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Citation for the original published paper (version of record):

Moreira, N., Bondelind, M. (2017). Safe drinking water and waterborne outbreaks. *Journal of Water and Health*, 15(1): 83-96. <http://dx.doi.org/10.2166/wh.2016.103>

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1 Safe drinking water and waterborne outbreaks

2 N. A. Moreira^{1,2}, M. Bondelind^{2*}

3 ¹ Cranfield Water Science Institute, Cranfield University, Bedfordshire, MK43 0AL, UK

4 ² Department of Civil and Environmental Engineering, Chalmers, Sven Hultins gata 8, 412 96
5 Göteborg, Sweden

6 *Corresponding author, email: mia.bondelind@chalmers.se

8 Abstract

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

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

24 Introduction

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

30 Waterborne outbreaks are caused by drinking water contamination worldwide (Karanis et al.
31 2007). One of the most challenging issues facing the drinking water treatment plants (WTP) are
32 the uncertainties related to climate change and the effect it will have on the surface water
33 quality. Increase of extreme hydrological events in addition to changes in air temperature may
34 increase the risk of WBOs. The most vulnerable water bodies to future climate changes are
35 likely to be shallow lakes, where the chemical processes will be altered by the impact of an
36 increase in water temperature, increases in pH and larger alkalinity generation in the lakes
37 themselves. Additionally, sewage discharge from combined sewage systems caused by heavy
38 rainfall has been demonstrated to spread waterborne pathogens within the surface waters.
39 Furthermore, increased temperatures may increase disinfection by-products formation rate in
40 surface waters at natural temperatures, between 5 and 30 °C (Delpha et al. 2009). Consequently,
41 environmental contamination, intensive livestock rearing, surface water and discharge of
42 wastewater into drinking water sources are risk factors that need to be addressed (Chalmers
43 2012).

44 In the production of safe and aesthetically suitable water for human consumption, the analysis
45 and evaluation of risks to the complete drinking water system, from the catchment until it
46 reaches the consumer, is considered of paramount importance by the World Health
47 Organisation (WHO). To achieve that aim, a framework for safe drinking water was developed
48 by the WHO throughout the application of guidelines designated as water safety plans (WSP)
49 (WHO 2011). Through the WSP, hazards and hazardous events that can affect the safety of the
50 production of drinking water from the catchment to consumer are identified. The risks
51 associated with the events are assessed and control points and barriers are implemented if
52 needed. The WSP should be reviewed regularly and continuously updated (Bartram et al. 2009).
53 To quantify the barrier effect and the treatment required the Microbial Barrier Analysis model
54 (MBA) can be used (Ødegaard & Østerhus 2014). First the raw water quality is evaluated and
55 according to the quality the necessary treatment efficiency is determined. Thereafter the
56 removal and inactivation efficiency of the barriers installed at the WTP are calculated. The
57 difference between the required and the calculated barrier efficiency shows if supplementary
58 surveillance or additional treatment is required.

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

67 **Method**

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

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

88 In this review drinking water outbreaks confined geographically to Europe, North America and
89 New Zealand have been reviewed. Here public national systems to register the occurrence of
90 waterborne outbreaks are available. In developing countries, the information related with
91 WBOs is less available or even absent and the countries have therefore not been included in

92 this review (Baldursson & Karanis 2011). Thus the available reports of incidents, according to
 93 the stipulated eligibility criteria, resulted in the inclusion of 15 countries: Canada, Denmark,
 94 Finland, France, Greece, Ireland, Italy, Netherlands, New Zealand, Norway, Spain, Sweden,
 95 Switzerland, UK and USA. The creation of public national systems to register the frequency
 96 and prevalence of waterborne outbreaks or protozoan infections may vary among the countries.
 97 The surveillance of potential factors of interest to the drinking water industry affecting the
 98 occurrence of parasite transmission hazards has to be known for the event to be included in this
 99 review.

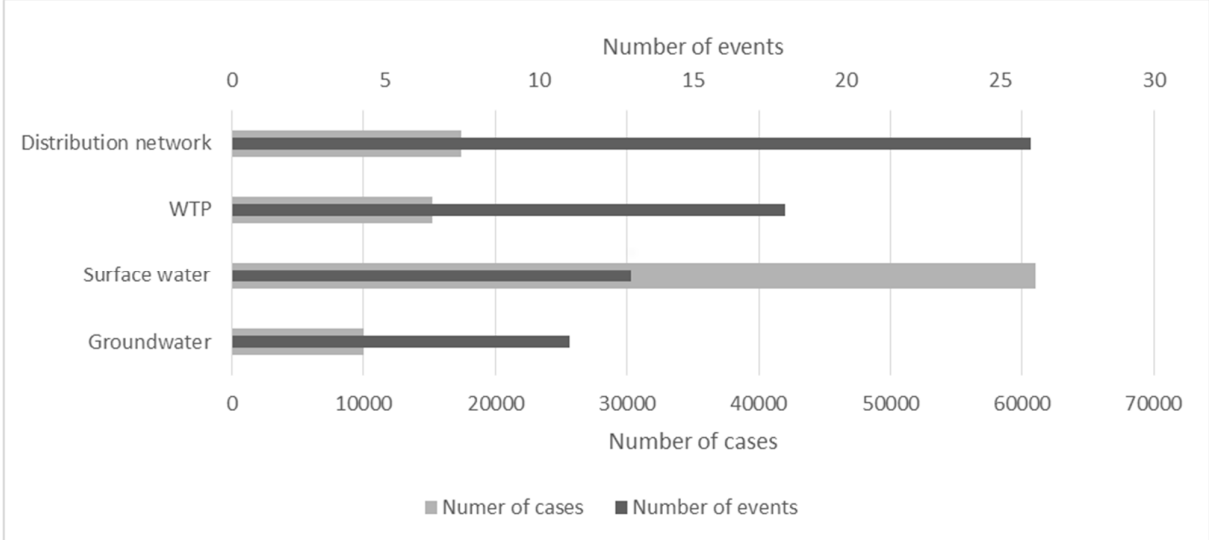
100 The results of this review are summarised in Tables 1-4 that present the year of the event;
 101 country and specific location (when available); estimated number of infections; population
 102 served by the water works or distribution system; causative agent; probable cause for the
 103 outbreak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

105 **Results**

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

108 **WBOs caused by raw water contamination**

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



113
 114 **Figure 1. The number of events of WBOs and the number of cases of illnesses among the consumers.**

115 11 drinking water-related outbreaks were associated with groundwater contamination, which
 116 instigated gastrointestinal illness amongst an estimated total of 10021 consumers (Table 1,
 117 Figure 1). Even though the large majority (82%) of reported outbreaks originated by
 118 groundwater contamination occurred before 2007, no time-related pattern can be inferred due
 119 to the significant delay between incidents and dates of reporting.

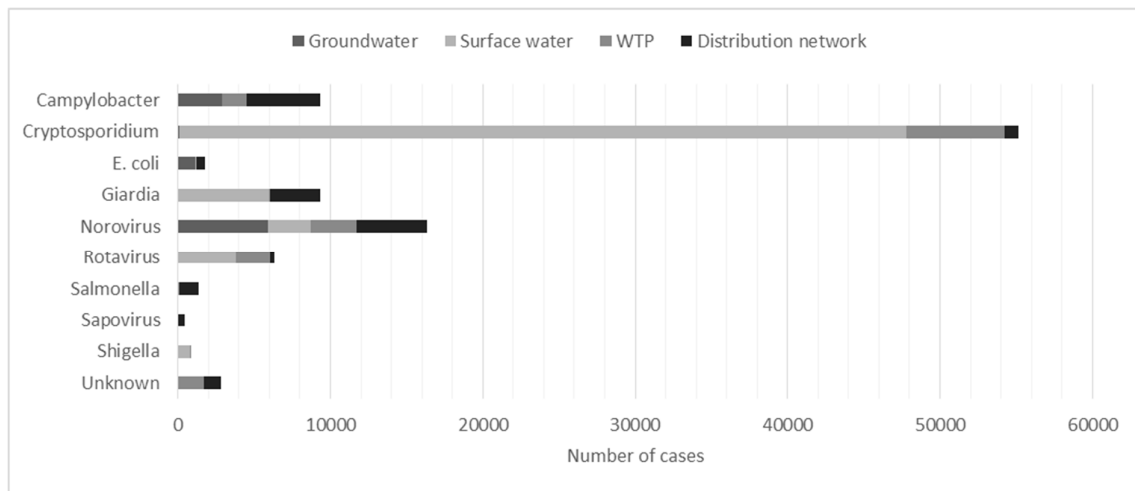
120 The aetiological agents for the events with groundwater contamination were norovirus in six
 121 outbreaks, *Cryptosporidium* in two events, one event with *Campylobacter*, one with two
 122 bacterial pathogens (*E. coli* and *Campylobacter*), and also one with both norovirus and

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

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

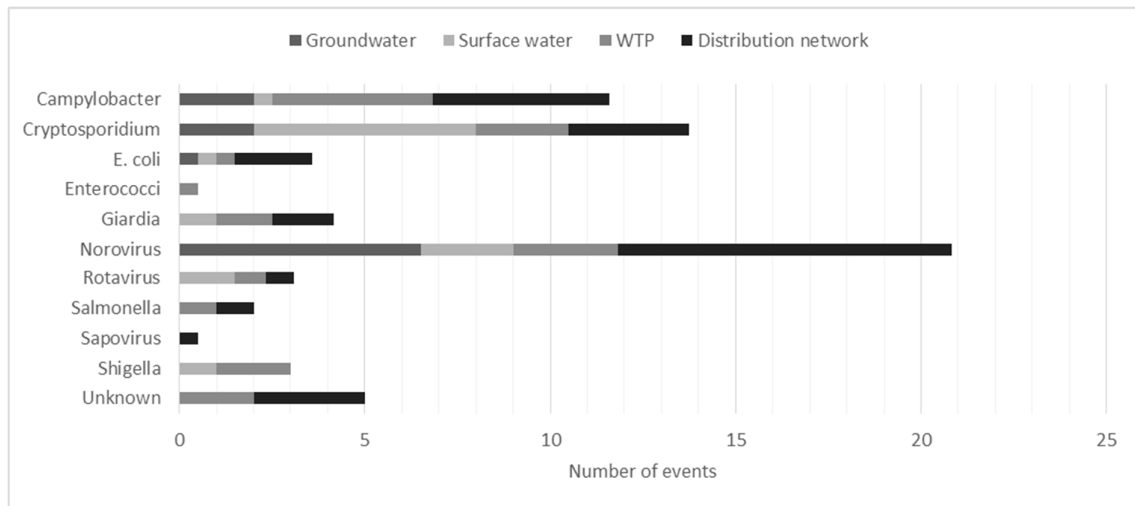
135 The outbreaks for the events with groundwater contamination show that five countries endured
136 more than a 1000 cases of infectious gastrointestinal illness, in one single event: Canada,
137 Finland, France, Greece and USA.

138



139

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



142

143

144

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.

145

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	<i>Campylobacter</i> and <i>E. coli</i>	Contamination from livestock faecal residue following heavy rainfall	(Hrudey et al. 2003)
2000	Clitheroe, UK	58	17252	<i>Cryptosporidium</i>	Contamination with animal faeces following abnormally heavy rain	(Howe et al. 2002)
2001	Southern Finland	1000	18000	<i>Campylobacter</i>	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	<i>Campylobacter</i> 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	<i>Cryptosporidium</i>	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)

146

147 13 waterborne outbreaks caused by contaminated surface water have been identified, Table 2
148 and Figure 1. A time-related pattern could be suggested for the outbreaks originated by surface
149 water contamination where a majority of the cases of illness (87%) occurred after 2007 but that
150 may be due to selection bias.

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

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

158 The highest number of estimated cases caused by surface water contamination were
159 concentrated in only one country (Sweden) responsible for 49400 infected drinking water
160 consumers, mainly due to two especially large outbreaks in 2010 and 2011. The second largest
161 number of affected consumers was located in Norway.

162 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	<i>Cryptosporidium</i>	Contamination with farmyard slurry and manure following very heavy rains	(Jennings & Rhatigan 2002)
2002	St. Maria de Palautordera, Spain	756	6343	<i>Shigella</i>	Heavy rain led mud and organic material into the WTP	(Arias et al. 2006)
2004	Bergen, Norway	6000	48000	<i>Giardia</i>	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	<i>Cryptosporidium</i>	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	<i>Cryptosporidium</i>	Low water levels in the river may have reduced dilution from sewage discharge	(Nichols et al. 2006)
2005	Oregon, USA	60	Unknown	<i>Campylobacter</i> and <i>E. coli</i>	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	<i>Cryptosporidium</i>	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	<i>Cryptosporidium</i>	Faecal contamination of raw water	(Widerström et al. 2014)
2011	Skellefteå, Sweden	20000	71580	<i>Cryptosporidium</i>	Contamination from wastewater	(Andersson et al. 2014)
2012	Elassona, Greece	3620	37264	Rotavirus	Heavy rain lead to increased coloured water	(Mellou et al. 2014)

163

164 **WBOs caused by treatment failure**

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

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

181 The location of seven of the reported illnesses caused by waterborne outbreaks originated from
182 treatment deficiencies in North America, where Canada had one outbreak and USA six
183 occurrences with significant impact. Within Europe a total number of eight outbreaks occurred
184 which corresponds to 43% of estimated cases. In Italy and France the outbreaks were larger and
185 caused more than 2500 cases of gastrointestinal illnesses. Finally, in New Zealand the three
186 reported WBOs only affected a smaller number of consumers.

188 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	<i>Campylobacter</i> , 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	<i>Giardia</i>	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	<i>Cryptosporidium</i>	Treatment deficiencies after maintenance work because of increased turbidity	(Stirling et al. 2001)
2001	Hawkes Bay, New Zealand	186	295	<i>Campylobacter</i>	Malfunction in the UV system and delayed installation of replacement components	(Thornley et al. 2002)
2001	Torres de Segre, Spain	344	1880	<i>Campylobacter</i>	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	<i>Cryptosporidium</i>	High demand and turbidity issues lead to unfiltered water mixed with filtered one	(O'Toole et al. 2004)
2004	New Zealand	23	Unknown	<i>Shigella</i>	Treatment failure and inadequate raw water source	(ESR 2005)
2004	Montana, USA	70	Unknown	<i>Salmonella</i>	UV disinfection unit found to be out of service	(Liang et al. 2006)
2005	Carlow, Ireland	31	25000	<i>Cryptosporidium</i> and <i>Giardia</i>	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	<i>Shigella</i>	Chlorinator froze and stopped working; possible illegal discharge of wastewater near raw water source	(Godoy et al. 2011)
2006	Indiana, USA	32	Unknown	<i>Campylobacter</i>	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 <i>E. Coli</i>	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	<i>Campylobacter</i>	Pump failure lead to exclusive use of river raw water; heavy rains resulted in increased turbidity, no multi-barrier approach	(Bartholomew et al. 2014)

189

190 **WBOs caused by distribution systems failure**

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

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

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

210

211 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	<i>Cryptosporidium</i>	Seepage of raw sewage from a septic tank into the water distribution system	(Glberman et al. 2002)
2000	South Wales, UK	281	Unknown	<i>Campylobacter</i>	Seepage of surface water contaminated by agricultural waste following heavy rainfall into drinking water reservoir	(Richardson et al. 2007)
2000	Ohio, USA	29	Unknown	<i>E. coli</i>	Possible back-siphonage from animal barn	(Lee et al. 2002)
2001	Darcy le Fort, France	563	1100	<i>Cryptosporidium</i> , rotavirus, <i>Campylobacter</i> and <i>E. coli</i>	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	<i>Cryptosporidium</i>	Wastewater into the drinking water supply due to a blocked drain	(Glberman 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	<i>Campylobacter</i> , norovirus and <i>Giardia</i>	Unspecified distribution system deficiency related with untreated groundwater	(Liang et al. 2006)
2007	Køge, Denmark	140	5802	<i>Campylobacter</i> , <i>E. coli</i> 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, <i>Campylobacter</i> and <i>Giardia</i>	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	<i>Campylobacter</i> and norovirus	Input of highly pressurised washwater from sewage plant into the drinking water system	(Breitenmoser et al. 2011)
2008	Northampton, UK	> 422	250000	<i>Cryptosporidium</i>	Dead rabbit found in a tank containing drinking water at the treatment works	(Smith et al. 2010) (Chalmers 2012)
2008	Colorado, USA	1300	Unknown	<i>Salmonella</i>	Likely animal contamination of a storage tank	(Brunkard et al. 2011)
2009	Utah, USA	8	Unknown	<i>Giardia</i>	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	<i>Campylobacter</i>	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	<i>Campylobacter</i>	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 <i>E. coli</i>	Main pipe accidentally 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)

212

213 Discussion

214 In this paper the causes of WBOs have been investigated. The main causes for contamination
215 of groundwater sources identified in this paper were the intrusion of animal faeces or
216 wastewater due to heavy rains Even if the large majority of the reported events occurred before
217 2007, a time-related pattern cannot be inferred and further measures to reduce the contamination

218 risks to the raw water and the catchment areas should be thoroughly implemented, with the
219 establishment of protection areas and identification of potential contamination sources, for
220 instance. The outbreaks originated by surface water contamination did on the other hand occur
221 after 2007 for the majority of the cases of illness, but this does not sanction any assumption
222 regarding the protection of raw water sources. The main causes for contamination of surface
223 waters, identified in this study, are the discharge of wastewater into the water source and
224 increased turbidity and colour of the water. These events may occur during heavy rains but also
225 at low water levels. This indicates that further measures to reduce the contamination risks to
226 the raw water and the catchment areas still needs to be implemented for surface water sources.
227 Measures that could be applied are the establishment of protection areas, the identification of
228 potential contamination sources and increased monitoring of raw water quality parameters.

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

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

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

259 In this study causes and pathogens of WBOs have been critically evaluated. Limitations in this
260 study are that outbreaks have only been evaluated if the cause of the event was indicated in the
261 reference and if the event was present in the chosen databases. In a recent review the responsible
262 authorities and the water industry were directly contacted about recent WBOs in the Nordic
263 countries (Guzman Herrador et al. 2015). In total, a number of 175 outbreaks were identified in
264 total which exceeds the number of outbreaks identified in our study. However, the number of
265 cases of illnesses is of the same order of magnitude for Sweden, Finland and Denmark, if
266 adjusted for the year 1998-1999 (Miettinen et al. 2001). Consequently, this indicates that the

267 identified causes for outbreaks in this review may not cover minor events that have only affected
268 a small number of consumers.

269 This work has not addressed the differences between small and large water treatment plants.
270 The tendency is that medium and large waterworks receive more attention than small ones in
271 these systematic approaches (Coulibaldy & Rodriguez 2004). In a study published in 2011 that
272 analysed small water treatment plants in Finland, it was indicated that nonconformity in the
273 production of microbiological safe drinking water is more probable in small rather than large
274 waterworks that were distributing water to a minimum of a 1000 consumers (Zacheus &
275 Miettinen 2011). Previous reviews have highlighted that the number of small waterborne
276 outbreaks that are not reported or that are merely poorly documented is not negligible (Hrudey
277 & Hrudey 2007). In countries like Finland where the number of affected consumers is below
278 0.01% (the USA EPA guideline), it is considered that the production of safe drinking water in
279 all types of settings and/or limitations is not guaranteed and more measures need to be
280 implemented (Zacheus & Miettinen 2011).

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

294 **Conclusions**

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

- 298 • *Groundwater sources*: intrusion of animal faeces or wastewater due to heavy rains;
- 299 • *Surface water sources*: discharge of wastewater into the water source and increased
300 turbidity and colour of the water;
- 301 • *WTP*: malfunctioning of the disinfection, increased turbidity, maintenance work, high
302 or low demand of water and malfunctioning equipment (e.g. pumps);
- 303 • *Distribution network*: cross-connections, pipe breaks and wastewater intrusion into the
304 pipe network. Also, cases of contamination of reservoirs are reported.

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

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