Safe drinking water and waterborne outbreaks

N. A. Moreira and M. Bondelind

ABSTRACT

The present work compiles a review on drinking waterborne outbreaks, with the perspective of production and distribution of microbiologically safe water, during 2000–2014. The outbreaks are categorised in raw water contamination, treatment deficiencies and distribution network failure. The main causes for contamination were: for groundwater, intrusion of animal faeces or wastewater due to heavy rain; in surface water, discharge of wastewater into the water source and increased turbidity and colour; at treatment plants, malfunctioning of the disinfection equipment; and for distribution systems, cross-connections, pipe breaks and wastewater intrusion into the network. Pathogens causing the largest number of affected consumers were *Cryptosporidium*, norovirus, *Giardia*, *Campylobacter*, and rotavirus. The largest number of different pathogens was found for the treatment works and the distribution network. The largest number of affected consumers with gastrointestinal illness was for contamination events from a surface water source, while the largest number of individual events occurred for the distribution network.

Key words | distribution network, drinking water, pathogens, waterborne outbreak, water safety plan, water treatment

N. A. Moreira
Cranfield Water Science Institute,
Cranfield University,
Bedfordshire MK43 0AL,
UK

N. A. Moreira
M. Bondelind (corresponding author)
Department of Civil and Environmental Engineering,
Chalmers,
Sven Hultins gata 8,
Göteborg 412 96,
Sweden
E-mail: *mia.bondelind@chalmers.se*

INTRODUCTION

Drinking water safety plays a significant role in establishing the quality of human life in modern societies. In that perspective, problems with microbial pathogens within the production and distribution of drinking water can have an important impact on public health. The occurrence of a waterborne disease outbreak (WBO) may also have the effect of lowering trust, increase perceived risk and decrease acceptance for the drinking water (Bratanova *et al.* 2013).

Waterborne outbreaks are caused by drinking water contamination worldwide (Karanis *et al.* 2007). One of the most challenging issues facing the drinking water treatment plants (WTP) are the uncertainties related to climate change and the effect it will have on the surface water quality. Increase of extreme hydrological events in addition to changes in air temperature may increase the risk of WBOs. The most vulnerable water bodies to future climate changes are likely to be shallow lakes, where the chemical processes will be altered by the impact of an increase in water temperature, increases in pH and larger alkalinity generation in the lakes themselves. Additionally, sewage discharge from combined sewage systems caused by heavy rainfall has been demonstrated to spread waterborne pathogens within the surface waters. Furthermore, increased temperatures may increase disinfection by-product formation rates in surface waters at natural temperatures, between 5 and 30 °C (Delpha *et al.* 2009). Consequently, environmental contamination, intensive livestock rearing, surface water and discharge of wastewater into drinking water sources are risk factors that need to be addressed (Chalmers 2012).

In the production of safe and aesthetically suitable water for human consumption, the analysis and evaluation of risks to the complete drinking water system, from the catchment until it reaches the consumer, is considered of paramount importance by the World Health Organization (WHO). To achieve that aim, a framework for safe drinking water was developed by the WHO throughout the application of

doi: 10.2166/wh.2016.103

guidelines designated as water safety plans (WSP) (WHO 2011). Through the WSP, hazards and hazardous events that can affect the safety of the production of drinking water from the catchment to consumer are identified. The risks associated with the events are assessed and control points and barriers are implemented if needed. The WSP should be reviewed regularly and continuously updated (Bartram *et al.* 2009). To quantify the barrier effect and the treatment required, the Microbial Barrier Analysis model (MBA) can be used (Ødegaard & Østerhus 2014). The raw water quality is evaluated and according to its quality the necessary treatment efficiency is determined. Thereafter the removal and inactivation efficiency of the barriers installed at the WTP are calculated. The difference between the required and the calculated barrier efficiency shows if supplementary surveillance or additional treatment is required.

In spite of the generalised use of risk ranking in WSP, the evaluation and comparison of water safety measures does not have a common and structured approach (Lindhe *et al.* 2013). As a result, the primary safety procedures against microbiological hazards are still capable sanitation and drinking water infrastructures (Baldursson & Karanis 2011). Thus, reviewing WBOs associated with drinking water production can help to shed light on the most problematic issues faced by the water industry. The aim of the present work is to review causes for drinking water disease outbreaks, assessing possible patterns and accountability issues for those events in order to improve drinking water safety.

METHOD

This study of causes for drinking water disease outbreaks is based on information and literature collected from sources including Scopus, Eurosurveillance, PubMed, New Zealand's Institute of Environmental Science and Research (ESR), Canada Communicable Disease Report (CCDR) and Morbidity and Mortality Weekly Report from the USA CDC (Centers for Disease Control and Prevention). Keywords used in the search comprised: waterborne, water treatment, outbreak, *Cryptosporidium*, *Campylobacter*, *Giardia*, norovirus, rotavirus, and adenovirus. The number of identified outbreaks may be misrepresentative because of the voluntary nature of reporting processes (Brunkard *et al.* 2011) or that the events may not have been mentioned in scientific publications. In total 66 reviewed articles were found to be eligible accordingly to the criteria: (i) data in the timeframe 2000–2014; (ii) drinking water outbreak confined geographically to Europe, North America and New Zealand; (iii) surveillance of potential factors of interest to the drinking water industry affecting the occurrence of parasite transmission hazards.

The time frame for this study is 2000–2014. Regulations are continuously being updated and implemented for improved safety of drinking water. Therefore, only recent events that may be of interest for the water industry today are included in this review. For example, the United Kingdom alone was responsible for 73.6% of the waterborne outbreaks in Europe until 2003 (Karanis *et al.* 2007). The implementation of a new set of regulations in the year 2000, concerning drinking water production, that took place in the UK led to reductions in cryptosporidiosis that were considered statistically relevant (Lake *et al.* 2007).

In this review drinking water outbreaks confined geographically to Europe, North America and New Zealand have been reviewed. Here public national systems to register the occurrence of waterborne outbreaks are available. In developing countries the information related with WBOs is less available or even absent and therefore these countries have not been included in this review (Baldursson & Karanis 2011). Thus the available reports of incidents, according to the stipulated eligibility criteria, resulted in the inclusion of 15 countries: Canada, Denmark, Finland, France, Greece, Ireland, Italy, Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, the UK and the USA. The creation of public national systems to register the frequency and prevalence of waterborne outbreaks or protozoan infections may vary among the countries. The surveillance of potential factors of interest to the drinking water industry affecting the occurrence of parasite transmission hazards has to be known for the event to be included in this review.

The results of this review are summarised in Tables 1–4 that present the year of the event; country and specific location (when available); estimated number of infections; population served by the water works or distribution system; causative agent; probable cause for the outbreak to occur; and key reference. The medium value was used when the number of estimated cases was presented in the form of an interval in the reviewed articles.

Table 1 | List of outbreaks originated from raw water contamination (groundwater)

Year	Location, country	Est. cases	Pop. served	Causative agent	Probable causes for outbreak occurring	Reference
2000	Walkerton, Canada	2,300	4,800	*Campylobacter* and *E. coli*	Contamination from livestock faecal residue following heavy rainfall	Hrudey *et al.* (2003)
2000	Clitheroe, UK	58	17,252	*Cryptosporidium*	Contamination with animal faeces following abnormally heavy rain	Howe *et al.* (2002)
2001	Southern Finland	1,000	18,000	*Campylobacter*	Floodwater from a dike contaminated by runoff (probably from animal sources)	Hänninen *et al.* (2003)
2002	Isère, France	2,000	5,600	Norovirus	Heavy rains lead to overflow in the sewage treatment works upstream and the flooding of raw water borehole	Tillaut *et al.* (2004)
2002	Transtrand, Sweden	500	772	Norovirus	Crack in sewage pipe 10 m from one of the supplying wells	Carrique-Mas *et al.* (2003)
2004	Ohio, USA	1,450	Unknown	*Campylobacter* and norovirus	Multiple contamination of aquifer from onsite septic systems, land application of sludge and infiltration of run-off	O'Reilly *et al.* (2007)
2005	Xanthi, Greece	709	13,956	Norovirus	Contamination of well following a heavy rain event	Papadopoulos *et al.* (2006)
2006	Xanthi, Greece	1,640	100,882	Norovirus	Groundwater contamination following a heavy rain event	Vantarakis *et al.* (2011)
2006	Portlaw, Ireland	8	Unknown	*Cryptosporidium*	Moderate risk of groundwater contamination previously identified; UV treatment unit was commissioned	HPSC (2007)
2009	Evertsberg, Sweden	200	400	Norovirus	Well contaminated by snowmelt	Riera-Montes *et al.* (2011)
2011	Agrigento, Italy	156	4,965	Norovirus	Infiltration of contaminated surficial waters following heavy rain	Giammanco *et al.* (2014)

RESULTS

Three areas of the WBOs origins in the drinking water systems are analysed in this paper: raw water contamination; treatment deficiencies at the waterworks; and distribution systems failure.

WBOs caused by raw water contamination

The probable causes for outbreaks correlated with the contamination of raw water in the catchment areas are shown in Tables 1 and 2 and Figures 1–3. The enteric disease outbreaks have been divided into two categories, specifying the origin of the drinking water supply: groundwater-related WBOs in Table 1, and surface water-related WBOs in Table 2.

Eleven drinking water-related outbreaks were associated with groundwater contamination, which instigated gastrointestinal illness amongst an estimated total of 10,021 consumers (Table 1, Figure 1). Even though the large majority (82%) of reported outbreaks originated by groundwater contamination occurred before 2007, no time-related pattern can be inferred due to the significant delay between incidents and dates of reporting.

The aetiological agents for the events with groundwater contamination were norovirus in six outbreaks, *Cryptosporidium* in two events, one event with *Campylobacter*, one with two bacterial pathogens (*Escherichia coli* and

Table 2 | List of outbreaks originated from raw water contamination (surface water)

Year	Location, country	Est. cases	Pop. served	Causative agent	Probable causes for outbreak occurring	Reference
2002	Midlands, Ireland	>31	25,000	*Cryptosporidium*	Contamination with farmyard slurry and manure following very heavy rains	Jennings & Rhatigan (2002)
2002	St. Maria de Palautordera, Spain	756	6,343	*Shigella*	Heavy rain led mud and organic material into the WTP	Arias *et al.* (2006)
2004	Bergen, Norway	6,000	48,000	*Giardia*	Leaking sewage pipes with drainage to the raw water source	Nygård *et al.* (2006), Røstum *et al.* (2009)
2005	Gwynedd and Anglesey, UK	231	60,000	*Cryptosporidium*	Natural (wildlife) contamination, septic tanks and sewage treatment works; streaming and stratification in raw water (lake); UV system subsequently installed	Mason *et al.* (2010), Chalmers *et al.* (2010)
2005	South East England, UK	140	Unknown	*Cryptosporidium*	Low water levels in the river may have reduced dilution from sewage discharge	Nichols *et al.* (2006)
2005	Oregon, USA	60	Unknown	*Campylobacter* and *E. coli*	Inadequate treatment after heavy rainfall conditions	Yoder *et al.* (2008)
2006	Cardrona, New Zealand	218	3,800	Norovirus	Contamination from sewage overflow	Hewitt *et al.* (2007)
2007	Galway, Ireland	304	Unknown	*Cryptosporidium*	Very wet winter contributed to contamination of lake probably due to run-off from land following slurry spreading	Pelly *et al.* (2007), HPSC (2008)
2008	Lilla Edet, Sweden	2,400	7,500	Norovirus	Contaminated raw water from point source pollution caused by wastewater	Larsson *et al.* (2013)
2009	San Felice del Benaco, Italy	299	3,360	Rotavirus and norovirus	Contamination of lake due to over-capacity of the sewage system and/or illegal discharge	Scarcella *et al.* (2009)
2010	Östersund, Sweden	27,000	51,000	*Cryptosporidium*	Faecal contamination of raw water	Widerström *et al.* (2014)
2011	Skellefteå, Sweden	20,000	71,580	*Cryptosporidium*	Contamination from wastewater	Andersson *et al.* (2014)
2012	Elassona, Greece	3,620	37,264	Rotavirus	Heavy rain lead to increased coloured water	Mellou *et al.* (2014)

Campylobacter), and also one with both norovirus and *Campylobacter*. Taking into account the information displayed in Table 1 and Figures 2 and 3, norovirus is the prevailing pathogen being present in seven of the WBOs, even though on one occasion as part of a multi-agent outbreak. *Campylobacter,* on the other hand, was present in three outbreaks, but only on one occasion was it the single detected aetiological agent.

Several causes of the WBOs for the events with groundwater contamination are presented, where heavy rain was linked to six outbreaks; contaminated runoff, decreased raw water quality, sewage contamination, and snowmelt were associated with one event each; finally, multiple contamination causes were responsible for one outbreak. Surficial run-off seems to be the suspected cause for the large majority (73%) of raw water contamination occurrences, since the events are mostly caused by infiltration of polluted water subsequent to heavy rainfall circumstances. In three outbreaks, animal faecal residues were the probable origin for the microbiological contamination.

The outbreaks for the events with groundwater contamination show that five countries endured more than a 1,000

Table 3 | List of outbreaks originated from treatment deficiencies at the WTPs

Year	Location, country	Est. cases	Pop. served	Causative agent	Probable causes for outbreak occurring	Reference
2000	Gourdon, France	2,600	7,088	*Campylobacter*, rotavirus and norovirus	Failure in the chlorination system (and possible contamination of groundwater from agricultural run-off)	Gallay *et al.* (2006)
2000	Colorado, USA	27	Unknown	*Giardia*	Multiple failures in the pumping mechanism and filtration system; inadequate time for chlorination due to increased demand	Lee *et al.* (2002)
2001	Saskatchewan, Canada	6,450	18,000	*Cryptosporidium*	Treatment deficiencies after maintenance work because of increased turbidity	Stirling *et al.* (2001)
2001	Hawkes Bay, New Zealand	186	295	*Campylobacter*	Malfunction in the UV system and delayed installation of replacement components	Thornley *et al.* (2002)
2001	Torres de Segre, Spain	344	1,880	*Campylobacter*	Failure in chlorination system	Godoy *et al.* (2002)
2001	Switzerland	650	Unknown	Norovirus	Treatment failure following deficiencies in chlorine and/or ozone application	Fretz *et al.* (2005)
2001	Pennsylvania, USA	19	Unknown	Unknown	Unspecified treatment deficiency; no chlorine residual in the drinking water	Blackburn *et al.* (2004)
2001	Wyoming, USA	83	Unknown	Norovirus	Failure of pellet chlorinator and septic tank contamination	Blackburn *et al.* (2004)
2004	Ireland	14	25,000	*Cryptosporidium*	High demand and turbidity issues lead to unfiltered water mixed with filtered water	O'Toole *et al.* (2004)
2004	New Zealand	23	Unknown	*Shigella*	Treatment failure and inadequate raw water source	ESR (2005)
2004	Montana, USA	70	Unknown	*Salmonella*	UV disinfection unit found to be out of service	Liang *et al.* (2006)
2005	Carlow, Ireland	31	25,000	*Cryptosporidium* and *Giardia*	Aging plant with turbidity problems in highly agricultural basin; sewage treatment plants upstream; rainfall peak	Roch *et al.* (2005)
2006	Apulia, Italy	2,860	Unknown	Rotavirus and norovirus	Technical problems with chlorination	Martinelli *et al.* (2007)
2006	Valencia d'Aneu, Spain	≥68	180	*Shigella*	Chlorinator froze and stopped working; possible illegal discharge of wastewater near raw water source	Godoy *et al.* (2011)
2006	Indiana, USA	32	Unknown	*Campylobacter*	Inadequate chlorination of the water supply; cross-contamination also possible when testing a new water main	Yoder *et al.* (2008)
2007	Florida, USA	1,663	Unknown	Unknown	Operation and maintenance deficiencies in water treatment	Brunkard *et al.* (2011)
2010	Åhus, Sweden	Unknown	Unknown	Enterococci and *E. coli*	Salt used in the water softening process was contaminated; rapid intervention of the municipality may have prevented an outbreak	Norberg (2010)
2012	Darfield, New Zealand	138	3,280	*Campylobacter*	Pump failure lead to exclusive use of river raw water; heavy rains resulted in increased turbidity, no multi-barrier approach	Bartholomew *et al.* (2014)

Table 4 | List of outbreaks originated from distribution systems failure

Year	Location, country	Est. cases	Pop. served	Causative agent	Probable causes for outbreak occurring	Reference
2000	Strasbourg, France	53	60,000	Unknown	Main repair in the network	Deshayes & Schmitt (2001)
2000	Bari, Italy	344	1,000	Norovirus	Break in pipeline public supply connecting to resort tank	Boccia *et al.* (2002)
2000	Belfast, UK	117	Unknown	*Cryptosporidium*	Seepage of raw sewage from a septic tank into the water distribution system	Glaberman *et al.* (2002)
2000	South Wales, UK	281	Unknown	*Campylobacter*	Seepage of surface water contaminated by agricultural waste following heavy rainfall into drinking water reservoir	Richardson *et al.* (2007)
2000	Ohio, USA	29	Unknown	*E. coli*	Possible back-siphonage from animal barn	Lee *et al.* (2002)
2001	Darcy le Fort, France	563	1,100	*Cryptosporidium*, rotavirus, *Campylobacter* and *E. coli*	Sewage contamination occurred in the distribution network upstream to the city	Dalle *et al.* (2003)
2001	Lleida, Spain	96	293	Norovirus	Contamination of reservoir due to lack of maintenance and structural deficiencies	Godoy *et al.* (2006)
2001	Utrecht, The Netherlands	37	1,866	Norovirus	Drinking water system connected to grey water system in maintenance work; cross-connection not removed	Fernandes *et al.* (2007)
2001	Belfast, UK	230	Unknown	*Cryptosporidium*	Wastewater into the drinking water supply due to a blocked drain	Glaberman *et al.* (2002)
2002	Vicenza, Italy	670	3,006	Unknown	Broken sewage pipe allowed untreated water from the river to enter the city aqueduct	Tramarin *et al.* (2002)
2002	Switzerland	125	Unknown	Norovirus	Faeces related contamination from a sewage leakage	Fretz *et al.* (2005)
2004	Ohio, USA	1,450	Unknown	*Campylobacter*, norovirus and *Giardia*	Unspecified distribution system deficiency related with untreated groundwater	Liang *et al.* (2006)
2007	Køge, Denmark	140	5,802	*Campylobacter*, *E. coli* and norovirus	Technical and human error at sewage treatment work allowed partially filtered wastewater to enter the drinking water system	Vestergaard *et al.* (2007)
2007	Nokia, Finland	8,453	30,016	Norovirus, *Campylobacter* and *Giardia*	Drinking water network contaminated by treated sewage effluent	Laine *et al.* (2010)
2007	Västerås, Sweden	400	Unknown	Unknown	Leaked sewage into drinking water network during maintenance work on a pipeline	Nilsson (2008)
2008	Zurich, Switzerland	126	2,000	*Campylobacter* and norovirus	Input of highly pressurised washwater from sewage plant into the drinking water system	Breitenmoser *et al.* (2011)
2008	Northampton, UK	>422	250,000	*Cryptosporidium*	Dead rabbit found in a tank containing drinking water at the treatment works	Smith *et al.* (2010), Chalmers (2012)

(*continued*)

Table 4 | continued

Year	Location, country	Est. cases	Pop. served	Causative agent	Probable causes for outbreak occurring	Reference
2008	Colorado, USA	1,300	Unknown	*Salmonella*	Likely animal contamination of a storage tank	Brunkard *et al.* (2011)
2009	Utah, USA	8	Unknown	*Giardia*	Cross-connection between potable and non-potable water sources resulting in backflow	Hilborn *et al.* (2013)
2010	Køge, Denmark	409	20,000	*Campylobacter*	Contamination of central water supply system by unknown mechanism	Gubbels *et al.* (2012)
2010	Öland, Sweden	200	Unknown	Norovirus	Untreated water from well in the drinking water network	Hallin (2012)
2010	Utah, USA	628	Unknown	*Campylobacter*	Cross-connection between potable and non-potable water sources resulting in backflow	Hilborn *et al.* (2013)
2012	Kilkis, Greece	79	1,538	Norovirus	Heavy snowfall and runoff, low temperatures and 15 days without use of school's public water supply increased microbial load	Mellou *et al.* (2013)
2012	Kalundborg, Denmark	187	Unknown	Norovirus	Contamination from sewage pipe due to fall in pressure, throughout water supply system repairs	van Alphen *et al.* (2014)
2012	Vuorela, Finland	800	2,931	Sapovirus and *E. coli*	Main pipe accidently broken during road construction; flushing after breakage repair proved insufficient and storage reservoir was contaminated	Jalava *et al.* (2014)
2013	Guipuzko, Spain	238	650	Norovirus and rotavirus	Cross-connection between drinking water supplies and industrial water taken from a river	Altzibar *et al.* (2015)

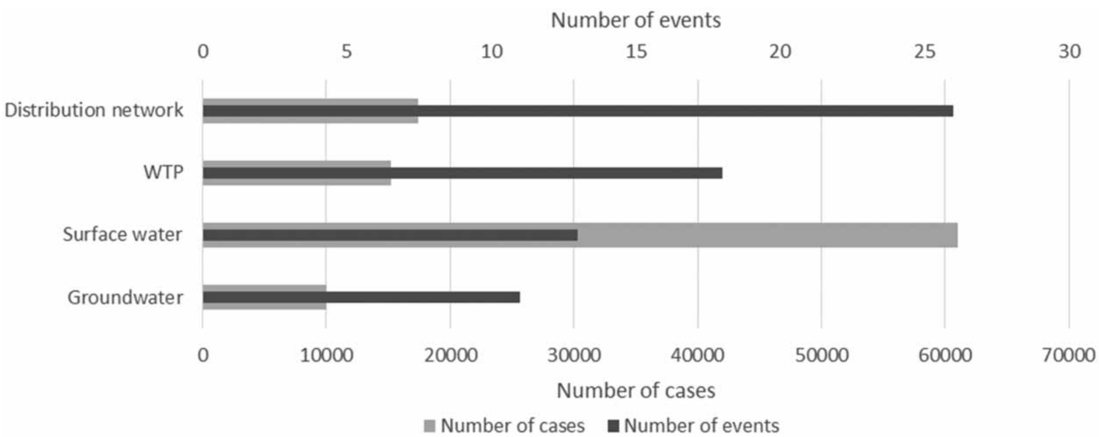

Figure 1 | The number of events of WBOs and the number of cases of illnesses among the consumers.

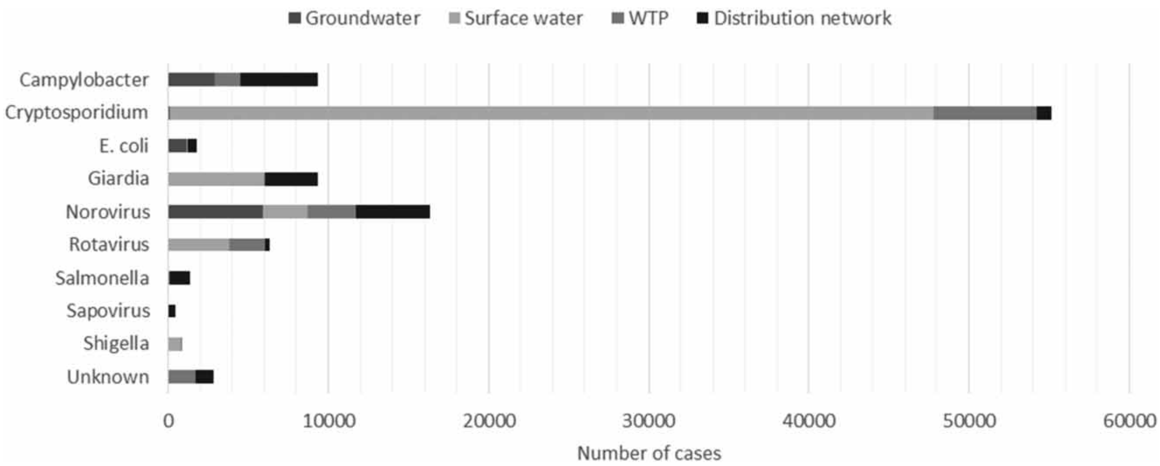

Figure 2 | The total number of affected consumers for each pathogen. If several pathogens were present during one outbreak, the number of affected consumers have been divided with the number of present pathogens.

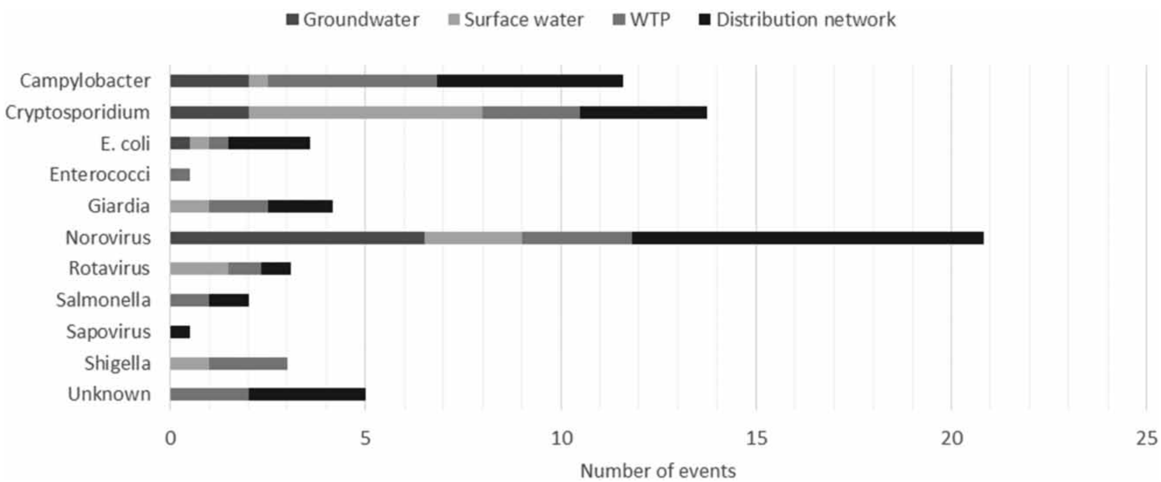

Figure 3 | The number of cases of WBOs where each pathogen was present. If several pathogens were present, each occasion has been divided into fractions for each pathogen.

cases of infectious gastrointestinal illness, in one single event: Canada, Finland, France, Greece and the USA.

Thirteen waterborne outbreaks caused by contaminated surface water have been identified (Table 2, Figure 1). A time-related pattern could be suggested for the outbreaks originated by surface water contamination where a majority of the cases of illness (87%) occurred after 2007, but that may be due to selection bias.

The aetiological agents for the events with surface water contamination were the protozoan pathogen *Cryptosporidium* in six events while norovirus was present in two outbreaks. *Shigella*, *Giardia*, and rotovirus were the causative pathogen in one outbreak each and multiple aetiologies were responsible in two outbreaks.

For surface water contamination events the causes of the WBOs were heavy rainfall, sewage contamination, animal or farming activities and increased organic matter. The majority of the infections in the identified events were related to wastewater contamination.

The highest number of estimated cases caused by surface water contamination was concentrated in only one country (Sweden), responsible for 49,400 infected drinking water consumers, mainly due to two especially large outbreaks in 2010 and 2011. The second largest number of affected consumers was located in Norway.

WBOs caused by treatment failure

Analysing the 18 reviewed incidents originated by treatment deficiencies in the drinking water production, which are displayed in Table 3 and Figures 1–3, it can be observed that several causative agents are present and no obvious one is predominant. Nevertheless, *Campylobacter* was the most frequent aetiology, present in almost one-third of the outbreaks although not exclusively in one of those events. Norovirus was present in two out of four outbreaks as part of a multiple pathogen occurrence. *Cryptosporidium* was responsible for three outbreaks but in one of those as part of a mixed-agent outbreak. Both rotavirus WBOs and one of the *Giardia* outbreaks were part of events with multiple aetiologies. *Shigella*, *Salmonella,* Enterococci and *E. coli* were also present in occurrences leading to the contamination of the drinking water.

The technical reasons that ultimately led to the outbreaks can be divided into two main groups. The first group has 11 outbreaks caused by disinfection-related problems and the second group has four WBOs related to difficulties with increased turbidity in the inflow of raw water. The treatment deficiencies were sometimes loosely associated with maintenance work or strain within the treatment process train in coping with increased demand. An event in Sweden demonstrates that chemicals used in the production of water can be contaminated. In this event salt used in the water softening process was contaminated with Enterococci and *E. coli*.

The location of seven of the reported illnesses caused by waterborne outbreaks originated from treatment deficiencies in North America, where Canada had one outbreak and the USA six occurrences with significant impact. Within Europe a total number of eight outbreaks occurred which corresponds to 43% of estimated cases. In Italy and France the outbreaks were larger and caused more than 2,500 cases of gastrointestinal illnesses. Finally, in New Zealand the three reported WBOs only affected a smaller number of consumers.

WBOs caused by distribution systems failure

The 26 incidents that were reviewed for this section, Table 4 and Figures 1–3, were the consequence of network malfunction. Multiple aetiologies were present in seven outbreaks, and in many of them bacterial, viral and protozoan pathogens were simultaneously identified. Three WBOs had unidentified aetiologies. In the remaining outbreaks one single aetiological agent was detected: norovirus was responsible for seven outbreaks, *Cryptosporidium* and *Campylobacter* were causative of three outbreaks each, *E. coli*, *Giardia* and *Salmonella* were the single agent in one outbreak each.

The available information regarding the causes of distribution systems failures show that cross-connections are the main cause for outbreaks in the distribution system. Other identified causes were maintenance or repair works in the water mains, intrusion of sewage due to leakage, distribution system reservoir contamination and regrowth in the distribution network due to low demand. The cause that affected the highest number of consumers was intrusion of water into the distribution network.

More than half of the estimated cases of illnesses caused by waterborne outbreaks originating from distribution systems failure were located in Finland and together with the USA almost three quarters of the affected consumers are accounted for. In the USA five outbreaks occurred while in Finland only two outbreaks were identified. Among the remaining countries the UK and Denmark have four and three identified outbreaks, respectively, while the remaining countries have fewer identified outbreaks.

DISCUSSION

In this paper the causes of WBOs have been investigated. The main causes for contamination of groundwater sources identified in this paper were the intrusion of animal faeces or wastewater due to heavy rains. Even if the large majority of the reported events occurred before 2007, a time-related pattern cannot be inferred and further measures to reduce the contamination risks to the raw water and the catchment areas should be thoroughly implemented, with the establishment of protection areas and identification of potential contamination sources, for instance. The outbreaks originated by surface water contamination did on the other hand occur after 2007 for the majority of the cases of illness, but this does not sanction any assumption regarding the protection of raw water sources. The main causes for contamination of surface waters, identified in this study, are the discharge of wastewater into the water source and increased turbidity and colour of the water. These events may occur during heavy rains but also at low water levels. This indicates that further measures to reduce the contamination risks to the raw water and the catchment areas still need to be implemented for surface water sources. Measures that could be applied are the establishment of protection areas, the identification of potential contamination sources and increased monitoring of raw water quality parameters.

Cryptosporidium, norovirus, *Giardia*, *Campylobacter* and rotavirus were the main pathogens causing the highest amount of affected consumers (Figure 2), however, the choice of keywords in the literature search may have introduced a bias which downplayed the role of other causative agents. The identified pathogens have in common a moderately to long persistence in water supplies and are moderately to highly infective (Åström 2011). Both *Cryptosporidium* and *Giardia* are highly resistant to chlorine disinfection, and turbidity control (e.g. chemical coagulation followed by filtration) is essential for adequate treatment of the water. The highest number of different pathogens has been identified for the WTP and the distribution network. Although the number of identified events was larger for the distribution system in comparison to the number of surface water outbreaks, the number of consumers with gastrointestinal illness was highest for contamination events related with a surface water source, around six times higher than for groundwater contamination (Figure 1). However, to prevent the outbreaks in these occasions the WTPs would have had to adequately treat the contaminated water and, thus, the failure has not only occurred in the source water but also at the WTPs.

The main failure at WTPs causing a WBO has been identified to be the malfunctioning of the UV treatment step or the chlorination equipment. Thereafter comes increased turbidity, maintenance work, high or low demand of water and malfunctioning equipment (e.g. pumps). For many of the events, several failures have occurred simultaneously. To reduce the risk of a WBO, a risk assessment tool for the disinfection step has been developed in Norway. The tool can be used to identify risks within the disinfection processes of chlorination, UV and ozonation, and thus enabling the prevention of WBOs (Ødegaard *et al.* 2006).

The distribution network had the highest number of individual events of WBOs. However, the number of affected consumers was low for each event, and therefore the total number of affected consumers is not very high. The causes identified in this study for WBOs at the distribution network were cross-connections, pipe breaks and wastewater intrusion into the network. Also, cases of contamination of distribution system reservoirs are reported. One event in Greece highlights the magnitude of the challenge posed by norovirus because of its persistence in water. Previous work has demonstrated a persistence that can be higher than 15 days (Seitz *et al.* 2011), and that it is resistant at low levels of chlorine disinfection (Kambhampati *et al.* 2015).

In this study causes and pathogens of WBOs have been critically evaluated. Limitations in this study are that outbreaks have only been evaluated if the cause of the event was indicated in the reference and if the event was present in the chosen databases. In a recent review the responsible authorities and the water industry were directly contacted about recent WBOs in the Nordic countries (Guzman Herrador *et al.* 2015). In total, 175 outbreaks were identified which exceeds the number of outbreaks identified in our study. However, the number of cases of illnesses is of the same order of magnitude for Sweden, Finland and Denmark, if adjusted for the year 1998–1999 (Miettinen *et al.* 2001). Consequently, this indicates that the identified causes for outbreaks in this review may not cover minor events that have only affected a small number of consumers.

This work has not addressed the differences between small and large WTPs. The tendency is that medium and large waterworks receive more attention than small ones in these systematic approaches (Coulibaldy & Rodriguez 2004). In a study published in 2011 that analysed small WTPs in Finland, it was indicated that nonconformity in the production of microbiological safe drinking water is more probable in small rather than large waterworks that were distributing water to a minimum of a 1,000 consumers (Zacheus & Miettinen 2011). Previous reviews have highlighted that the number of small waterborne outbreaks that are not reported or that are merely poorly documented is not negligible (Hrudey & Hrudey 2007). In countries like Finland where the number of affected consumers is below 0.01% (the US EPA guideline), it is considered that the production of safe drinking water in all types of settings and/or limitations is not guaranteed and more measures need to be implemented (Zacheus & Miettinen 2011).

The main objective for the water treatment systems is to deliver drinking water to consumers that is both aesthetically suitable and safe (Zhang *et al.* 2012). With continuously changing raw water quality, variations in water demand and operational challenges at the WTP, risk assessment of the water treatment systems have become increasingly important. This has also been stressed by the World Health Organization. Many tools are available for risk assessment of the water treatment systems. However, identifying possible risk scenarios proves challenging. We expect that this critical evaluation of the causes of WBOs will help the water industry in their work with WSP to identify risks that may lead to waterborne outbreaks. This paper clearly demonstrates the need for further research to reduce the risks of WBOs and the need for well-founded guidelines for identification of risks in the production of drinking water. Additionally, it is suggested that experiences on WBOs are shared within and between water companies and researchers to improve risk analysis tools and risk reduction measures in order to provide safe drinking water.

CONCLUSIONS

The importance of identifying and addressing the potential risks in the drinking water systems is of the foremost significance to prevent outbreaks and assure the deliverance of safe water to consumers. The main causes of contamination identified in this review are as follows:

- *Groundwater sources*: intrusion of animal faeces or wastewater due to heavy rains.
- *Surface water sources*: discharge of wastewater into the water source and increased turbidity and colour of the water.
- *WTP*: malfunctioning of the disinfection, increased turbidity, maintenance work, high or low demand of water and malfunctioning equipment (e.g. pumps).
- *Distribution network*: cross-connections, pipe breaks, wastewater intrusion into the pipe network, and contamination of reservoirs.

The main pathogens causing the highest amount of affected consumers are *Cryptosporidium*, norovirus, *Giardia*, *Campylobacter* and rotavirus, but it is possible that survey bias had an impact on these results. The highest number of different pathogens has been identified for the WTP and the distribution network. The highest number of affected consumers with gastrointestinal illness was for contamination events with a surface water source, while the highest number of events of WBOs occurred for the distribution network.

REFERENCES

Altzibar, J. M., Zigorraga, C., Rodriguez, R., Leturia, N., Garmendia, A., Rodriguez, A., Alkorta, M. & Arriola, L. 2015 Outbreak of acute gastroenteritis caused by contamination of drinking water in a factory, the Basque Country. *J. Water Health* **13** (1), 168–173.

Andersson, T., Bjelkmar, P., Hulth, A., Lindh, J., Stenmark, S. & Widerström, M. 2014 Syndromic surveillance for local outbreak detection and awareness: evaluating outbreak signals of acute gastroenteritis in telephone triage, web-based queries and over-the-counter pharmacy sales. *Epidemiol. Infect.* **142**, 303–313.

Arias, C., Sala, M. R., Dominguez, A., Bartolomé, R., Benavente, A., Veciana, P., Pedrol, A. & Hoyo, G. 2006 Waterborne epidemic outbreak of Shigella sonnei gastroenteritis in Santa Maria de Palautordera, Catalonia, Spain. *Epidemiol. Infect.* **134** (3), 598–604.

Åström, J. 2011 Microbial Risks in Surface Water Sources. PhD Thesis. Chalmers University of Technology, Gothenburg.

Baldursson, S. & Karanis, P. 2011 Waterborne transmission of protozoan parasites: review of worldwide breaks – an update 2004–2010. *Water Res.* **45**, 6603–6614.

Bartholomew, N., Brunton, C., Mitchell, P., Williamson, J. & Gilpin, B. 2014 A waterborne outbreak of campylobacteriosis in the South Island of New Zealand due to a failure to implement a multi-barrier approach. *J. Water Health* **12** (3), 555–563.

Bartram, J., Corrales, L., Davison, A., Deere, D., Drury, D., Gordon, B., Howard, G., Rinehold, A. & Stevens, M. 2009 *Water Safety Plan Manual: Step-by-Step Risk Management for Drinking Water Suppliers.* WHO, Geneva.

Blackburn, B. G., Craun, G., Yoder, J., Hill, V. & Calderon, R. 2004 *Surveillance for Waterborne-Disease Outbreaks Associated with Drinking Water – United States, 2001–2002.* Centers for Disease Control and Prevention, Atlanta.

Boccia, D., Eugenio Tozzi, A., Cotter, B., Rizzo, C., Russo, T., Buttinelli, G., Caprioli, A., Marziano, M. L. & Ruggeri, F. M. 2002 Waterborne outbreak of Norwalk-like virus gastroenteritis at a tourist resort, Italy. *Emerg. Infect. Dis.* **8** (6), 563–568.

Bratanova, B., Morrison, G., Fife-Schaw, C., Chenoweth, J. & Mangold, M. 2013 Restoring drinking water acceptance following a waterborne disease outbreak: the role of trust, risk perception, and communication. *J. Appl. Soc. Psychol.* **43**, 1761–1770.

Breitenmoser, A., Fretz, R., Schmid, J., Besl, A. & Etter, R. 2011 Outbreak of acute gastroenteritis due to a washwater-contaminated water supply, Switzerland, 2008. *J. Water Health* **9** (3), 569–576.

Brunkard, J. M., Ailes, E., Roberts, V., Hill, V. & Hilborn, E. 2011 Surveillance for waterborne disease outbreaks associated with drinking water – United States, 2007–2008. *MMWR Morbid. Mortal. Wkly Rep.* **60** (12), 38–75.

Carrique-Mas, J., Andersson, Y., Petersén, B., Hedlund, K.-O., Sjögren, N. & Giesecke, J. 2003 A Norwalk-like virus waterborne community outbreak in a Swedish village during peak holiday season. *Epidemiol. Infect.* **131**, 737–744.

Chalmers, R. M. 2012 Waterborne outbreaks of cryptosporidiosis. *Ann. Ist. Super Sanità* **48** (4), 429–446.

Chalmers, R. M., Robinson, G., Elwin, K., Hadfield, S., Thomas, E., Watkins, J., Casemore, D. & Kay, D. 2010 Detection of Cryptosporidium species and sources of contamination with Cryptosporidium hominis during a waterborne outbreak in northwest Wales. *J. Water Health* **8** (2), 311–325.

Coulibaldy, H. D. & Rodriguez, M. 2004 Development of performance indicators for small Quebec drinking water utilities. *J. Environ. Manage.* **74**, 243–255.

Dalle, F., Roz, P., Dautin, G., Di-Palma, M., Kohli, E., Sire-Bidault, C., Fleischmann, M. G., Gallay, A., Carbonel, S., Bon, F., Tillier, C., Beaudeau, P. & Bonnin, A. 2003 Molecular characterization of isolates of waterborne Cryptosporidium spp. collected during an outbreak of gastroenteritis in South Burgundy, France. *J. Clin. Microbiol.* **41** (6), 2690–2693.

Delpha, I., Jung, A.-V., Baures, E., Clement, M. & Thomas, O. 2009 Impacts of climate change on surface water quality in relation to drinking water production. *Environ. Int.* **35**, 1225–1233.

Deshayes, F. & Schmitt, M. 2001 Pollution du réseau d'eau potable à Strasbourg et survenue concomitante de gastroentérites. *BEH* **2**, 5–7. Available from: www.invs.sante.fr/beh/2001/02/beh_02_2001.pdf.

ESR 2005 *Annual Summary of Outbreaks in New Zealand 2004*. Institute of Environmental Science and Research. Available from: https://surv.esr.cri.nz/PDF_surveillance/AnnualRpt/AnnualOutbreak/2004/2004OutbreakRpt.pdf.

Fernandes, T., Schout, C., Husman, A., Eilander, A., Vennema, H. & Van Duynhoven, Y. 2007 Gastroenteritis associated with accidental contamination of drinking water with partially treated water. *Epidemiol. Infect.* **135**, 818–826.

Fretz, R., Svoboda, P., Lüthi, T. M., Tanner, M. & Baumgartner, A. 2005 Outbreaks of gastroenteritis due to infections with Norovirus in Switzerland, 2001–2003. *Epidemiol. Infect.* **133** (3), 429–437.

Gallay, A., De Valk, H., Cournot, M., Ladeuil, B., Hemery, C., Castor, C., Bon, F., Mégraud, F., Le Cann, P., Desenclos, J. C. & Outbreak Investigation Team 2006 A large multi-pathogen waterborne community outbreak linked to faecal contamination of a groundwater system, France, 2000. *Clin. Microbiol. Infect.* **12**, 561–570.

Giammanco, G., Di Bartolo, I., Purpari, G., Costantino, C., Rotolo, V., Spoto, V., Geraci, G., Bosco, G., Petralia, A., Guercio, A., Macaluso, G., Calamusa, G., Dr Grazia, S., Ruggeri, F. M., Vitale, F., Maida, C. M. & Mammina, C. 2014 Investigation and control of a Norovirus outbreak of probable waterborne transmission through a municipal groundwater system. *J. Water Health* **12** (3), 452–464.

Glaberman, S., Moore, J., Lowery, C., Chalmers, R., Sulaiman, I., Elwin, K., Rooney, P. J., Millar, B. C., Dooley, J. S., Lal, A. A. & Xiao, L. 2002 Three drinking water-associated Cryptosporidiosis outbreaks, Northern Ireland. *Emerg. Infect. Dis.* **8** (6), 631–633.

Godoy, P., Artigues, A., Nuín, C., Aramburu, J., Pérez, M., Domínguez, A. & Salleras, L. 2002 Brote comunitario de gastroenteritis por Campylobacter jejuni originado por el consumo de agua del suministro público. *Med. Clin.* **119** (18), 696–698.

Godoy, P., Nuín, C., Alsedà, M., Llovet, T., Mazan, R. & Domínguez, Á. 2006 Brote de gastroenteritis por Norovirus causado por el consumo de agua de suministro público. *Rev. Clin. Esp.* **206** (9), 435–437.

Godoy, P., Bartolomé, R., Torres, J., Espinet, L., Escobar, A., Nuin, C. & Domínguez, A. 2011 Brote de gastroenteritis por el consumo de agua de suministro público causado por Shigella sonnei. *Gac. Sanit.* **25** (5), 363–367.

Gubbels, S. M., Kuhn, K. G., Larsson, J. T., Adelhardt, M., Engberg, J., Ingildsen, P., Hollesen, L. W., Muchitsch, S., Molbak, K. & Ethelberg, S. 2012 A waterborne outbreak with a single clone of Campylobacter jejuni in the Danish town of Køge in May 2010. *Scand. J. Infect. Dis.* **44**, 586–594.

Guzman Herrador, B. R., Carlander, A., Ethelberg, S., De Blasio, B. F., Kuusi, M., Lund, V., Löfdahl, M., MacDonald, E., Nichols, G., Schönning, C., Sudre, B., Trönnberg, L., Vold, L., Semenza, J. C. & Nygård, K. 2015 Waterborne outbreaks in the Nordic countries, 1998 to 2012. *Eurosurveillance* **20** (24), 1–10.

Hallin, E. 2012 *Norovirus i vatten – en litteraturstudie (Norovirus in rater – a literature review)*. Svenskt Vatten Utveckling, Stockholm.

Hänninen, M., Haajanen, H., Pummi, T., Wermundsen, K., Katila, M.-L., Sarkkinen, H., Miettinen, I. & Rautelin, H. 2003 Detection and typing of Campylobacter jejuni and Campylobacter coli and analysis of indicator organisms in three waterborne outbreaks in Finland. *Appl. Environ. Microbiol.* **69** (3), 1391–1396.

Hewitt, J., Bell, D., Simmons, G., Rivera-Aban, M., Wolf, S. & Greening, G. 2007 Gastroenteritis outbreak caused by waterborne Norovirus at a New Zealand Ski Resort. *Appl. Environ. Microbiol.* **73** (24), 7853–7857.

Hilborn, E. D., Wade, T., Hicks, L., Garrison, L. & Gargano, J. 2013 *Surveillance for Waterborne Disease Outbreaks Associated with Drinking Water and Other Nonrecreational Water – United States, 2009–2010.* Centers for Disease Control and Prevention, Atlanta.

Howe, A. D., Forster, S., Morton, S., Marshall, R., Osborn, K., Wright, P. & Hunter, P. 2002 Cryptosporidium oocysts in a water supply associated with a Cryptosporidiosis outbreak. *Emerg. Infect. Dis.* **8** (6), 619–624.

HPSC 2007 *Annual Report 2006*. Health Protection Surveillance Centre, Dublin.

HPSC 2008 *Annual Report 2007*. Health Protection Surveillance Centre, Dublin.

Hrudey, S. E. & Hrudey, E. 2007 Published case studies of waterborne disease outbreaks – evidence of a recurrent threat. *Water Environ. Res.* **79** (3), 233–245.

Hrudey, S. E., Payment, P., Huck, P. M., Gillham, R. W. & Hrudey, E. J. 2003 A fatal waterborne disease epidemic in Walkerton, Ontario: comparison with other waterborne outbreaks in the developed world. *Water Sci. Technol.* **47** (3), 7–14.

Jalava, K., Rintala, H., Ollgren, J., Maunula, L., Gomez-Alvarez, V., Revez, J., Palander, M., Antikainen, J., Kauppinen, A., Räsänen, P., Siponen, S., Nyholm, O., Kyyhkynen, A., Hakkarainen, S., Merentie, J., Pärnänen, M., Loginov, R., Ryu, H., Kuusi, M., Siitonen, A., Miettinen, I., Santo Domingo, J. W., Hänninen, M.-L. & Pitkänen, T. 2014 Novel microbiological and spatial statistical methods to improve strength of epidemiological evidence in a community-wide waterborne outbreak. *PLoS ONE* **9** (8), 104713.

Jennings, P. & Rhatigan, A. 2002 Cryptosporidiosis outbreak in Ireland linked to public water supply. *Eurosurveillance* **6** (22). Available from: www.eurosurveillance.org/ViewArticle.aspx?ArticleId=2089.

Kambhampati, A., Koopmans, M. & Lopman, B. A. 2015 Burden of norovirus in healthcare facilities and strategies for outbreak control. *J. Hosp. Infect.* **89**, 296–301.

Karanis, P., Kourenti, C. & Smith, H. 2007 Waterborne transmission of protozoan parasites: a worldwide review of outbreaks and lessons learnt. *J. Water Health* **5** (1), 1–38.

Laine, J., Huovinen, E., Virtanen, M. J., Snellman, M., Lumio, J., Ruutu, P., Kujansuu, E., Vuento, R., Pitkänen, T., Miettinen, I., Herrala, J., Lepistö, O., Antonen, J., Helenius, J., Hänninen, M. L., Maunula, L., Mustonen, J., Kuusi, M. & Pirkanmaa, Waterborne Outbreak Study Group 2010 An extensive gastroenteritis outbreak after drinking-water contamination by sewage effluent, Finland. *Epidemiol. Infect.* **139** (7), 1105–1113.

Lake, I. R., Nichols, G., Bentham, G., Harrison, F., Hunter, P. & Sari Kovats, R. 2007 Cryptosporidiosis decline after regulation, England and Wales, 1989–2005. *Emerg. Infect. Dis.* **13** (4), 623–625.

Larsson, C., Andersson, Y., Allestam, G., Lindqvist, A., Nenonen, N. & Bergstedt, O. 2013 Epidemiology and estimated costs of a large waterborne outbreak of norovirus infection in Sweden. *Epidemiol. Infect.* **142**, 592–600.

Lee, S. H., Levy, D., Craun, G., Beach, M. & Calderon, R. 2002 *Surveillance for Waterborne-Disease Outbreaks – United States, 1999–2000*. Centers for Disease Control and Prevention, Atlanta.

Liang, J. L., Dziuban, E. J., Craun, G., Hill, V. & Moore, M. R. 2006 *Surveillance for Waterborne Disease and Outbreaks Associated with Drinking Water and Water not Intended for Drinking – United States, 2003–2004*. Centers for Disease Control and Prevention, Atlanta.

Lindhe, A., Rósen, L., Norberg, T., Røstum, J. & Petersson, T. 2013 Uncertainty modelling in multi-criteria analysis of water safety measures. *Environ. Sys. Decis.* **33**, 195–208.

Martinelli, D., Prato, R., Chironna, M., Sallustio, A., Caputi, G., Conversano, M., Ciofi Degli Atti, M., D'Ancona, F. P., Germinario, C. A. & Quarto, M. 2007 Large outbreak of viral gastroenteritis caused by contaminated drinking water in Apulia, Italy, May–October 2006. *Eurosurveillance* **12** (16), E070419.1

Mason, B. W., Chalmers, R. M., Carnicer-Pont, D. & Casemore, D. P. 2010 A Cryptosporidium hominis outbreak in North-West Wales associated with low oocyst counts in treated drinking water. *J. Water Health* **8** (2), 299–310.

Mellou, K., Sideroglou, T., Potamiti-Komi, M., Kokkinos, P., Ziros, P., Georgakopoulou, T. & Vantarakis, A. 2013 Epidemiological investigation of two parallel gastroenteritis outbreaks in school settings. *BMC Public Health* **13** (241), 1–7.

Mellou, K., Katsioulis, A., Potamiti-Komi, M., Pournaras, S., Kyritsi, M., Katsiaflaka, A., Kallimani, A., Kokkinos, P., Petinaki, E., Sideroglou, T., Georgakopoulou, T., Vantarakis, A. & Hadjichristodoulou, C. 2014 A large waterborne gastroenteritis outbreak in central Greece, March 2012: challenges for the investigation and management. *Epidemiol. Infect.* **142**, 40–50.

Miettinen, I. T., Zacheus, O., Von Bonsdorff, C. H. & Vartiainen, T. 2001 Waterborne epidemics in Finland in 1998–1999. *Water Sci. Technol.* **43**, 67–71.

Nichols, G., Chalmers, R., Lake, I., Sopwith, W., Regan, M., Hunter, P., Grenfell, P., Harrison, F. & Lane, C. 2006 *Cryptosporidiosis: A Report on the Surveillance and Epidemiology of Cryptosporidium Infection in England and Wales*. Drinking Water Directorate Contract Number DWI 70/2/201, 129.

Nilsson, L. 2008 *Cirkulation: Många sårbara punkter i dricksvattenkedjan*. Available from: www.cirkulation.com/2008/02/manga-sarbara-punkter-i-dricksvattenkedjan/. (accessed 13 October 2014).

Norberg, P. 2010 *Orsaksutredning bakteriekontamination av Åhus dricksvatten 2010*. C4 Teknik, Kristianstads Kommun, Kristianstad.

Nygård, K., Schimmer, B., Søbstad, Ø., Walde, A., Tveit, I., Langeland, N., Hausken, T. & Aavitsland, P. 2006 A large community outbreak of waterborne giardiasis-delayed detection in a non-endemic urban area. *BMC Public Health* **6** (141), doi:10.1186/1471-2458-6-141.

Ødegaard, H. & Østerhus, S. 2014 *Microbial Barrier Analysis (MBA) – A Guideline*. Norsk Vann, Hamar.

Ødegaard, H., Fiksdal, L. & Østerhus, S. 2006 *Optimal desinfeksjonspraksis for drikkevann fase 1, Report 147*. Norsk vann og avløp BA, Norvar, Hamar.

O'Toole, C. E., Jennings, P., Meagher, G. & Kelly, I. 2004 Cryptosporidium outbreak in a continuously tested public water supply. *Epi-Insight (National Disease Surveillance Centre)* **5** (10), 1.

O'Reilly, C. E., Bowen, A., Perez, N., Sarisky, J., Shepherd, C. A., Miller, M. D., Hubbard, B. C., Herring, M., Buchanan, S. D., Fitzgerald, C. C., Hill, V., Arrowood, M. J., Xiao, L. X., Hoekstra, R. M., Mintz, E. D., Lynch, M. F. & Outbreak Working Group 2007 A waterborne outbreak of gastroenteritis with multiple etiologies among Resort Island Visitors and Residents: Ohio, 2004. *Clin. Infect. Dis.* **44** (4), 506–512.

Papadopoulos, V., Vlachos, O., Isidoridou, E., Kasmeridis, C., Pappa, Z., Goutzouvelidis, A. & Filippou, F. 2006 A gastroenteritis outbreak due to Norovirus infection in Xanthi, Northern Greece: management and public health consequences. *J. Gastrointest. Liver Dis.* **15** (1), 27–30.

Pelly, H., Cormican, M., O'Donovan, D., Chalmers, R. M., Hanahoe, B., Cloughley, R., McKeown, P. & Corbett-Feeney, G. 2007 A large outbreak of cryptosporidiosis in western Ireland linked to public water supply: a preliminary report. *Eurosurveillance* **12** (18). Available from: www.eurosurveillance.org/ViewArticle.aspx?ArticleId=3187.

Richardson, G., Thomas, D., Smith, R. M. & Nehaul, L. 2007 A community outbreak of Campylobacter jejuni infection from a chlorinated public water supply. *Epidemiol. Infect.* **135** (7), 1151–1158.

Riera-Montes, M., Brus Sjölander, K., Allestam, G., Hallin, E., Hedlund, K.-O. & Löfdahl, M. 2011 Waterborne norovirus outbreak in a municipal drinking-water supply in Sweden. *Epidemiol. Infect.* **139** (12), 1928–1935.

Roch, B. A., O'Byrne, A. M., Leane, G., O'Hare, C. & Menton, F. 2005 *Cryptosporidiosis Outbreak in Carlow Town and Environs 2005.* Health Service Executive – South Eastern Area. Department of Public Health, Kilkenny.

Røstum, J., Aasen, A. & Eikebrokk, B. 2009 Risk and vulnerability assessment ("Ros-Analysis") of the Bergen water supply system – a source to tap approach. In: *Risk Management of Water Supply and Sanitation Systems* (P. Hlavinek, C. Popovska, J. Marsalek, I. Mahrikova & T. Kukharchyk, eds). Springer, The Netherlands, pp. 73–83.

Scarcella, C., Carasi, S., Cadoria, F., Macchi, L., Pavan, A., Salamana, M., Alborali, G. L., Losio, M. N., Boni, P., Lavazza, A. & Seyler, T. 2009 An outbreak of viral gastroenteritis linked to municipal water supply, Lombardy, Italy, June 2009. *Eurosurveillance* **14** (29), 1–3.

Seitz, S. R., Leon, J. S., Schwab, K. J., Lyon, G. M., Dowd, M., McDaniels, M., Abdulhafid, G., Fernandez, M. L., Lindesmith, L. C., Baric, R. S. & Moe, C. L. 2011 Norovirus infectivity in humans and persistence in water. *Appl. Environ. Microbiol.* **77** (19), 6884–6888.

Smith, S., Elliot, A. J., Mallaghan, C., Modha, D., Hippisley-Cox, J., Large, S., Regan, M. & Smith, G. E. 2010 Value of syndromic surveillance in monitoring a focal waterborne outbreak due to an unusual Cryptosporidium genotype in Northamptonshire, United Kingdom, June–July 2008. *Eurosurveillance* **15** (33), 1–9.

Stirling, R., Aramini, J., Ellis, A., Lim, G., Meyers, R., Fleury, M. & Werker, D. 2001 Waterborne cryptosporidiosis outbreak, North Battleford, Saskatchewan, Spring 2001. *Can. Commun. Dis. Rep.* **27** (22), 185–192.

Thornley, C., McDowell, R., Lopez, L. & Baker, M. 2002 *Annual Summary of Outbreaks in New Zealand 2001 ESR*. Available from: https://surv.esr.cri.nz/PDF_surveillance/AnnualRpt/AnnualOutbreak/2001/2001OutbreakRpt.pdf.

Tillaut, H., Encrenaz, N., Checlair, E., Alexandre-Bird, A., Santo, E. & Beaudeau, P. 2004 Epidémie de gastro-entérite, Isère, novembre 2002. *BEH* **12** (3–4), 47–48. Available from: http://opac.invs.sante.fr/doc_num.php?explnum_id=5801.

Tramarin, A., Fabris, P., Bishai, D., Selle, V. & De Lalla, F. 2002 Waterborne infections in the era of bioterrorism. *Lancet* **360** (9346), 1699.

van Alphen, L. B., Dorléans, F., Schultz, A., Fonager, J., Ethelberg, S., Dalgaard, C., Adelhardt, M., Engberg, J. H., Fischer, T. K. & Lassen, S. G. 2014 The application of new molecular methods in the investigation of a waterborne outbreak of Norovirus in Denmark, 2012. *PLoS ONE* **9** (9), e105053.

Vantarakis, A., Mellou, K., Spala, G., Kokkinos, P. & Alamanos, Y. 2011 A gastroenteritis outbreak caused by Noroviruses in Greece. *Int. J. Environ. Res. Public Health* **8**, 3468–3478.

Vestergaard, L., Olsen, K., Stensvold, C., Böttiger, B., Adelhardt, M., Lisby, M., Mørk, L. & Mølbak, K. 2007 Outbreak of severe gastroenteritis with multiple aetiologies caused by contaminated drinking water in Denmark, January 2007. *Eurosurveillance* **12** (13), 3164.

WHO 2011 *Guidelines for Drinking-Water Quality*. 4th edn. World Health Organization, Geneva.

Widerström, M., Schönning, C., Lilja, M., Lebbad, M., Ljung, T., Allestam, G., Ferm, M., Björkholm, B., Hansen, A., Hiltula, J., Långmark, J., Löfdahl, M., Omberg, M., Reuterwall, C., Samuelsson, E., Widgren, K., Wallensten, A. & Lindh, J. 2014 Large outbreak of Cryptosporidium hominis infection transmitted through the public water supply, Sweden. *Emerg. Infect. Dis.* **20** (4), 581–589.

Yoder, J., Hlavsa, M., Craun, G., Hill, V., Roberts, V., Yu, P., Hicks, L. A., Alexander, N. T., Calderon, R. L., Roy, S. L. & Beach, M. J. 2008 Surveillance for waterborne disease and outbreaks associated with drinking water and water not intended for drinking – United States, 2005–2006. *MMWR Morb. Mortal. Wkly Rep.* **57** (SS-9), 39–69.

Zacheus, O. & Miettinen, I. 2011 Increased information on waterborne outbreaks through efficient notification system enforces actions towards safe drinking water. *J. Water Health* **9** (4), 763–772.

Zhang, K., Achari, G., Sadiq, R., Langford, C. & Dore, M. 2012 An integrated performance assessment framework for water treatment plants. *Water Res.* **46**, 1673–1683.

First received 26 April 2016; accepted in revised form 2 September 2016. Available online 25 October 2016