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Safe drinking water and waterborne outbreaks

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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.

Keywords: distribution network, drinking water, pathogens, water treatment, water safety plan, waterborne outbreak.

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-products formation rate in surface waters at natural temperatures, between 5 and 30 ºC (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 Organisation (WHO). To achieve that aim, a framework for safe drinking water was developed by the WHO throughout the application of 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). First the raw water quality is evaluated and according to the 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 water safety plans, 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 a 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 to assess 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 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 the countries have therefore 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, UK and 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.

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 1-2 and Figure 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.

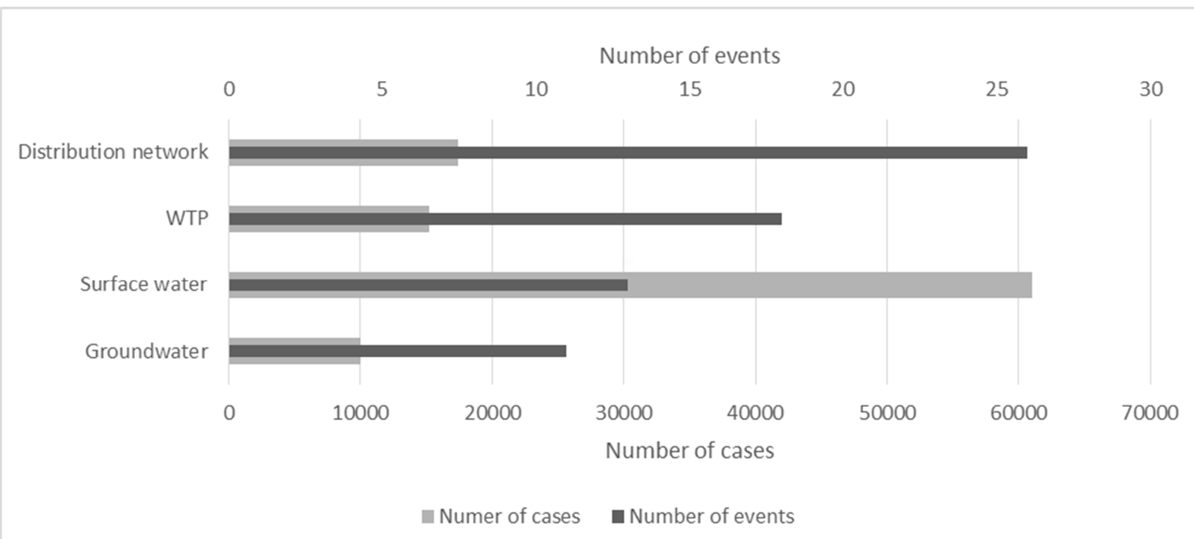

Figure 1. The number of events of WBOs and the number of cases of illnesses among the consumers.

11 drinking water-related outbreaks were associated with groundwater contamination, which instigated gastrointestinal illness amongst an estimated total of 10021 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 (*E. coli* and *Campylobacter*), and also one with both norovirus and

Campylobacter. Taking into account the information displayed in Table 1 and Figure 2-3, norovirus is the prevailing pathogen being present in seven of the WBOs, even though in one occasion as part of a multi-agent outbreak. *Campylobacter,* on the other hand, was present in three outbreaks, but only in one occasion it was 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 1000 cases of infectious gastrointestinal illness, in one single event: Canada, Finland, France, Greece and USA.

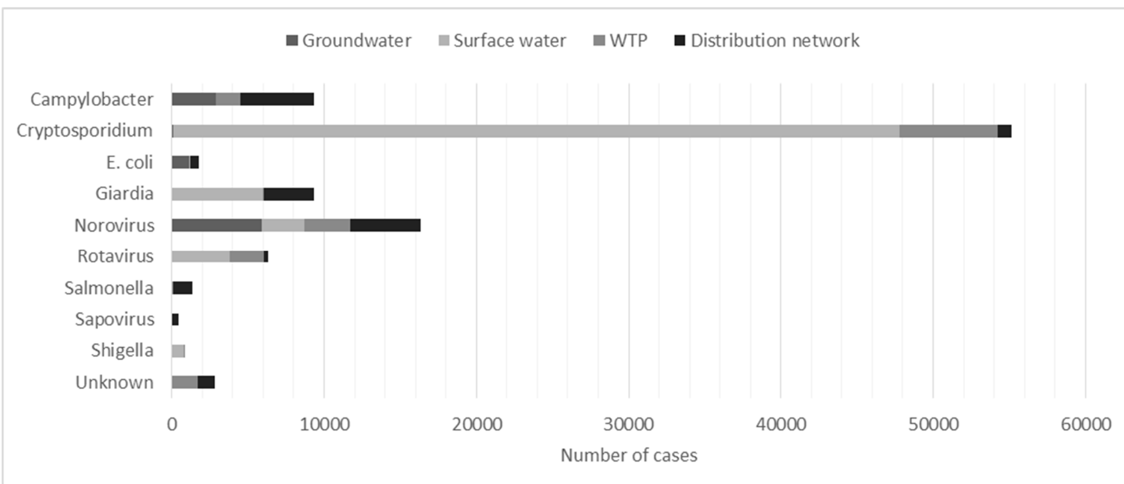

Figure 2. The total number of affected consumers for each pathogen. If several pathogens were present during one outbreak, the number of affected consumers have been divided with the number of present pathogens.

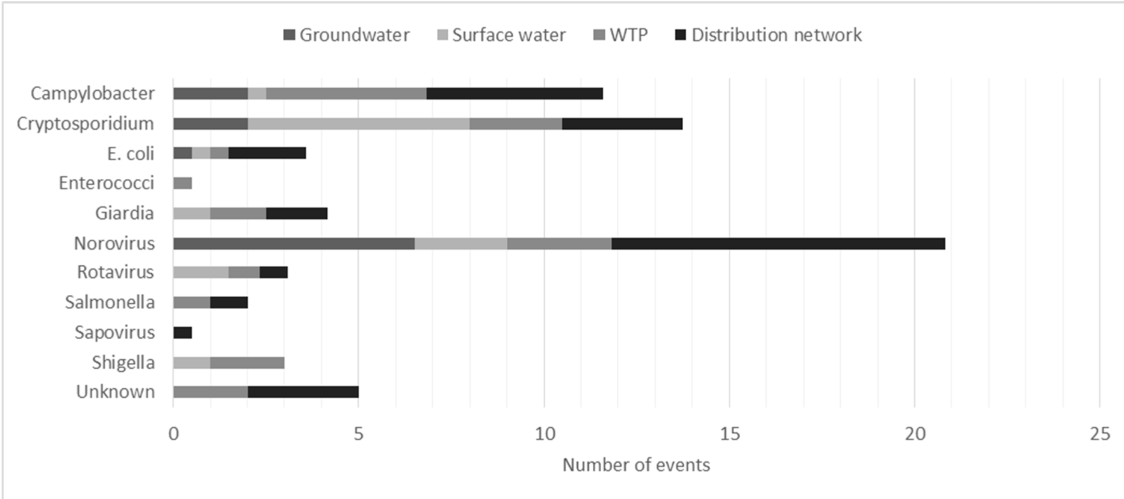

Figure 3 The number of cases of WBOs where each pathogen was present. If several pathogens were present, each occasion has been divided into fractions for each pathogen.

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	2300	4800	*Campylobacter* and *E. coli*	Contamination from livestock faecal residue following heavy rainfall	(Hrudey et al. 2003)
2000	Clitheroe, UK	58	17252	*Cryptosporidium*	Contamination with animal faeces following abnormally heavy rain	(Howe et al. 2002)
2001	Southern Finland	1000	18000	*Campylobacter*	Floodwater from a dike contaminated by runoff (probably from animal sources)	(Hänninen et al. 2003)
2002	Isère, France	2000	5600	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 10m from one of the supplying wells	(Carrique-Mas et al. 2003)

Year	Location, country	Est. cases	Pop. served	Causative agent	Probable causes for outbreak occurring	Reference
2004	Ohio, USA	1450	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	13956	Norovirus	Contamination of well following a heavy rain event	(Papadopoulos et al. 2006)
2006	Xanthi, Greece	1640	100882	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	4965	Norovirus	Infiltration of contaminated surficial waters following heavy rain	(Giammanco et al. 2014)

13 waterborne outbreaks caused by contaminated surface water have been identified, Table 2 and 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 norovirus 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 were concentrated in only one country (Sweden) responsible for 49400 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.

 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	25000	*Cryptosporidium*	Contamination with farmyard slurry and manure following very heavy rains	(Jennings & Rhatigan 2002)
2002	St. Maria de Palautordera, Spain	756	6343	*Shigella*	Heavy rain led mud and organic material into the WTP	(Arias et al. 2006)
2004	Bergen, Norway	6000	48000	*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	60000	*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	3800	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	2400	7500	Norovirus	Contaminated raw water from point source pollution caused by wastewater	(Larsson et al. 2013)

Year	Location, country	Est. cases	Pop. served	Causative agent	Probable causes for outbreak occurring	Reference
2009	San Felice del Benaco, Italy	299	3360	Rotavirus and norovirus	Contamination of lake due to over-capacity of the sewage system and/or illegal wastage	(Scarcella et al. 2009)
2010	Östersund, Sweden	27000	51000	*Cryptosporidium*	Faecal contamination of raw water	(Widerström et al. 2014)
2011	Skellefteå, Sweden	20000	71580	*Cryptosporidium*	Contamination from wastewater	(Andersson et al. 2014)
2012	Elassona, Greece	3620	37264	Rotavirus	Heavy rain lead to increased coloured water	(Mellou et al. 2014)

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, Figure 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 even though 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 is 11 outbreaks caused by disinfection-related problems and in the second group four WBOs were related with 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 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 2500 cases of gastrointestinal illnesses. Finally, in New Zealand the three reported WBOs only affected a smaller number of consumers.

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	2600	7088	*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	6450	18000	*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	1880	*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)

Year	Location, country	Est. cases	Pop. served	Causative agent	Probable causes for outbreak occurring	Reference
2004	Ireland	14	25000	*Cryptosporidium*	High demand and turbidity issues lead to unfiltered water mixed with filtered one	(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	25000	*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	2860	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	1663	Unknown	Unknown	Operation and maintenance deficiencies in water treatment	(Brunkard et al. 2011)

Year	Location, country	Est. cases	Pop. served	Causative agent	Probable causes for outbreak occurring	Reference
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	3280	*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)

WBOs caused by distribution systems failure

The 26 incidents that were reviewed for this chapter, Table 4 and Figure 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 USA almost three quarters of the affected consumers are accounted for. In USA five outbreaks occurred while in Finland only two outbreaks were identified. Among the remaining countries UK and Denmark have four respectively three identified outbreaks while the remaining countries have fewer identified outbreaks.

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	60000	Unknown	Main repair in the network	(Deshayes & Schmitt 2001)
2000	Bari, Italy	344	1000	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	1100	*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	1866	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	3006	Unknown	Broken sewage pipe allowed untreated water from the river to enter the city aqueduct	(Tramarin et al. 2002)

Year	Location, country	Est. cases	Pop. served	Causative agent	Probable causes for outbreak occurring	Reference
2002	Switzerland	125	Unknown	Norovirus	Faeces related contamination from a sewage leakage	(Fretz et al. 2005)
2004	Ohio, USA	1450	Unknown	*Campylobacter*, norovirus and *Giardia*	Unspecified distribution system deficiency related with untreated groundwater	(Liang et al. 2006)
2007	Køge, Denmark	140	5802	*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	8453	30016	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	2000	*Campylobacter* and norovirus	Input of highly pressurised washwater from sewage plant into the drinking water system	(Breitenmoser et al. 2011)
2008	Northampton, UK	> 422	250000	*Cryptosporidium*	Dead rabbit found in a tank containing drinking water at the treatment works	(Smith et al. 2010) (Chalmers 2012)
2008	Colorado, USA	1300	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)

Year	Location, country	Est. cases	Pop. served	Causative agent	Probable causes for outbreak occurring	Reference
2010	Køge, Denmark	409	20000	*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	1538	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	2931	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)

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 needs 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 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, a number of 175 outbreaks were identified in total 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 water treatment plants. 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 water treatment plants 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 1000 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 USA 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 Organisation. 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 a 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:

- *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 and wastewater intrusion into the pipe network. Also, cases of contamination of reservoirs are reported.

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.

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