficiency of well/spring water (non-community system combined untreated groundwater and chlorinated spring water. Rodents the suspected cause of contamination of a storage reservoir. No data regarding *Giardia* in the rodents)	Barwick *et al.* 2000
Jun 1997	New York, USA	50	Mixed aetiology (chlorinated, unfiltered lake water. Beaver found in a valve box near the reservoir; no data for presence of *Giardia* in the beaver. Treatment deficiency)	Barwick *et al.* 2000
May 1998	Florida, USA	7	Consumption of untreated well water	Barwick *et al.* 2000
Dec 1998–Jan 1999	House, Florida, USA	2	Consumption of untreated well water (recent rainfall and possible flooding the suspected causes of contamination)	Barwick *et al.* 2000; Lee *et al.* 2002
May–Aug 2000	Community, Rheinland-Pfalz, Germany	8	Consumption of contaminated drinking water. No filtration	Gornik *et al.* 2000
Jun 2000	Camp, Minnesota, USA	12	Consumption of untreated well water (possible contamination of well by animal faeces)	Lee *et al.* 2002
Jul 2000	Rafting trip, New Mexico, USA	4	Unknown	Lee *et al.* 2002
Aug 2000	Resort, Colorado, USA	27	Treatment deficiency of river water (a pump failure and a defective filter cartridge resulted in river water entering the drinking water holding tank without filtration. *Giardia* cysts in a sample from the water holding tank. No information regarding chlorine levels from water samples)	Lee *et al.* 2002
Sep 2000	House, New Hampshire, USA	5	Treatment deficiency of river water	Lee *et al.* 2002
Sep 2000	House, Florida, USA	2	Distribution system deficiency of well water	Lee *et al.* 2002
Nov 2000	Rengsdorf, Neuwied Germany	ND	Contamination of drinking water. Chlorination as only treatment	Messner 2001
Apr–Jul 2001	Bay of Plenty & Manawatu, New Zealand	14	Treatment deficiency of creek water (poor maintenance of a creek drinking water supply treatment at a farm. Removal of a course filter at the creek due to ongoing clogging prior to the outbreak. Replacement of the under-sink filter cartridge with one of unknown specifications from a door-to-door salesman. Subsequent person-to-person-transmission)	Webber 2002
Nov–Dec*	Creston, British Columbia, Canada	83	Unknown	Isaac-Renton *et al.* 1994
Jan–Mar *	Creston, British Columbia, Canada	124	Contaminated community drinking water supply (infected beaver found above the drinking water intake. No change in drinking water source and no introduction of drinking water treatment of any kind after the first outbreak in the area)	Wallis 1987; Isaac-Renton *et al.* 1994

Table 3 | (*continued*)

Month/year	Location/country	Est. cases	Suspected cause(s) (comments)	Key references
ND	Kimberley, British Columbia, Canada	ND	Surface water source with chlorination as only treatment	Wallis 1987
ND	Botwood Peterview, Newfoundland, Canada	ND	Treatment deficiencies (chlorination as only treatment, minimal contact time before water reached the first customer)	Wallis *et al.* 1996
ND	Corner Brook, Newfoundland, Canada	ND	Treatment deficiencies (chlorination as only treatment, minimal contact time before water reached the first customer)	Wallis *et al.* 1996
ND	St Quentin, New Brunswick, Canada	ND	Treatment deficiencies (chlorination as only treatment, minimal contact time before water reached the first customer)	Wallis *et al.* 1996
ND	Plaster Rock, New Brunswick, Canada	ND	Treatment deficiencies (chlorination as only treatment, minimal contact time before water reached the first customer)	Wallis *et al.* 1996

ND: no data.
*No further detailed data available.

responsible for one outbreak associated with a swimming pool (Table 6) and an outbreak of *B. hominis* had unknown origin (Table 6). The water–food connection became apparent for two of those outbreaks, as disease occurred following the consumption of fresh raspberries and vegetables contaminated by irrigation waters containing *C. cayetanensis* and *I. belli* oocysts, respectively (Table 6). To date, no study has adequately estimated the proportion of foodborne diseases associated with contaminated water (Rose *et al.* 2001).

Outbreaks associated with recreational water

Of the reported outbreaks of giardiasis and cryptosporidiosis, 13.6% (18) and 50.3% (83), respectively, were associated with contaminated recreational water (Table 6). Swimming in contaminated waters and swimming pools is now recognized as an important transmission route for *Cryptosporidium* and *Giardia*. Contamination of natural bodies of recreational water can result from numerous sources, including urban and non-urban runoff, industrial pollution, storm waters, and human or animal wastes (Smith *et al.* 1995; Kramer *et al.* 1998), whereas contamination in swimming pools is often associated with accidental faecal contamination, particularly of toddler and paddling pools, but can also be caused by poorly constructed and/or maintained plumbing (Joce *et al.* 1991).

Outbreaks associated with free-living amoebae

Naegleria, *Acanthamoeba* and *Balamuthia* are aerobic, free-living, opportunistic human pathogens that live in aquatic habitats and feed on bacteria. Rarely, *Naegleria*, *Acanthamoeba* and *Balamuthia* invade the human central nervous system, causing primary amoebic meningoencephalitis (*N. fowleri*) and granulomatous amoebic encephalitis (*Acanthamoeba*, *Balamuthia mandrillaris*), which are fatal in most instances. Waterborne transmission, acquired through forceful inhalation, when amoebae are forced up nasal passages when jumping into warm (optimal temp. for *N. fowleri* = 40–45°C; optimal temp. for *Acanthamoeba* = 25–30°C) calm, surface waters or poorly maintained swimming pools, is uncommon. Excluding the more numerous individual case reports, *Naegleria* was responsible for a large-scale outbreak

Table 4 | Outbreaks of cryptosporidiosis associated with contaminated drinking water worldwide

Month/year	Location/country	Est. cases	Suspected cause (comments)	Key references
1983	Cobham, UK	16	Most likely through contaminated spring (water partly derived from the spring, chlorinated, softened and filtered. Although no detection of the parasite, the geographical distribution of the cases suggested waterborne spread of the disease)	Galbraith *et al.* 1987
May–Jul 1984	Braun Station, Texas, USA	*c.* 2,000	Mixed aetiology (**two distinct outbreaks**; one in May and one in July. Artesian well used as water supply; chlorination only; potential treatment deficiency; influence of the well water by the community's sewage system)	Solo-Gabriele & Neumeister 1996
1985	Cobham, UK	>50	Most likely through contaminated spring (same area as in 1983. Period of heavy rainfall preceded)	Galbraith *et al.* 1987
May–Jun 1986	Sheffield, UK	537	Contaminated water reservoir (heavy rainfall preceded. Oocysts detected in faecal samples from grazing cattle on farms adjoining the reservoir area, in faeces from a brown trout caught in the reservoir, and in surface waters from the reservoir and feeder streams)	Smith & Rose 1990; Craun *et al.* 1998
Jan–Feb 1987	Carrollton, Georgia, USA	*c.* 13,000	Treatment deficiencies of river water (first cryptosporidiosis outbreak associated with a filtered water supply. Evidence of primary pollution of the river by a sewage overflow, farm effluent and runoff from cattle grazing areas. Inadequate coagulation, non-operational flocculators, restarting of filters without backwashing. Changes in water treatment around the holiday season. Potential further secondary spread by person-to-person transmission)	Hayes *et al.* 1989; Solo-Gabriele & Neumeister 1996
Apr 1988	Ayrshire, UK	Many 100s	Contaminated public water system (first cryptosporidiosis outbreak associated with a fully UK public water supply. Oocysts detected in the treated chlorinated water supply system. Absence of faecal bacterial indicators. No oocysts in untreated water. Post-treatment contamination, rather than a failure of the water-treatment processes. Contamination of a break-pressure tank containing final water for distribution due to irregular seepage of oocyst-containing water, that increased during heavy rains in late March. Cattle slurry sprayed on ground in the vicinity of the break-pressure tank the likely source of contamination of treated water)	Smith *et al.* 1989; Barer & Wright 1990
Dec 1988–Apr 1989	Swindon & Oxfordshire, UK	516	Contaminated raw river water (Thames) (three water treatment works located in the upper Thames catchment contaminated with oocysts. Agricultural input strongly suspected in one of the water plants. Much of the area adjacent to the river used as a pasture for cattle. Mild weather during winter 1988, increased grazing and heavy rainfall in November 1988. Obvious failure of normal treatment to remove oocysts, no faults in any of the three treatment works observed)	Richardson *et al.* 1991; Poulton *et al.* 1991
Jan–Jun 1989	Loch Lomond, UK	442	Multiplicity of risk factors. Treatment deficiencies of loch water (surface water) (oocysts detected in loch water, which was microstrained and chlorinated, but not filtered. Post-treatment contamination also suspected. Contact with patients with symptoms, travelling away from home and contact with farm or other animals contributed to the outbreak)	Badenoch 1990; Barer & Wright 1990; Craun *et al.* 1998

Table 4 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause (comments)	Key references
Feb–May 1989	SE Thames, UK	65	Unknown (water considered as possible source)	Joseph *et al.* 1991; Craun *et al.* 1998
Dec 1989–May 1990	N Humberside, UK	477	Treatment deficiencies of river water (reservoir filled by river water. Part of flow bypassed slow sand filters. Closure of the intake pumps; use of bottom draw-off point and turbidity readings higher than normal. Heavy rainfall between 10 and 20 December 1989)	Badenoch 1990; Craun *et al.* 1998
Dec 1990–Jan 1991	Isle of Thanet, UK	47	Treatment deficiencies of river water (wells supplemented by Stour River. Possible accidental contamination of river water during autumn, when slurry was washed off farmland; heavy local rainfall; the river in spate; half of treatment process shut down due to mechanical problems and increased rainfall turbidity. No oocysts identified in untreated or treated water. River Stour treatment plant designed for short-term use, but operated for most of 1990 due to low rainfall and drought conditions)	Joseph *et al.* 1991; Craun *et al.* 1998
Jan–Apr 1991	S London, UK	44	Consumption of tap water (no evidence of environmental contamination; apparent breaches or operational irregularities in the water distribution system. No indication of a problem through routine monitoring indices)	Maguire *et al.* 1995
Aug 1991	Picnic facility, Berks County, Pennsylvania, USA	551	Treatment deficiencies of well water (treatment limited to chlorination. More than one pathogens in raw water, but only *Cryptosporidium* in stool samples. Septic tank effluent and infiltration from a nearby creek the potential sources of contamination)	Solo-Gabriele & Neumeister 1996
Feb–May 1992	Jackson County, Oregon, USA	15,000	Mixed aetiology (two distinct water supplies possibly involved, one in Medford and the other in Talent city. Medford used a spring as water source. Chlorination only; evidence of influence by surface water. Talent's water source is a river which receives treated wastewater. Drought conditions limited the dilution of wastewater by natural stream flow. Small rainfall contributed to contaminated runoff from adjacent agricultural land. Numerous plant deficiencies)	Solo-Gabriele & Neumeister 1996
Apr 1992	Rural community, N England, UK	63	Consumption of unboiled domestic tap water (public supply both chlorinated and filtered. No oocysts identified in pre- and post-treatment waters)	Furtado *et al.* 1998
Apr 1992	Boarding school, NW England, UK	42	Contaminated surface water supply (private surface water supply. Chlorination only. Slurry spraying on adjacent land the suspected source of contamination)	Furtado *et al.* 1998
Jun–Nov 1992	Torbay, UK	108	Mixed aetiology (two rivers and a well in riverside gravelled deposits. Contamination of the well or failure in the filtration of river water. No oocysts identified in raw or treated water samples. Increased turbidity of the well in week before the outbreak)	Craun *et al.* 1998; Furtado *et al.* 1998
Nov 1992	Urban community, Mersey, UK	47	Consumption of unboiled tap water (public ground water supply chlorinated and filtered. No routine testing in raw water prior to the outbreak. No oocysts identified in raw or treated water)	Furtado *et al.* 1998

Table 4 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause (comments)	Key references
Nov–Dec 1992	Bradford, UK	125	Contaminated tap water. Treatment deficiencies (heavy rains in the catchment area of the reservoir supplying raw water to a single treatment works, parts of which built in 1860. Oocysts identified in treated water from that source and in sand from one of the filters. A slow sand filter was just put back in service after routine maintenance, thus, had not reached peak efficiency. Increased turbidity and colour in treated water)	Atherton *et al.* 1995; Craun *et al.* 1998
Nov 1992–Feb 1993	N Warrington, UK	1,840	Contaminated groundwater source (deep wells in sandstone. Shaft-3 from Houghton Green water treatment works, sunk at the turn of the century, the most plausible route of entry of pollution as, during very heavy rainfall in October and November 1992, it drained surface floodwater from a field containing livestock faeces, thereby bypassing natural sandstone filtration. Seepage of foul sewage into Houghton Green shaft-1 from a cross-connection the second possible mechanism of contamination)	Bridgman *et al.* 1995; Craun *et al.* 1998
Mar 1993	Kitchener-Waterloo, Ontario, Canada	*c.* 23,900	Contaminated water source. Treatment deficiencies of well and river water (wells under influence of Grand River bank. Use of surface water from a newly constructed filtration plant. Agricultural activity in Grand River watershed combined with heavy snowmelt and spring runoff. High turbidities. Ozone applied, but not at levels sufficient for disinfection)	Craun *et al.* 1998
Mar–Apr 1993	Milwaukee, Wisconsin, USA	403,000	Treatment deficiencies of lake water (the largest documented outbreak of waterborne disease in US; potentially 112 deaths. Two water-treatment plants, located in the northern and in the southern >part of the city, obtained water from Lake Michigan. Increased turbidity and bacterial counts of treated water at the southern plant to unprecedented levels from March 23 to April 5. Plant temporarily closed on 9 April. Problems at other plants as well due to bad quality of Lake Michigan source water at that time. Oocysts identified in water from ice made in southern Milwaukee during those weeks. More than a 100-fold increase in the rate of isolation of *Cryptosporidium*. Apparently inadequate removal by the coagulation and filtration process of oocysts entered the southern water-treatment plant. Recent change in the coagulant (PACl instead of alum). Lack of historical use records. Recycling of filter backwash water. Possible sources of oocysts included cattle along two rivers that flow into the Milwaukee harbour, slaughterhouses and human sewage. Rivers swelled by severe spring rains and snow runoff before the outbreak may have transported oocysts into Lake Michigan and from there to the intake of the southern water-treatment plant)	MacKenzie *et al.* 1994; Fox & Lytle 1996
Mar–Apr 1993	US Coast Guard cutter, Milwaukee, Wisconsin, USA	42	Consumption of contaminated city water (cutter docked in Milwaukee on 21 March 1993, and filled its tanks with city water during the massive cryptosporidiosis outbreak. No oocysts in a water sample taken from the tanks, probably due to its relatively small volume, 40 lt)	Moss *et al.* 1998
Apr 1993	Private home, Yakima County, Washington, USA	7	Consumption of untreated groundwater (use of water from a shallow private well contaminated by surface water. Presumptive oocysts in the well water. Potential influence by melting snow and spring rains contaminated by cattle, sheep, or elk faeces)	Dworkin *et al.* 1996; Kramer *et al.* 1996; Solo-Gabriele & Neumeister 1996

Table 4 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause (comments)	Key references
Apr–May 1993	Wessex, UK	40	Contaminated tap water. Chlorination as only treatment (wells used as water supply. Oocysts in the distribution system reservoir, but not in treated water. No source or cause of contamination identified)	Craun *et al.* 1998; Furtado *et al.* 1998
May 1993	Medieval building, N Humberland, UK	6	Contaminated water supply (consumption of unboiled water from a private untreated water supply dating from the 19th century. Presence of carcasses of three lambs in a collection chamber connected with the water supply, or run-off of slurry from surrounding fields, the presumed sources of contamination. *Campylobacter* also isolated from two of the six cases with cryptosporidiosis; five further cases with *Campylobacter* only)	Duke *et al.* 1996
Jun 1993	Yorkshire, UK	97	Consumption of tap water. Treatment deficiencies (local public water supply chlorinated and filtered. No oocysts identified in raw or treated water. Poor quality raw surface water and a chlorination failure for a period of over 10 hours at the time of the outbreak)	Furtado *et al.* 1998
Jul 1993	Urban community, Wessex, UK	27	Consumption of tap water (public surface water supply chlorinated and filtered. No oocysts identified in treated water)	Furtado *et al.* 1998
Aug 1993	Lake resort, Cook County, Minnesota, USA	27	Basically unknown. Contaminated lake water (*Cryptosporidium* oocysts and *Giardia* cysts in lake water, but not in finished water. An episode of low water pressure within the distribution system during the outbreak. Backflow from a toilet facility, effluent from a resort's septic tank system and leakage of septic tank effluent into a raw water intake line that flowed under negative pressure, the suspected sources of contamination)	Kramer *et al.* 1996; Solo-Gabriele & Neumeister 1996
Dec 1993–May 1994	Clark County (+ Las Vegas), Nevada, USA	103	Most likely through consumption of tap water (first cryptosporidiosis outbreak in a potable water system with no apparent treatment deficiencies or breakdowns. Modern facility, excellent water quality. Epidemiologic data implicated the public water supply. Only presumptive oocysts in the source, Lake Mead, in finished water, and in filter backwash sampled later. A treated wastewater discharge, sewage from boats moored at a nearby marina, a nearby bathing beach and post-contamination of treated water, the possible sources of contamination. Outbreak coincided with the annual turnover of the lake caused by the weakening of the lake's thermocline. At least 20 deaths among HIV-infected people due to cryptosporidiosis)	Roefer *et al.* 1996; Kramer *et al.* 1996; Solo-Gabriele & Neumeister 1996
Late summer 1994	Building, Hiratsuka, Kanagawa, Japan	461	Contaminated drinking water (oocysts detected in tap water and other water samples taken from several water tanks and pits of the building. Post-treatment contamination of municipal drinking water with sanitary sewage through the connecting pipes. Accidental malfunction of the drainage system the suspected cause. Wastewater pump found broken at the time of the outbreak)	Kuroki *et al.* 1996
Aug–Sep 1994	Walla Walla, Washington State, USA	134	Sewage contaminated well (water supply consisted of two artesian wells; no treatment. Well 1 built in 1908, well 2 in the 1970s. Wells near cattle-grazing areas and adjacent to a piped irrigation system that distributes treated wastewater. Outbreak caused when the damaged irrigation system allowed treated wastewater to flow into well 1, the outer casing of which was extensively rusted. Presumptive oocysts in well water and in treated wastewater. *G. lamblia* in two case-patients and in treated wastewater)	Dworkin *et al.* 1996; Kramer *et al.* 1996; Solo-Gabriele & Neumeister 1996

Table 4 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause (comments)	Key references
Aug–Dec 1994	SW Thames, Wessex, Oxford, UK	224	Contaminated tap water (more than one community affected. Significant association with increased consumption of tap water from both chlorinated and filtered public supplies deriving some of their water from a common river source)	Furtado *et al.* 1998; McLauchlin *et al.* 1998
Oct 1994	Trent, UK	33	Most likely through contaminated tap water (public surface water supply chlorinated and filtered. No oocysts in a storage reservoir or in treated water)	Furtado *et al.* 1998
Jan–Feb 1995	Drug rehabilitation community, Emilia Romagna, Italy	294	Treatment deficiencies of public water the most probable cause (first large cryptosporidiosis outbreak in Italy. Two covered water storage tanks, fed from the public water supply, supplied the community with water. Oocysts in water samples from both tanks. Contaminated water probably originated from outside the community. Twenty-two cases HIV-positive; seven deaths)	Pozio *et al.* 1997
Summer 1995	*Farm*, Ireland	13	Most likely through unintentional ingestion of untreated farm animal contaminated water (illness strongly associated with children having visited an open farm and played in sand to which animals had access, at the edge of a stream, beside a picnic area)	Sayers *et al.* 1996
Jul–Aug 1995	Torbay, UK	575	Contaminated river and tap water (high concentrations of oocysts in sewage discharged to river. Oocysts identified in treated water both chlorinated and filtered)	Craun *et al.* 1998; Furtado *et al.* 1998
Jul–Aug 1995	Day camp, Gainesville, Alachua County, Florida, USA	77	Contaminated tap water (inadequate backflow prevention at the point of distribution the potential source of contamination. Contaminated water from a garbage-can washer might have backflowed into the camp's kitchen plumbing system. A hose attached to the water supply on the garbage-can washer, used to fill potable water coolers, could have come in contact with wastewater and under negative pressure could have drawn wastewater into the distribution system. Faeces of unknown origin near the hose nozzle)	Craun *et al.* 1998; Solo-Gabriele & Neumeister 1996
Jul–Sep 1995	Spijkenisse & Haarlem, Netherlands	71	Basically unknown (first cryptosporidiosis outbreak in the Netherlands. No common source identified. Household contact with people with diarrhoea, and swimming in municipal pools significantly associated with illness)	van Asperen *et al.* 1996
1996	Kelowna, British Columbia, Canada	*c.* 4,000	Contaminated surface water source (lake). Treatment deficiency (cattle the suspected source of oocysts in the unfiltered lake water source)	Craun *et al.* 1998
1996	Clovis, California, USA	*c.* 500	Contaminated water park	CCN 1997*a*,*b*
1996	Eagle Harbor, Florida, USA	16	Unknown	CCN 1996
Jan 1996	N England, UK	126	Contaminated drinking water supply (agricultural pollution occurred upstream of the water treatment plant. Storms and heavy rainfall in the area prior to the outbreak)	CDR 1996
Feb 1996	Collingwood, Ontario, Canada	*c.* 189	Contaminated surface water source (lake). Treatment deficiency (a 100-year storm prior to the outbreak. Unfiltered lake water source. No coliforms in disinfected water)	Craun *et al.* 1998

Table 4 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause (comments)	Key references
Feb 1996	Yorkshire, UK	20	Contaminated drinking water supply (increased water turbidity, associated with algal bloom, for water held in the storage reservoirs before entering the treatment plant)	CDR 1996
Mar–Jun 1996	Wirral Peninsula, England, UK	80	Contaminated drinking water (use of river water as water source. High numbers of oocysts in raw water, low numbers in treated water from the indicated water treatment plant. No obvious failure in water treatment procedures)	CDR 1996; Hunter & Quigley 1998
May–Jun 1996	Cranbrook, British Columbia, Canada	>2,000	Contaminated drinking water. Treatment deficiency of surface water (unfiltered reservoir water source. Grazing cattle on watershed positive for oocysts)	Craun *et al.* 1998; Ong *et al.* 1999
Jun 1996	Saitama, Japan	8,705	Contaminated drinking water (oocysts detected in untreated and treated water)	Smith & Rose 1998
Aug 1996	Beach, Indiana, USA	3	Contaminated lake (after heavy rains, runoff that contained cattle faeces passed from a pasture into the lake. One of the stool specimens *Giardia*-positive as well)	Levy *et al.* 1998
Jan–Feb 1997	Anglia & Oxford, UK	20	Contaminated public water supply	CDR 1997
Jan–Feb 1997	N Thames, UK	10	Contaminated drinking water	CDR 1997
Jan–Mar 1997	Anglia & Oxford, UK	22	Contaminated public water supply	CDR 1997
Feb 1997	Shoal Lake, Ontario, Canada	>100	Contaminated drinking water	CCN 1997*c*
Feb–Apr 1997	Hertfordshire & NW London, UK	345	Contaminated tap water (first cryptosporidiosis outbreak caused by filtered borehole water. Consumption of unboiled tap water originated from one deep chalk borehole. Oocysts detected in drinking water)	Willocks *et al.* 1998; Smith & Rose 1998
May–Jun 1997	NW, UK	346	Basically unknown (water suggested as possible risk factor. No other significant risk factor revealed)	CDR 1997
Dec 1997	S Thames, UK	26	Unknown cause	CDR 1998
Spring 1998	Guadarrama, Madrid, Spain	21	Consumption of tap water likely contaminated with oocysts. Treatment deficiencies (significant statistical association within tap water consumption and gastroenteritis)	Perez *et al.* 2000
Apr 1998	Chilliwack, British Columbia, Canada	25–30	Most likely through contaminated water supply (town system usually fed by deep underground wells, with occasional supplements from mountain streams. Faeces from an infected animal might have entered the city system from a stream used to supplement the city reservoirs one week before the outbreak)	CCN 1998*b*
Apr 1998	NW, UK	24	Contaminated private water supply	CDR 1999
Apr 1998	NW, UK	62	Contaminated public water supply (statistically significant association with water)	CDR 1999

Table 4 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause (comments)	Key references
Jul 1998	Subdivision, Texas, USA	1,400	Treatment deficiency of well water (raw sewage flow through underground fissures in a creek bed and into an aquifer located near five municipal utility district wells. Contamination of 4 of the 5 wells. Spill of sewage caused by a lightning storm that shorted the controls of a sewage treatment plant. Chlorine disinfection as only treatment)	Barwick *et al.* 2000
Jul 1998	Children's group home, New Mexico, USA	32	Unknown or miscellaneous deficiency (consumption of chlorinated well water from spigots supplied by an irrigation well. Although well water not intended for drinking, spigots not marked as non-potable. No sanitary seal protection of the well. Swimming in a pool filled with water from the well)	Barwick *et al.* 2000
Apr–May 1999	NW England, UK	347	Contaminated unfiltered surface water (oocysts in raw inlet water from the implicated water treatment works, in faecal specimens from sheep grazing around the implicated water reservoir, and in treated water sample)	Hunter 1999; CDR 2000
Sep–Dec 1999	Yorkshire, UK	28	Basically unknown (although rise in number of cases suspected to be related to water, no failure of water quality detected and no statistical evidence of association)	CDR 2000
Mar 2000	NW, UK	58	Contaminated water source (cases exposed within a single water supply zone with a spring source that was contaminated by animal faeces; animal grazing nearby and heavy rain. Well heads to the spring damaged. Oocysts identified in a public water reservoir and within the water distribution system)	CDR 2001
Apr–May 2000	Belfast, Ireland	129	Most likely through contaminated drinking water	Glaberman *et al.* 2002
May 2000	Farm holiday centre, SW, UK	8	Treatment deficiencies of a private water supply (water supply partially or incompletely treated)	CDR 2001
Aug 2000	Belfast, Ireland	117	Sewage contaminated drinking water (ingress of human sewage from a septic tank into the drinking water distribution system)	Glaberman *et al.* 2002
Dec 2000	Florida, USA	5	Distribution system deficiency of well water (repeated history of water main breaks)	Lee *et al.* 2002
Mar–May 2001	N Battleford, Saskatchewan, Canada	5,800–7,100	Treatment deficiencies of surface river water (a solid contact filtration unit apparently failed to operate correctly after being serviced and brought back on line. Oocysts in finished drinking water during the outbreak investigation)	CCDR 2001
Apr–May 2001	Belfast, Ireland	230	Human sewage pollution of drinking water, treatment deficiencies (a blocked drain at the water filtration plant caused untreated water to enter the finished water supply)	Health Stream 2001; Glaberman *et al.* 2002
Sep 2001	Dracy le Fort County, France	563	Contaminated tap water (oocysts in water samples collected from the public network. Probably a human sewage contamination)	Dalle *et al.* 2003

Table 4 | *(continued)*

Month/year	Location/country	Est. cases	Suspected cause (comments)	Key references
Apr–May 2001	Ireland	29	Contaminated surface water supply. Treatment deficiencies (first cryptosporidiosis outbreak in Ireland associated with a public water supply. Spring-fed lake, surrounded by farmland, as water source. Oocysts detected in raw and treated water, and in the environment surrounding the lake. Dry weather followed by very heavy rains, which would have facilitated the ingress of animal excrement into the lake. Water treatment included chlorination, but no filtration)	Jennings & Rhatigan 2002
Mar 2002	School, Yorkshire & Humberside, UK	50	Most likely through contaminated private spring water supply (a simultaneous outbreak of *Cryptosporidium* and *Campylobacter*)	CDR 2003*b*
Nov 2002	Community, SE, UK	21	Most likely through contaminated public water supply (occasional detection of single oocyst numbers in water supplied from two water companies. No problems at the works identified)	CDR 2003*b*
Nov–Dec 2002	Community, SE, UK	31	Most likely through contaminated public water supply	CDR 2003*b*

associated with a contaminated swimming pool in the Czech Republic (Kadlec *et al.* 1980; Table 6). *Acanthamoeba* was the causative agent of an outbreak associated with a contaminated municipal water supply in the USA (Meier *et al.* 1998; Table 5) and has a marked seasonality (peaking in June and November) and may be affected by climatic conditions (Rose *et al.* 2001).

Outbreaks associated with foreign travel

Pathogenic enteric protozoa are common causes of traveller's diarrhoea and important risk factors include point of origin and destination of the traveller, host factors, and exposure to contaminated food and water (Lima 2001). At least 23 (7.1%) of the reported waterborne outbreaks have been associated with waterborne disease acquired during foreign travel, or during short- to long-term residence in endemic areas (Table 7), where environmental contamination with transmissive stages is expected to be more abundant. Infection of indigenous hosts in endemic areas can be asymptomatic, and such individuals would be contributors of transmissive stages to both food and water in the absence of signs and symptoms of disease.

DISCUSSION

This review is based on literature and data collected from a variety of sources including MEDLINE, electronic archives from Eurosurveillance, Communicable Disease Report (CDR) and Canada Communicable Disease Report (CCDR) and published, original articles. Reporting of outbreaks is fundamental to furthering our understanding of the significance of waterborne protozoan parasites in causing morbidity and mortality. We document 325 outbreaks associated with waterborne transmission of pathogenic protozoa, most of which were recorded in the USA (52.6%) or Europe (32.6%). That the majority of outbreaks were documented from North America and Europe is not surprising, as they have had clinical and environmental community-based surveillance and reporting systems for infectious diseases in place for some time. Furthermore, outbreak control team reports of such outbreaks are encouraged or required by law, in an attempt to determine the causes and sources of the outbreaks and to emphasize lessons that can be learned from

Table 5 | Waterborne outbreaks associated with other protozoan parasitic agents worldwide

Time period	Location, country	Est. cases	Aetiologic agent (comments)	Key references
Sep 1950	Royal Air Force Station, UK	17	*Entamoeba histolytica* (Sewage contamination of the private borehole water supply due to a broken sewer)	Glaberman *et al.* 2002
1961–1970	USA	14	*Entamoeba histolytica* (Occurrence of **two distinctive outbreaks**. Contaminated private water system)	Taylor *et al.* 1972
1961–1970	USA	25	*Entamoeba histolytica* (Contaminated public water system)	Taylor *et al.* 1972
May–Jun 1971	Truk, Caroline Islands, USA	110	*Balantidium coli* (Faecal contaminated water supplies due to occurrence of a devastating typhoon. Low hygiene standards. High numbers of pigs in close contact to people. Primitive catchment water supplies disrupted by the typhoon, forcing people to use ground or surface facilities already contaminated by pig faeces. Destruction of pig pens and defecation privies led to more intimate contact between pigs and people)	Walzer *et al.* 1973
May–Jun 1977	Antofagasta City, Chile	90	*Isospora belli* (Consumption of vegetables irrigated with water from an industrial treatment plant for sewage)	Sagua *et al.* 1978
1979	Panama	32 US soldiers	*Toxoplasma gondii* (Most likely through consumption of contaminated creek water. Possible contamination of the creek with oocysts excreted by jungle cats. Most of the affected individuals claimed to have treated their drinking water with iodine tablets)	AWWA 1999
Christmas 1986	Ski resort, Sälen, Sweden	>1,400	*Entamoeba histolytica* and *Giardia lamblia* (Sewage contaminated drinking water. Overflow of sewage water into the drinking water system)	Andersson & de Yong 1989
May–Sep 1988	Siena, Italy	5	*Blastocystis hominis* (Aetiology unknown. Probably an imported infection. A family outbreak, started when two adopted children were brought from India and the Ivory Coast, two weeks prior to the outbreak period)	Guglielmetti *et al.* 1989
Jul 1990	Hospital, Chicago, Illinois, USA	21	*Cyclospora cayetanensis* (Contaminated building's water reservoir. The stirring up of stagnant water in a storage tank, followed repairs in a water pump, the most likely source of contamination. Algae and diatoms detected in water, but not *Cyclospora*)	WER 1991; Herwaldt *et al.* 1992; Huang *et al.* 1995
Nov 1991–Mar 1993	Chancay, Peru	3	*Cyclospora cayetanensis* (Most likely through consumption of non-filtered, unchlorinated canal water. A family outbreak. One of the two breeding ducks with asymptomatic *Cyclospora* infection)	Zerpa *et al.* 1995
Jul 1993–Dec 1994	Iowa, USA	43	*Acanthamoeba* (Most likely through contamination of the municipal water supplies due to a regional flooding. Incidence of illness in the Iowa counties affected by the flooding was more than 10 times higher than in the unaffected counties. The presence of a humidifier in the home and having household water originated from a private well instead of the municipal water supply proved protective)	Meier *et al.* 1998
Aug–Sep 1993	Private school, Taichung City, Taiwan	730 students	*Entamoeba histolytica and Shigella sonnei* (Sewage cross-contamination of the underground well water supply. Well located 10 metres away from the toilet and provided water to the school though a submersible pump. A 20-year-old water system. The pump's overflow pipes pierced the lining of the well below ground level through a hole, permitting seepage of ground water into the well. No cases among the teaching staff, who were provided with water from the city supply and not from the well)	Chen *et al.* 2001

Table 5 | (*continued*)

Time period	Location, country	Est. cases	Aetiologic agent (comments)	Key references
Oct 1994–Apr 1995	Victoria, British Columbia, Canada	2,894–7,718	*Toxoplasma gondii* (Most likely through faecal contamination of a water reservoir by infected animals; possible treatment deficiencies. The largest documented toxoplasmosis outbreak and the first to be linked to municipal drinking water. Municipal water system with two disinfection plants, supplying unfiltered, chloraminated surface water. Use of a weak chemical for primary disinfection. The plant apparently associated with the outbreak distributed water from the relatively small Humpback reservoir. Short retention time in the intake reservoir. Two peaks in turbidity and faecal coliform counts in Humpback Reservoir water during December 1994 and March 1995, following periods of excess rainfall associated with runoff into the reservoir. Each peak preceded a peak in the epidemic curve. Cougars and domestic and feral cats present in the watershed, some of them *Toxoplasma*-positive)	Bowie *et al.* 1997
1995–2000	USA & Canada	*c.* 3,200	*Cyclospora cayetanensis* (Most likely though consumption of contaminated Guatemalan raspberries served at separated social events. Approximately 115 mini-outbreaks reported. Simultaneous and persistent contamination on multiple Guatemalan farms the most likely explanation. Potential contamination of the raspberries through spraying with insecticides and fungicides diluted with contaminated water from the farms' water supplies. Many water supplies vulnerable to contamination, particularly during the rainy season due to surface water runoff. Sub-optimal construction, maintenance of wells near deep latrines or seepage pits. After the first large-scale outbreaks in 1996 and 1997, only farms that met certain standards, including water, sanitation, and worker hygiene issues, were allowed to export fresh raspberries to the United States during the spring season. After two more US outbreaks in 2000, the implicated farm common to both events was no longer allowed to export raspberries during the spring of 2001. No US cyclosporiasis outbreaks associated with Guatemalan raspberries were identified that spring)	Herwaldt *et al.* 1997; MMWR 1998; Herwaldt 2000; Ho *et al.* 2002; Murrow *et al.* 2002
May–Nov 1995	Lyon, France	200	*Microsporidium* (Most likely through contamination and treatment deficiencies of surface water. A specific water treatment plant implicated. Pumping of lake water directly from a recreational area mainly frequented by swimmers. Treatment using flocculation, ozoflotation and filtration, instead of chlorination)	Cotte *et al.* 1999
Oct–Nov 1996	Hengshui, Chongyi County, China	1,122	*Blastocystis hominis* (Spread through contaminated water)	Wu *et al.* 2000
May–Sep 1998	Tbilisi, Georgia	177	*Entamoeba histolytica* (Either faecal contamination after the implicated water treatment works, or inadequate filtration process, the suspected causes for this outbreak. Between 600 and 700 breakdowns of the water supply and sewerage system were reported at that time. Filters of poor quality and lack of routine maintenance at the implicated water treatment works)	Kreidl *et al.* 1999
2001	Santa Isabel do Ivai, Parana State, Brazil	290	*Toxoplasma gondii* (Most likely through faecal contamination of an underground water reservoir. Reservoir based at a ruined site, full of cracks, bordered by pastures containing livestock, only 30 meters from a suburb with many dogs and cats. No filtration. A cat and its kittens known to live in the reservoir ruins the suspected cause of contamination)	Taverne 2002

Table 6 | Protozoan parasitic outbreaks associated with recreational water worldwide

Time period	Location, country	Est. cases	Aetiologic agent (comments)	Key references
1962–1965	Usti nad Labem, Czech Republic	16	*Naegleria fowleri* (Contaminated indoor swimming pool and treatment deficiencies of pool water. Large-scale outbreak. Fatal infection for all cases. Pool water not examined for protozoa, causative agent unknown at that time. Swimming pool reconstructed and reopened in 1967. Pathogenic *N. fowleri* strains isolated for the first time from this pool in 1977, and repeatedly afterwards during 1977–78. A cavity in the damaged pool wall, the possible place for survival and reproduction of the *Naegleria* virulent strains. Fatal cases attributed to critical amount of parasites washed out into the swimming pool, combined with low free chlorine levels. Chlorination not continual, carried out by hand, at the time of the outbreak)	Kadlec *et al.* 1980
May 1982	Pool complex, Thurston County, Washington, USA	70	*Giardia lamblia* (Contaminated swimming pool. Reports for turbid water and low free chlorine residuals in one pool. Possible faecal accidents)	Harter *et al.* 1984
Fall 1985	Indoor swimming pool, NE New Jersey, USA	9	*Giardia lamblia* (Contaminated swimming pool. Faecal accident caused by handicapped child while in the pool. Chlorine levels not recorded that day. Zero chlorine level performed the following day)	Porter *et al.* 1988
Mar–Apr 1986	Hotel, Winnipeg, Manitoba, Canada	59	*Giardia lamblia* (Contaminated water slide pool, probably through emptying of an adjacent toddlers' wading pool into the implicated water slide pool)	Greensmith *et al.* 1988
Jan–Mar 1988	Brisbane, Queensland, Australia	52	*Cryptosporidium parvum* (Contaminated swimming pool complex. Oocysts detected in 3 of the 4 implicated swimming pools)	Stafford *et al.* 2000
Jul–Aug 1988	Los Angeles County, California, USA	44	*Cryptosporidium parvum* (Contaminated swimming pool. Faecal accident in the pool in early July. Inadequately maintained filtration system; 30% diminished filtration flow rate; inoperative diatomaceous earth (DE) filter. Repeated exposure to pool water; possible constant pool contamination)	Sorvillo *et al.* 1990, 1992
Aug–Oct 1988	Sports centre, Yorkshire, UK	67	*Cryptosporidium parvum* (Sewage contaminated swimming pool. Oocysts detected in pool water. Significant plumbing defects and a break in surface water collection pipe allowed ingress of sewage from the main server into the circulating pool water. Additional operational problems identified later)	Joce *et al.* 1991
Nov 1990–Jan 1991	Recreation centre, British Columbia, Canada	23	*Cryptosporidium parvum* (Contaminated children's swimming pool. Unusually frequent defecations, including liquid stools, before and during the outbreak. Free available chlorine residual frequently fallen below the minimum recommended level)	Bell *et al.* 1993
Jun 1991	Park, Maryland, USA	14	*Giardia lamblia* (Contaminated swimming pool)	Moore *et al.* 1993
Jul 1991	Day care centre, Georgia, USA	9	*Giardia lamblia* (Contaminated wading pool)	Moore *et al.* 1993
Jul 1991	Day care centre, Georgia, USA	7	*Giardia lamblia* (Contaminated wading pool)	Moore *et al.* 1993
Jul 1991	Campground, Washington, USA	4	*Giardia lamblia* (Contaminated lake)	Moore *et al.* 1993
Mar 1992	Leisure centre, SW, UK	12	*Cryptosporidium parvum* (Contaminated swimming pool. Most of the cases children using a learner pool. Oocysts in one water sample from the pool. Treatment by filtration and side-stream ozonation)	Hunt *et al.* 1994; Furtado *et al.* 1998
Jun–Oct 1992	Lane County, Oregon, USA	500	*Cryptosporidium parvum* (Contaminated wave pool. Oocysts in filter backwash water)	Moore *et al.* 1993; McAnulty *et al.* 1994
Aug 1992	Idaho, USA	26	*Cryptosporidium parvum* (Contaminated water slide)	Moore *et al.* 1993
Jan 1993	West Midlands, UK	23	*Cryptosporidium parvum* (Contaminated school swimming pool)	Furtado *et al.* 1998

Table 6 | *(continued)*

Time period	Location, country	Est. cases	Aetiologic agent (comments)	Key references
Apr 1993	Resort hotel, Oshkosh, Wisconsin, USA	51	*Cryptosporidium parvum* (Contaminated swimming pool. Treatment by filtration and chlorination. Non-recognized faecal accident(s) caused by swimmer(s) infected in the massive Milwaukee outbreak the most likely source of contamination)	MacKenzie *et al.* 1995; Kramer *et al.* 1996
Jul–Sep 1993	Dane County, Wisconsin, USA	85	*Cryptosporidium parvum* (Contaminated swimming pools)	Bongard *et al.* 1994
Jul 1993	Park, Maryland, USA	12	*Giardia lamblia* (Unintentional ingestion of untreated lake water)	Kramer *et al.* 1996
Aug 1993	River, Washington, USA	6	*Giardia lamblia* (Unintentional ingestion of untreated river water)	Kramer *et al.* 1996
Aug 1993	Motel, Wisconsin, USA	64	*Cryptosporidium parvum* (Contaminated swimming pool. Treatment by filtration and chlorination)	Kramer *et al.* 1996
Aug 1993	Wisconsin, USA	54	*Cryptosporidium parvum* (Contaminated swimming pool. Treatment by filtration and chlorination)	Kramer *et al.* 1996
Aug 1993	Wisconsin, USA	5	*Cryptosporidium parvum* (Contaminated swimming pool. Treatment by filtration and chlorination)	Kramer *et al.* 1996
Aug–Sep 1993	Madison, Wisconsin, USA	ND	*Cryptosporidium parvum* (Contaminated swimming pool. Occurrence of a faecal accident)	Graczyk *et al.* 1997
Sep 1993	Swimming club, New Jersey, USA	43	*Giardia lamblia* (Unintentional ingestion of untreated lake water)	Kramer *et al.* 1996
1994	Clark County, Nevada, USA	*c.* 80	*Cryptosporidium parvum* (Contaminated swimming pool. Occurrence of a faecal accident)	Graczyk *et al.* 1997
Jun 1994	Indiana, USA	80	*Giardia lamblia* (Contaminated swimming pool and wading pool. Intermittent breakdown of the swimming pool's filter. Lack of filtration in the wading pool)	Kramer *et al.* 1996
Jul 1994	Motel, Missouri, USA	101	*Cryptosporidium parvum* (Contaminated swimming pool. Treatment by filtration and chlorination)	Kramer *et al.* 1996
Jul–Aug 1994	Lake Nummy, New Jersey, USA	2,070	*Cryptosporidium parvum* (Contaminated shallow lake park. First cryptosporidiosis outbreak associated with recreational exposure to lake water. A backup of the septic-tank system due to a pump failure; large oocyst numbers possibly flushed into the lake by contaminated runoff of rainwater from the area that had been flooded by sewage from the septic-tank system. Use of the lake by bathers already suffering from diarrhoeal illness. High levels of faecal coliforms in the bathing area and in the adjacent canoe-docking area. Evidence of diaper-aged children repeatedly been in the water during the summer; rinse of soiled diapers in the swimming area; several faecal accidents in the water)	Kramer *et al.* 1998
Sep 1994–Jan 1995	Sutherland, Sydney, Australia	70	*Cryptosporidium parvum* (Contaminated swimming pool. Oocysts detected in pool water; presumably contamination by infected bathers)	Lemmon *et al.* 1996
Oct 1994	Leisure centre, SW, UK	14	*Cryptosporidium parvum* (Contaminated swimming pool(s). Evidence of secondary spread within the community)	Furtado *et al.* 1998
Jun 1995	Kansas, USA	24	*Cryptosporidium parvum* (Contaminated swimming pool)	Levy *et al.* 1998
Jul 1995	Water park, Georgia, USA	5,449	*Cryptosporidium parvum* and *Giardia lamblia* (Contaminated children's pool. Possible faecal accident)	Levy *et al.* 1998
Jul 1995	Nebraska, USA	14	*Cryptosporidium parvum* (Contaminated swimming pool. Runoff containing livestock faeces the suspected cause)	Levy *et al.* 1998

Table 6 | *(continued)*

Time period	Location, country	Est. cases	Aetiologic agent (comments)	Key references
Oct 1995	Trent, UK	3	*Cryptosporidium parvum* (Contaminated paddling pool. Children in diapers allowed to use the pool. Poor supervision and maintenance standards)	Furtado *et al.* 1998
Jul–Aug 1996	Andover, Hampshire, UK	8	*Cryptosporidium parvum* (Contaminated swimming pool. Although no oocysts in backwash water, presence of *Enterobius* ova indicated faecal contamination)	Sundkvist *et al.* 1997
Jun 1996	Florida, USA	77	*Giardia lamblia* and *Cryptosporidium parvum* (Contaminated children's wading pool. Wading pool supplied by municipal well water that was coagulated, settled, filtered, and chlorine-disinfected)	Levy *et al.* 1998
Jun 1996	Ft Lauderdale, Florida, USA	22	*Cryptosporidium parvum* (Contaminated shallow wading pool. Excessive number of swimmers; loss of water clarity, possible faecal accidents; inadequate filtration; inoperative ozonator)	Levy *et al.* 1998
Aug 1996	Amusement park, California, USA	3,000	*Cryptosporidium parvum* and *Giardia lamblia* (Contaminated swimming pool. Park patrons exposed to untreated water, both at the swimming pool, and when water from a jet-ski spayed an audience watching a show)	Levy *et al.* 1998
1997–1998	New Zealand	>300	*Cryptosporidium parvum* (Contaminated swimming pools)	CCN 1997*c*, 1998*a*, *c*
May 1997	SW, UK	9	*Cryptosporidium parvum* (Contaminated swimming pool)	CDR 1997
May 1997	NW, UK	13	*Cryptosporidium parvum* (Most likely through ingestion of contaminated river water while swimming)	CDR 1997
Jun–Jul 1997	Minnesota Zoo, Minnesota, USA	369	*Cryptosporidium parvum* (Exposure to a contaminated water sprinkler fountain. Although designed and built in 1994 as a decorative display, the zoo fountain was a popular attraction for children on hot summer days. Water filtered, chlorinated, re-circulated and routinely replaced, yet the filter was not flushed. A child wearing diapers and playing in the fountain the suspected source of contamination)	Deneen *et al.* 1998
Dec 1997–Apr 1998	New South Wales, Australia	1,060	*Cryptosporidium parvum* (Contaminated public swimming pools)	Puech *et al.* 2001
Mar 1998	N Thames, UK	6	*Cryptosporidium parvum* (Contaminated swimming pool. Defective plumbing water treatment)	CDR 1999
Apr 1998	Swim club, Minnesota, USA	45	*Cryptosporidium parvum* (Contaminated swimming pool. An infected child who had swam in the pool before the outbreak the suspected source of contamination)	Barwick *et al.* 2000
Jun 1998	Wisconsin, USA	12	*Cryptosporidium parvum* (Contaminated community pool. Faecal accident the suspected source of contamination)	Barwick *et al.* 2000
Jul 1998	Wisconsin, USA	12	*Cryptosporidium parvum* (Contaminated community pool. Faecal accident the suspected source of contamination)	Barwick *et al.* 2000
Jul 1998	Wisconsin, USA	9	*Cryptosporidium parvum* (Contaminated community pool. Faecal accident the suspected source of contamination)	Barwick *et al.* 2000
Jul 1998	State park, Pennsylvania, USA	8	*Cryptosporidium parvum* (Swimming in a contaminated lake)	Barwick *et al.* 2000
Jul 1998	Minnesota, USA	7	*Cryptosporidium parvum* (Contaminated community pool. Unknown source of contamination)	Barwick *et al.* 2000
Jul 1998	Day care centre, Florida, USA	7	*Cryptosporidium parvum* (Contaminated swimming pool. Although unknown source of contamination, many reports of babies in diapers swimming in the pool)	Barwick *et al.* 2000
Aug 1998	Oregon, USA	69	*Cryptosporidium parvum* (Contaminated community pool. Although unknown source of contamination, faecal contamination was suspected)	Barwick *et al.* 2000

Table 6 | *(continued)*

Time period	Location, country	Est. cases	Aetiologic agent (comments)	Key references
Sep–Nov 1998	E Anglia & Oxford, UK	14	*Cryptosporidium parvum* (Public swimming pool complex implicated)	CDR 1999
Nov 1998	N Thames, UK	9	*Cryptosporidium parvum* (Contaminated public swimming pool. Ozonation plant failure)	CDR 1999
1999	S Island, New Zealand	7	*Cryptosporidium parvum* (Contaminated swimming pool)	CCN 1999
Jul 1999	Massachusetts, USA	18	*Giardia lamblia* (Contaminated pond)	Lee *et al.* 2002
Jul 1999	Trailer park, Minnesota, USA	10	*Cryptosporidium parvum* (Contaminated swimming pool)	Lee *et al.* 2002
Jul 1999	Wisconsin, USA	10	*Cryptosporidium parvum* (Contaminated municipal pool)	Lee *et al.* 2002
Jul 1999	SW, UK	11	*Cryptosporidium parvum* (Contaminated swimming pool. Faecal accident the suspected source of contamination)	CDR 2000
Jul–Nov 1999	Leisure complex, SE, UK	14	*Cryptosporidium parvum* (Contaminated swimming pool. History of regular contamination by deliberate defecation)	CDR 2000
Aug 1999	Beach park, Florida, USA	38	*Shigella sonnei* and *Cryptosporidium parvum* (Contaminated interactive fountain)	Lee *et al.* 2002
Aug 1999	House, Florida, USA	6	*Cryptosporidium parvum* (Contaminated swimming pool)	Lee *et al.* 2002
Aug–Oct 1999	W Midlands, UK	16	*Cryptosporidium parvum* (Contaminated swimming pool. Faecal accident the suspected source of contamination. *Cryptosporidium* oocysts in pool water sample)	CDR 2000
Aug–Nov 1999	SE, UK	54	*Cryptosporidium parvum* and *Giardia lamblia* (Contaminated swimming pool. Cryptosporidium oocysts and Giardia-like cysts in filter samples)	CDR 2000
Sep 1999	Leisure complex, W Midlands, UK	8	*Cryptosporidium parvum* (Contaminated swimming pool)	CDR 2000
Sep–Nov 1999	Leisure centre, London, UK	30	*Cryptosporidium parvum* (Contaminated swimming pools. Faecal accident the suspected source of contamination)	CDR 2000
Nov 1999	Leisure centre, Trent, UK	19	*Cryptosporidium parvum* and *Giardia lamblia* (Contaminated swimming pool. Faecal accident the suspected source of contamination)	CDR 2000
March–Jun 2000	Children's nursery, Wales, UK	17	*Giardia lamblia* (Contaminated water play)	CDR 2001
May–Jun 2000	Trent UK	41	*Cryptosporidium parvum* (Contaminated swimming pool. Oocysts detected in pool water and in pool filters)	CDR 2001
Jun 2000	Private swim club, Ohio, USA	700	*Cryptosporidium parvum* (Contaminated swimming pool. Repeated recontamination by infected swimmers)	Lee *et al.* 2002
Jun 2000	Nebraska, USA	225	*Cryptosporidium parvum* (Contaminated swimming pools. Repeated recontamination by infected swimmers)	Lee *et al.* 2002
Jun 2000	Georgia, USA	36	*Cryptosporidium parvum* (Contaminated swimming pools. Cases swam in a community pool and an inflatable pool)	Lee *et al.* 2002
Jul 2000	Swimming beach, Minnesota, USA	220	*Cryptosporidium parvum* (Contaminated lake)	Lee *et al.* 2002
Jul 2000	S Carolina, USA	26	*Cryptosporidium parvum* (Contaminated swimming pool)	Lee *et al.* 2002
Jul 2000	Day camp, Minnesota, USA	7	*Cryptosporidium parvum* (Contaminated municipal pool)	Lee *et al.* 2002
Jul 2000	Hotel, Minnesota, USA	6	*Cryptosporidium parvum* (Contaminated swimming pool)	Lee *et al.* 2002
Jul 2000	Apartment complex, Florida, USA	3	*Cryptosporidium parvum* (Contaminated municipal pool)	Lee *et al.* 2002
Aug 2000	Colorado, USA	112	*Cryptosporidium parvum* (Contaminated swimming pool)	Lee *et al.* 2002

Table 6 | *(continued)*

Time period	Location, country	Est. cases	Aetiologic agent (comments)	Key references
Aug 2000	Resort, Florida, USA	19	*Cryptosporidium parvum* (Contaminated municipal pool)	Lee *et al.* 2002
Aug 2000	Country club, Florida, USA	5	*Cryptosporidium parvum* (Contaminated swimming pool)	Lee *et al.* 2002
Aug 2000	Condominium, Florida, USA	5	*Cryptosporidium parvum* (Contaminated swimming pool)	Lee *et al.* 2002
Aug 2000	Minnesota, USA	4	*Cryptosporidium parvum* (Contaminated municipal pool)	Lee *et al.* 2002
Aug–Sep 2000	London, UK	3	*Cryptosporidium parvum* (Contaminated public swimming pool. Oocysts detected in pool water, and in pool filter sand)	CDR 2001
Sep 2000	London, UK	10	*Cryptosporidium parvum* (Contaminated public swimming pool. Oocysts detected in pool water, and in pool filter sand)	CDR 2001
Sep 2000	Eastern, UK	7	*Cryptosporidium parvum* (Contaminated public swimming pool. Oocysts detected in pool water, and in pool filter sand)	CDR 2001
Sep–Oct 2000	SW, UK	12	*Cryptosporidium parvum* (Contaminated public swimming pool)	CDR 2001
Sep–Oct 2000	Trent, UK	9	*Cryptosporidium parvum* (Association with public swimming pool. Oocysts not detected in pool water, however, indicator organisms found)	CDR 2001
Oct–Nov 2000	SW, UK	5	*Cryptosporidium parvum* (Contaminated club swimming pool. One viable oocyst detected in a pool filter)	CDR 2001
Feb–Mar 2001	SE, UK	5	*Cryptosporidium parvum* (Contaminated public swimming pools. Oocysts detected in main and learner pools. Inadequate treatment of pool water)	CDR 2002
May 2001	Hotel, Dauphin, Manitoba, Canada	59	*Cryptosporidium parvum* (Contaminated swimming pool. Swimming in the hotel pool highly associated with illness)	CCDR 2002
Jun 2001	SE, UK	152	*Cryptosporidium parvum* (Contaminated school outdoor swimming pool. No obvious faecal incident or contamination event)	CDR 2002
Aug 2001	SW, UK	14	*Cryptosporidium parvum* (Cases exposed to stream water flowing through a beach. Effluent from water treatment plant enters stream. Also problem with illegal tipping into sewer, possibly from campsite chemical toilets)	CDR 2002
Oct–Nov 2001	Leisure centre, SW, UK	3	*Cryptosporidium parvum* (Contaminated swimming pool)	CDR 2002
Apr 2002	Activity centre, NW, UK	4	*Cryptosporidium parvum* and *rotavirus* (Most likely through recreational exposure to a range of water sources)	CDR 2003*b*
Sep 2002–Feb 2003	Leisure centre, SE, UK	20	*Cryptosporidium parvum* (Oocyst-contaminated sand taken from the filters of the main pool and the leisure pool. Faecal incident suspected)	CDR 2003*b*
Jan–Apr 2003	Yorkshire & Humberside, UK	66	*Cryptosporidium parvum* (Contaminated hydro swimming pool. Faecal incident suspected)	CDR 2003*b*

Table 7 | Waterborne protozoan parasitic outbreaks associated with travellers, foreign residents worldwide

Month year	Location, country	Est. cases	Aetiologic agent (comments)	Key references
World War I	Near East	Among foreign military forces	*Isospora belli* (Aetiology unknown)	Faust *et al.* 1961
World War II	SW Pacific Islands	Among foreign military forces	*Isospora belli* (Aetiology unknown)	Faust *et al.* 1961
Dec 1946–Jan 1947	Apartment building, Tokyo, Japan	116 American occupants	*Giardia lamblia* and *Entamoeba histolytica* (Sewage contamination of the building's water supply)	Davis & Ritchie 1948
Feb–May 1970	Hotels, Leningrad, Russia	107 American travellers	*Giardia lamblia* (Consumption of tap water in Leningrad's hotels. **Two distinctive outbreaks**; 23 athletes in February and March, 84 scientists in May. Treatment deficiencies; probably separated water supplies from the residents; use of chloramines or a combined available chlorine for disinfection; poor operation of the filtration process)	Walzer *et al.* 1971; Brodsky *et al.* 1974
1971 & 1973	Hotels, Leningrad, Russia	15 students from Finland	*Giardia lamblia* (Consumption of tap water)	Jokipii & Jokipii 1974
1973	Leningrad, Russia	15 American scientists	*Giardia lamblia* (Consumption of tap water)	Brodsky *et al.* 1974
Mar 1975	Russia	72 American travellers	*Giardia lamblia* (Consumption of tap water)	CDC 1975
Oct 1976	Madeira, Portugal	27 American travellers	*Giardia lamblia* (Most likely through consumption of tap water. Drinking water reported to be chlorinated)	CDC 1977*b*
Jun–Sep 1979	California, USA	74 travellers	*Giardia lamblia* (Distribution system deficiency. Travellers had visited Cattail Cove State Park in Arizona. Recreation area served by chlorinated shallow well water, pumped to two storage facilities. Cross-connections and poor plumbing may have resulted in contamination of the drinking water by an irrigation system that sprayed sewage effluent)	Lin 1985
Apr–Jun 1985	Kathmandu, Nepal	247 expatriate residents	*Blastocystis hominis* or *Cyclospora cayetanensis* (An outbreak of unknown aetiology. Doubts expressed at that time whether *Blastocystis* had been the real causative agent of the outbreak, and not some other, unidentified pathogen. Five years later it was reported that *Cyclospora* (CLB), and not *Blastocystis*, might have been the causative agent of this outbreak)	Babcock *et al.* 1985; Shlim *et al.* 1991
May–Sep 1988	Hotel, Phuket Island, Thailand	42 Italian tourists	*Entamoeba histolytica* and *Giardia lamblia* (Consumption of drinks with ice, ice cream and raw fruit in ice significantly associated with both infections)	de Lalla *et al.* 1992
Jun–Nov 1989	Kathmandu, Nepal	55 foreign residents	*Cyclospora cayetanensis* (Aetiology basically unknown. *Cyclospora* detected in stool specimens of all patients. Unknown organism at that time, characterized as CLB, cyanobacterium-like body. Being a foreign resident in Nepal was a risk factor for acquiring the disease. Water pumped from an underground holding tank to a tin rooftop tank. All patients reported boiling their water before drinking)	Shlim *et al.* 1991
May–Oct 1990	Kathmandu, Nepal	85 foreign residents	*Cyclospora cayetanensis* (Unknown cause/multiple causes)	Rabold *et al.* 1994

Table 7 | *(continued)*

Month year	Location, country	Est. cases	Aetiologic agent (comments)	Key references
Jun 1994	British military detachment, Pokhara, Nepal	12 British soldiers and dependants	*Cyclospora cayetanensis* (Contaminated water supply. *Cyclospora* oocysts detected in a 2-litre water sample from a storage tank that fed chlorinated, filtered water to all homes in the area. Water free of coliforms. Adequate chlorination during the outbreak)	Rabold *et al.* 1994
May–Jun 1997	Crete, Greece	70 English tourists	*Giardia lamblia* (Most likely through contaminated hotel water. Room water smelling of sewage or being discoloured. Consumption of reconstituted orange juice associated with certainty of diagnosis. Chlorinated, generally unfiltered water supply)	Hadjichristodoulou *et al.* 1998; Hardie *et al.* 1999
Sep 1998	Hotel, Marmaris, Turkey	15 Danish and Swedish tourists	*Cryptosporidium parvum* (Faecal contamination of drinking water. One week prior to the outbreak, the hotel, supplied by its own private water supply, had opened a shunt pipe to the public community water system to fill its water tank. This pipe had been blocked at one end and out of use for four years. Nine different microbial agents isolated from the holiday-makers)	Engberg *et al.* 1998
May–Jul 2000	Hotel, Majorca, Spain	112 British tourists	*Cryptosporidium parvum* (No cases among guests and workers at the resort. Oocysts detected in the filters from the hotel swimming pool)	de Mateo-Ontanon 2000; Smerdon 2000
Aug 2001	Military Base, Baden-Wuerttemberg, Germany	200 soldiers	*Cryptosporidium parvum* (Aetiology basically unknown. Soldiers brought to the implicated base for five-day field training. Oocysts detected in stool specimens from ill soldiers, but not in water samples from the base)	Robert Koch Institut 2001
Jul 2003	Majorca, Spain	142 British tourists	*Cryptosporidium parvum* (Oocysts identified in water backwashed from filters at a hotel swimming pool where many of the cases had been bathing)	CDR 2003*a*
ND	Hotel, Caribbean, St Lucia	38 American tourists	*Cryptosporidium parvum* (Most likely through consumption of contaminated tap water or food. A small river used as water source. Treatment by chemical coagulation, sedimentation, filtration, and chlorination. Consumption of tap water from the hotel significantly associated with illness)	Ma *et al.* 1985

ND: no data.

Table 8 | Summarised data on waterborne outbreaks caused by protozoan parasitic agents worldwide

	Number of waterborne outbreaks caused by protozoan parasitic agents worldwide										
Suspected cause	***Giardia lamblia***	***Cryptosporidium parvum***	***Entamoeba histolytica***	***Cyclospora cayetanensis***	**Toxoplasma gondii**	**Isospora belli**	***Blastocystis hominis***	***Balantidium coli***	***Microsporidia***	***Acanthamoeba***	***Naegleria fowleri***
Contaminated water source (lake, river, well, etc)	9 (6.8%)	17 (10.3%)	2	–	2	–	–	1	–	1	–
Contaminated water system (community, private, etc)	5 (3.8%)	6 (3.6%)	3	1	–	–	1	–	–	–	–
Contaminated drinking tap water	3 (2.3%)	18 (10.9%)	1	–	–	–	–	–	–	–	–
Treatment distribution system deficiency	28 (21.2%)	10 (6.1%)	–	–	–	–	–	–	–	–	–
Use of chlorinated unfiltered water	8 (6.1%)	–	–	–	–	–	–	–	–	–	–
Use of untreated surface water	8 (6.1%)	1 (0.6%)	–	1	–	–	–	–	–	–	–
Use of untreated groundwater	5 (3.8%)	1 (0.6%)	–	–	–	–	–	–	–	–	–
Association with recreational water (swimming pools, etc)	18 (13.6%)	83 (50.3%)	–	–	–	–	–	–	–	–	1
Association with foreign travel residence	10 (7.6%)	5 (3%)	2	3 (4?)	–	2	1?	–	–	–	–
Mixed aetiology	32 (24.2%)	18 (10.9%)	1	1	1	1	–	–	1	–	–
Unknown cause	6 (4.5%)	6 (3.6%)	–	–	–	–	1	–	–	–	–
Total	132 (100%)	165 (100%)	9	6 (7?)	3	3	2 (3?)	1	1	1	1

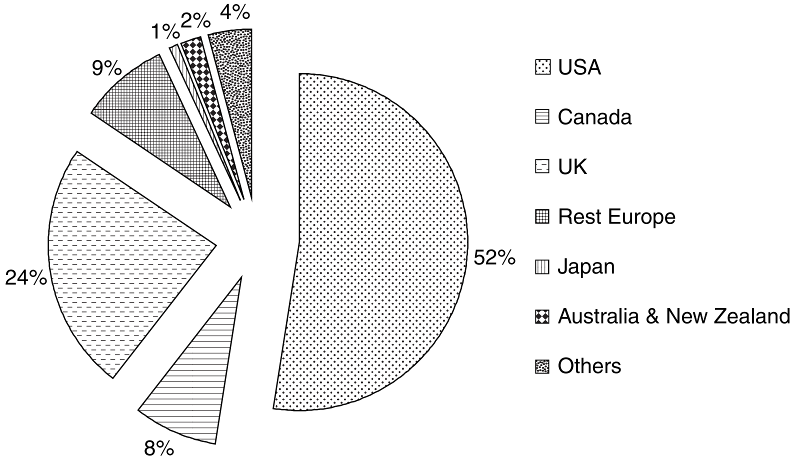

Figure 1 | Distribution of waterborne protozoan outbreaks worldwide.

outbreak investigations. However, it is somewhat surprising that these North American and European outbreaks accounted for as many as 93% of all reports. Similarly, UK waterborne outbreaks accounted for 73.6% of European outbreaks.

Given that the majority of outbreaks of waterborne cryptosporidiosis and giardiasis occurred in North America and the UK (Tables 3 and 4) it is probable that enhanced surveillance and more effective reporting systems are in place and that lessons have been learnt from earlier outbreaks. Without rigorous investigation and reporting of outbreaks, we cannot determine either the extent to which waterborne pathogenic protozoa affect morbidity and mortality, globally, or the effectiveness of water treatment systems in controlling these pathogens.

G. duodenalis was responsible for the largest number of recorded outbreaks (32%), with *Cryptosporidium* sp. accounting for 23.7% of recorded outbreaks. For drinking water outbreaks, deficiencies in water treatment processes are the most cited reasons (Tables 3, 4 and 8), although post treatment contamination should also be considered (Table 8). Deficiencies include insufficient barriers, inadequate or poorly operated treatment and disinfection systems (Tables 3 and 4), which, when they occur in conjunction with sufficient human infectious (oo)cysts/spores to penetrate such barriers, can lead to waterborne outbreaks. The latest report of the UK Group of Experts on current knowledge on *Cryptosporidium* in Water supplies, which assessed the lessons learned from suspected waterborne outbreaks of cryptosporidiosis (the results of research carried out since 1995), addressed the need for further advice on protection of water resources, including surface and groundwaters, the provision of additional water treatment, the design of monitoring programmes and strategies and the management of outbreaks of drinking water-related illness, and considered further appropriate research, is available on the Internet (www.dwi.gov.uk/pubs/bouchier/index.htm).

The majority of outbreaks associated with recreational water (63.9%; Tables 6 and 8) are due to *Giardia* (13.6%) or *Cryptosporidium* (50.3%), where the vehicle is normally swimming pool water, frequently contaminated following accidental faecal discharge into the pool water (Tables 6 and 8). Treatment/operational/disinfection failures increase the likelihood of disease transmission because (oo)cysts are not removed or killed by optimized water treatment schedules. These include (a) effective circulation of water with the pool or pool system, (b) effective use of optimally dosed chemical coagulant, and (c) an optimally operated, well designed, constructed and maintained sand filtration system. Toddler pools are the most frequently affected (Table 6). Again, the majority of outbreaks occurred in North America and the UK (94.8%, 92/97; Table 6), and of the 97 documented, 60.8% ($n = 59$) occurred in North America, while 34% ($n = 33$) occurred in the UK. Again, enhanced surveillance and more effective reporting systems are the likely reasons for this geographical distribution. Guidance on optimizing swimming pools for removing *Cryptosporidium* oocysts is available on the Internet (www.pwtag.org/home.html). The guidance aims to minimize the threat from *Cryptosporidium* by optimizing flow rates, filter operation through effective coagulation and backwash practices, disinfection, and auditing maintenance practice while offering advice for fouling of water and hygiene. Such guidance should also be effective at controlling the larger (oo)cysts of the enteric protozoan parasites listed in Table 1.

Lessons learnt: The example of *Cryptosporidium*

Cryptosporidium poses the biggest threat to the water industry as, initially, many outbreaks were caused by this ‘little known’ parasite which penetrated multi-barrier water treatment systems that were thought to be effective in providing ‘safe’ drinking water (Smith & Rose 1990, 1998). The emergence of cryptosporidiosis challenged our knowledge of its occurrence, prevalence, epidemiology, treatment and transmission routes, and as a drinking water-related illness, challenged the adequacy of conventional water treatment processes. Concern about this organism was further heightened by the scant knowledge of its distribution and occurrence in the environment and the absence of a simple and reliable means of detecting the organism in water (Anon 1990; Smith & Lloyd 1997).

Occurrence in humans

The fact that waterborne outbreaks have been documented indicates that a risk of disease is present, but with what frequency? The major drivers for obtaining a clearer understanding of the threat of waterborne disease include: (a) standardized testing for human disease through these pathogens in clinical microbiology laboratories; (b) an effective infrastructure to inform public health professionals; (c) communication between all professionals involved in waterborne disease surveillance; (d) determining the occurrence of these pathogens in the aquatic environment; (e) determining the effectiveness of drinking water technologies for pathogen/surrogate removal and (f) determining the waterborne route of transmission epidemiologically. This has been accomplished to differing degrees in different countries and differing regions of the same country, for example, for *Cryptosporidium* but during its emergence as a public health threat, relatively little was known of its occurrence and prevalence. Through standardization of diagnostic methods, the importance of human cryptosporidiosis, the reservoirs of infection and major contributors to environmental contamination, waterborne and foodborne disease are better understood, as is the importance of the waterborne route of transmission (Anon 1990, 1995, 1999). Yet, for many of the pathogenic protozoa listed in Table 1, relatively little of the above is known.

Molecular biology has provided new insights into the taxonomy and epidemiology of *Cryptosporidium*, including previously unrecognized differences in disease, symptomatology, zoonotic potential, risk factors and environmental contamination, using molecular tools appropriate for species, genotype and subtype analysis (Cacciò *et al.* 2005). Seven *Cryptosporidium* species and two genotypes cause human disease, and molecular approaches have enabled a greater understanding of the contributions of humans and livestock as reservoirs of infection. Differences in geographical and temporal distribution, disease presentations and risk factors for infection have been identified for *C. parvum* and *C. hominis*, the most commonly reported causes of human cryptosporidiosis (Cacciò *et al.* 2005). Such typing and subtyping analyses require the use of validated molecular methods, which have proven public health significance, and with their adoption, disease and source tracking become possible. Again, knowledge gained from research into *Cryptosporidium* should be useful in understanding the epidemiology of other enteric pathogenic protozoa.

Occurrence in the aquatic environment

Without knowing the occurrence of (oo)cysts and spores of parasitic protozoa in water, it is difficult to determine what risk they present to consumers of contaminated potable water.

Standardized methods are required to determine the occurrence of (oo)cysts and spores in raw water abstracted for potable water, water treatment systems, potable water and recreational waters. A variety of standardized methods already exist for *Giardia* and *Cryptosporidium* (*Methods for the Examination of Waters & Associated Materials* 1999) and the (oo)cysts of the majority of waterborne parasitic protozoa are similar to, or larger than those of *Giardia* and

Cryptosporidium (Table 1). We anticipate that current methods should prove useful for entrapping the (oo)cysts of the waterborne parasitic protozoa listed in Table 1, possibly with the exception of the microsporidia. Their identification in water concentrates presents issues similar to those encountered with *Giardia* and *Cryptosporidium* (oo)cysts prior to the development of fluorescein isothiocyanate (FITC)-labelled genus specific monoclonal antibodies (FITC-mAbs) for their detection (Smith 1996), but the use of quality controlled, validated, PCR-based tools should overcome many of the problems associated with the lack of diagnostic FITC-mAbs.

Although widely used worldwide, current methods for the isolation and enumeration of *Giardia* and *Cryptosporidium* (oo)cysts in water (*Methods for the Examination of Waters & Associated Materials* 1999) have numerous limitations. They are time-consuming and inefficient, and provide minimal information about the biology of the organism. Furthermore, some advocate the analysis of only a fraction of the concentrate. Minimizing the portion of sample concentrate examined can reduce the level of confidence in the result obtained, and this issue requires appreciation by water regulators. Several alternative methods, or modifications to existing methods, have been published in the literature, but many lack corroboration with established methods using a variety of water types in multi-centre investigations. Advances that increase information about the biology and development of these pathogens should be encouraged. Currently, there are few hard scientific data available identifying the advantages of alternative methods and, in such a void, standardized methods are as effective as any alternative, and should be encouraged. Improvements in 'standard' methods can only occur when assurance quality control (AQC) data, accrued by the developers and users of such methods, are released into the public domain (Smith & Hayes 1996). Discussion, dissemination and publication of scientific data are seen as fundamental requirements for generating confidence in alternative methods. Although time-consuming, users, regulators and policy-makers must encourage participation in round robin testing and competent quality assurance schemes. Data generated from such interactive trials should be the final arbitrator.

Furthermore, current methods do not provide information on the infectivity, pathogenicity and virulence of the organisms detected, nor can they determine the source from which the organism is derived. This presents a major challenge for the future monitoring of waterborne parasites in drinking water supplies.

Removal/destruction in water treatment

Given the common occurrence of *Cryptosporidium* spp. oocysts in source waters (Gold & Smith 2002), its ability to survive in cold aquatic environments, its low infectious dose, and the disinfection resistance of oocysts, optimization of multi-barrier approaches, including appropriate chemical pretreatment, 'best operational practice', and frequent, routine monitoring of filtration performance offer the best options for its control in water treatment systems (Smith & Lloyd 1997; Craun *et al.* 1998; Smith & Grimason 2003). Reductions of between 1.25 and 2.45 $\log_{10}$ oocysts can be achieved in optimally run conventional water treatment systems (Smith & Grimason 2003). Similarly, those disinfectants, such as ultraviolet irradiation and ozone (Wallis & Campbell 2002), that are effective in inactivating waterborne *Cryptosporidium* and *Giardia* (oo)cysts are expected to prove useful for other waterborne protozoa (Smith & Grimason 2003).

The European perspective

Water shortage is an urgent public health problem currently facing some mainland European countries, particularly those in southern and eastern Europe (WHO 2002). Ongoing demographic changes can affect both water quality and demand through increased agricultural, industrial and domestic use, while unplanned urbanization leads to over-exploitation of local water resources and threatens the quality of local water bodies through release of inadequately treated wastewater (WHO 2002). Effective wastewater treatment safeguards public health against infections. Partnerships and co-operation between European countries are needed, at all levels, to provide financial and institutional support for improved wastewater disposal and better management and protection of water resources.

Enteric protozoan pathogens of humans have increased in importance in Europe, particularly since their association with waterborne transmission. In the UK, cryptosporidiosis is the most common cause of outbreaks linked to mains water supply (Hunter 2000). Based on the likelihood of waterborne *Cryptosporidium* contamination from the catchment following risk assessment, the UK Government introduced legislation that requires water providers to implement continuous monitoring for *Cryptosporidium* (Barrell *et al.* 2000). In England and Wales, a continuing risk of cryptosporidiosis from treated water supplies has been confirmed, reinforcing government advice to water utilities for optimizing particle removal (Furtado *et al.* 1998). Such advice has reduced *Cryptosporidium* contamination of UK drinking water (Drury 2004).

Mainland Europe

Giardia and *Cryptosporidium* (oo)cysts have been detected in selected German surface and drinking waters (Gornik & Exner 1991; Karanis *et al.* 1998). Limited data are available regarding the occurrence and distribution of pathogenic protozoa in water in southern and eastern European countries. In Greece, *Giardia* and *Cryptosporidium* were detected in surface water reservoirs, swimming pools and drinking water samples (Karanis *et al.* 2001, 2002). In Russia, monitoring of treated water for the presence of *Giardia* cysts, prior to it entering the distribution system, has been required for all water treatment plants using surface waters since 1997. Treated wastewater analyses showed that contamination of surface waters with *Giardia* cysts mainly results from secondary wastewater discharges in the Moscow Region (Larin & Kashkarova 2002). High *Giardia* cyst densities (305 cysts l^{-1}) were detected in surface water sources in the Moscow region (Larin & Kashkarova 2002) during 1999–2000 together with an increase in the cyst densities during autumn/winter. Two of the four water treatment plants in Moscow that receive water from the Moscow River were contaminated periodically with a considerable number of *Giardia* cysts (Larin & Kashkarova 2002). In contrast, *Cryptosporidium* oocysts ($0.89\,l^{-1}$) occurred randomly in samples, without identifiable seasonality. Giardiasis and cryptosporidiosis are not reportable in Russia.

Dolejs *et al.* (2000) reported the presence of *Cryptosporidium* oocysts (up to $74\,l^{-1}$) and *Giardia* cysts (up to $4.9\,l^{-1}$) in Czech raw water sources. Preliminary investigations on the occurrence of *Giardia* and *Cryptosporidium* in Bulgarian (Sofia, Varna) and south Russian (Rostov) water supplies indicate high levels of (oo)cyst contamination (Karanis *et al.* 2005). In Sofia, (oo)cysts were detected in rivers (*Giardia* = 280 cysts l^{-1}; *Cryptosporidium* = 92 oocysts l^{-1}), reservoirs (20 cysts l^{-1}), wells (4 oocysts l^{-1}) and sewage effluent (604 cysts l^{-1}; 32 oocysts l^{-1}). No other reports on the occurrence and distribution of *Giardia* and *Cryptosporidium* in eastern European countries are available. Better surveillance and reporting systems and outbreak management strategies are needed to assess the risk of waterborne transmission of protozoa in European countries.

CONCLUSIONS

We reviewed 325 outbreaks of human disease attributed to the waterborne transmission of pathogenic protozoa. The presence of enteric protozoan parasites in aquatic ecosystems and their redistribution by such ecosystems make it imperative to develop prevention strategies for water and food safety. Determining the incidence and prevalence of human enteric protozoan parasites such as *Giardia*, *Cryptosporidium*, *Entamoeba*, *Cyclospora*, *Toxoplasma*, *Isospora*, *Blastocystis*, *Balantidium*, the microsporidia, *Acanthamoeba*, *Naegleria* and *Neospora* in different populations using parasitological, serological and molecular diagnostic tools will provide baseline data against which the risk factors associated with waterborne and foodborne transmission can be identified. While current diagnostic tests for enteric protozoa are effective for detecting clinically ill cases, they may not be sufficiently sensitive for detecting asymptomatic carriers. Standardized methods in both clinical and environmental settings are required to maximize public health surveillance, while reporting of outbreaks will provide better insight into the public health impact of waterborne pathogenic protozoa.

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