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

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
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.
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

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Location, country</th>
<th>Est. cases</th>
<th>Pop. served</th>
<th>Causative agent</th>
<th>Probable causes for outbreak occurring</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Walkerton, Canada</td>
<td>2,300</td>
<td>4,800</td>
<td><em>Campylobacter</em> and <em>E. coli</em></td>
<td>Contamination from livestock faecal residue following heavy rainfall</td>
<td>Hrudey et al. (2005)</td>
</tr>
<tr>
<td>2000</td>
<td>Clitheroe, UK</td>
<td>58</td>
<td>17,252</td>
<td><em>Cryptosporidium</em></td>
<td>Contamination with animal faeces following abnormally heavy rain</td>
<td>Howe et al. (2002)</td>
</tr>
<tr>
<td>2001</td>
<td>Southern Finland</td>
<td>1,000</td>
<td>18,000</td>
<td><em>Campylobacter</em></td>
<td>Floodwater from a dike contaminated by runoff (probably from animal sources)</td>
<td>Hänninen et al. (2003)</td>
</tr>
<tr>
<td>2002</td>
<td>Isère, France</td>
<td>2,000</td>
<td>5,600</td>
<td>Norovirus</td>
<td>Heavy rains lead to overflow in the sewage treatment works upstream and the flooding of raw water borehole</td>
<td>Tillaut et al. (2004)</td>
</tr>
<tr>
<td>2002</td>
<td>Transtrand, Sweden</td>
<td>500</td>
<td>772</td>
<td>Norovirus</td>
<td>Crack in sewage pipe 10 m from one of the supplying wells</td>
<td>Carrique-Mas et al. (2005)</td>
</tr>
<tr>
<td>2004</td>
<td>Ohio, USA</td>
<td>1,450</td>
<td>Unknown</td>
<td><em>Campylobacter</em> and norovirus</td>
<td>Multiple contamination of aquifer from onsite septic systems, land application of sludge and infiltration of run-off</td>
<td>O’Reilly et al. (2007)</td>
</tr>
<tr>
<td>2005</td>
<td>Xanthi, Greece</td>
<td>709</td>
<td>13,956</td>
<td>Norovirus</td>
<td>Contamination of well following a heavy rain event</td>
<td>Papadopoulos et al. (2006)</td>
</tr>
<tr>
<td>2006</td>
<td>Xanthi, Greece</td>
<td>1,640</td>
<td>100,882</td>
<td>Norovirus</td>
<td>Groundwater contamination following a heavy rain event</td>
<td>Vantarakis et al. (2011)</td>
</tr>
<tr>
<td>2006</td>
<td>Portlaw, Ireland</td>
<td>8</td>
<td>Unknown</td>
<td><em>Cryptosporidium</em></td>
<td>Moderate risk of groundwater contamination previously identified; UV treatment unit was commissioned</td>
<td>HPSC (2007)</td>
</tr>
<tr>
<td>2009</td>
<td>Evertsberg, Sweden</td>
<td>200</td>
<td>400</td>
<td>Norovirus</td>
<td>Well contaminated by snowmelt</td>
<td>Riera-Montes et al. (2011)</td>
</tr>
<tr>
<td>2011</td>
<td>Agrigento, Italy</td>
<td>156</td>
<td>4,965</td>
<td>Norovirus</td>
<td>Infiltration of contaminated surficial waters following heavy rain</td>
<td>Giammanco et al. (2014)</td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Year</th>
<th>Location, country</th>
<th>Est. cases</th>
<th>Pop. served</th>
<th>Causative agent</th>
<th>Probable causes for outbreak occurring</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Gourdon, France</td>
<td>2,600</td>
<td>7,088</td>
<td>Campylobacter, rotavirus and norovirus</td>
<td>Failure in the chlorination system (and possible contamination of groundwater from agricultural run-off)</td>
<td>Gallay et al. (2006)</td>
</tr>
<tr>
<td>2000</td>
<td>Colorado, USA</td>
<td>27</td>
<td>Unknown</td>
<td>Giardia</td>
<td>Multiple failures in the pumping mechanism and filtration system; inadequate time for chlorination due to increased demand</td>
<td>Lee et al. (2002)</td>
</tr>
<tr>
<td>2001</td>
<td>Saskatchewan, Canada</td>
<td>6,450</td>
<td>18,000</td>
<td>Cryptosporidium</td>
<td>Treatment deficiencies after maintenance work because of increased turbidity</td>
<td>Stirling et al. (2001)</td>
</tr>
<tr>
<td>2001</td>
<td>Hawkes Bay, New Zealand</td>
<td>186</td>
<td>295</td>
<td>Campylobacter</td>
<td>Malfunction in the UV system and delayed installation of replacement components</td>
<td>Thornley et al. (2002)</td>
</tr>
<tr>
<td>2001</td>
<td>Torres de Segre, Spain</td>
<td>344</td>
<td>1,880</td>
<td>Campylobacter</td>
<td>Failure in chlorination system</td>
<td>Godoy et al. (2002)</td>
</tr>
<tr>
<td>2001</td>
<td>Switzerland</td>
<td>650</td>
<td>Unknown</td>
<td>Norovirus</td>
<td>Treatment failure following deficiencies in chlorine and/or ozone application</td>
<td>Fretz et al. (2005)</td>
</tr>
<tr>
<td>2001</td>
<td>Pennsylvania, USA</td>
<td>19</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unspecified treatment deficiency; no chlorine residual in the drinking water</td>
<td>Blackburn et al. (2004)</td>
</tr>
<tr>
<td>2001</td>
<td>Wyoming, USA</td>
<td>83</td>
<td>Unknown</td>
<td>Norovirus</td>
<td>Failure of pellet chlorinator and septic tank contamination</td>
<td>Blackburn et al. (2004)</td>
</tr>
<tr>
<td>2004</td>
<td>Ireland</td>
<td>14</td>
<td>25,000</td>
<td>Cryptosporidium</td>
<td>High demand and turbidity issues lead to unfiltered water mixed with filtered water</td>
<td>O’Toole et al. (2004)</td>
</tr>
<tr>
<td>2004</td>
<td>New Zealand</td>
<td>23</td>
<td>Unknown</td>
<td>Shigella</td>
<td>Treatment failure and inadequate raw water source</td>
<td>ESR (2005)</td>
</tr>
<tr>
<td>2004</td>
<td>Montana, USA</td>
<td>70</td>
<td>Unknown</td>
<td>Salmonella</td>
<td>UV disinfection unit found to be out of service</td>
<td>Liang et al. (2006)</td>
</tr>
<tr>
<td>2005</td>
<td>Carlow, Ireland</td>
<td>31</td>
<td>25,000</td>
<td>Cryptosporidium and Giardia</td>
<td>Aging plant with turbidity problems in highly agricultural basin; sewage treatment plants upstream; rainfall peak</td>
<td>Roch et al. (2005)</td>
</tr>
<tr>
<td>2006</td>
<td>Apulia, Italy</td>
<td>2,860</td>
<td>Unknown</td>
<td>Rotavirus and norovirus</td>
<td>Technical problems with chlorination</td>
<td>Martinelli et al. (2007)</td>
</tr>
<tr>
<td>2006</td>
<td>Valencia d’Aneu, Spain</td>
<td>≥68</td>
<td>180</td>
<td>Shigella</td>
<td>Chlorinator froze and stopped working; possible illegal discharge of wastewater near raw water source</td>
<td>Godoy et al. (2011)</td>
</tr>
<tr>
<td>2006</td>
<td>Indiana, USA</td>
<td>32</td>
<td>Unknown</td>
<td>Campylobacter</td>
<td>Inadequate chlorination of the water supply; cross-contamination also possible when testing a new water main</td>
<td>Yoder et al. (2008)</td>
</tr>
<tr>
<td>2007</td>
<td>Florida, USA</td>
<td>1,663</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Operation and maintenance deficiencies in water treatment</td>
<td>Brunkard et al. (2011)</td>
</tr>
<tr>
<td>2010</td>
<td>Åhus, Sweden</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Enterococci and E. coli</td>
<td>Salt used in the water softening process was contaminated; rapid intervention of the municipality may have prevented an outbreak</td>
<td>Norberg (2010)</td>
</tr>
<tr>
<td>2012</td>
<td>Darfield, New Zealand</td>
<td>138</td>
<td>3,280</td>
<td>Campylobacter</td>
<td>Pump failure lead to exclusive use of river raw water; heavy rains resulted in increased turbidity, no multi-barrier approach</td>
<td>Bartholomew et al. (2014)</td>
</tr>
</tbody>
</table>
Table 4 | List of outbreaks originated from distribution systems failure

<table>
<thead>
<tr>
<th>Year</th>
<th>Location, country</th>
<th>Est. cases</th>
<th>Pop. served</th>
<th>Causative agent</th>
<th>Probable causes for outbreak occurring</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Strasbourg, France</td>
<td>53</td>
<td>60,000</td>
<td>Unknown</td>
<td>Main repair in the network</td>
<td>Deshayes &amp; Schmitt (2001)</td>
</tr>
<tr>
<td>2000</td>
<td>Bari, Italy</td>
<td>344</td>
<td>1,000</td>
<td>Norovirus</td>
<td>Break in pipeline public supply connecting to resort tank</td>
<td>Boccia et al. (2002)</td>
</tr>
<tr>
<td>2000</td>
<td>Belfast, UK</td>
<td>117</td>
<td>Unknown</td>
<td>Cryptosporidium</td>
<td>Seepage of raw sewage from a septic tank into the water distribution system</td>
<td>Glaberman et al. (2002)</td>
</tr>
<tr>
<td>2000</td>
<td>South Wales, UK</td>
<td>281</td>
<td>Unknown</td>
<td>Campylobacter</td>
<td>Seepage of surface water contaminated by agricultural waste following heavy rainfall into drinking water reservoir</td>
<td>Richardson et al. (2007)</td>
</tr>
<tr>
<td>2000</td>
<td>Ohio, USA</td>
<td>29</td>
<td>Unknown</td>
<td>E. coli</td>
<td>Possible back-siphonage from animal barn</td>
<td>Lee et al. (2002)</td>
</tr>
<tr>
<td>2001</td>
<td>Darcy le Fort, France</td>
<td>563</td>
<td>1,100</td>
<td>Cryptosporidium, rotavirus, Campylobacter and E. coli</td>
<td>Sewage contamination occurred in the distribution network upstream to the city</td>
<td>Dalle et al. (2005)</td>
</tr>
<tr>
<td>2001</td>
<td>Lleida, Spain</td>
<td>96</td>
<td>293</td>
<td>Norovirus</td>
<td>Contamination of reservoir due to lack of maintenance and structural deficiencies</td>
<td>Godoy et al. (2006)</td>
</tr>
<tr>
<td>2001</td>
<td>Utrecht, The Netherlands</td>
<td>37</td>
<td>1,866</td>
<td>Norovirus</td>
<td>Drinking water system connected to grey water system in maintenance work; cross-connection not removed</td>
<td>Fernandes et al. (2007)</td>
</tr>
<tr>
<td>2001</td>
<td>Belfast, UK</td>
<td>230</td>
<td>Unknown</td>
<td>Cryptosporidium</td>
<td>Wastewater into the drinking water supply due to a blocked drain</td>
<td>Glaberman et al. (2002)</td>
</tr>
<tr>
<td>2002</td>
<td>Vicenza, Italy</td>
<td>670</td>
<td>3,006</td>
<td>Unknown</td>
<td>Broken sewage pipe allowed untreated water from the river to enter the city aqueduct</td>
<td>Tramarin et al. (2002)</td>
</tr>
<tr>
<td>2002</td>
<td>Switzerland</td>
<td>125</td>
<td>Unknown</td>
<td>Norovirus</td>
<td>Faeces related contamination from a sewage leakage</td>
<td>Fretz et al. (2005)</td>
</tr>
<tr>
<td>2004</td>
<td>Ohio, USA</td>
<td>1,450</td>
<td>Unknown</td>
<td>Campylobacter, norovirus and Giardia</td>
<td>Unspecified distribution system deficiency related with untreated groundwater</td>
<td>Liang et al. (2006)</td>
</tr>
<tr>
<td>2007</td>
<td>Köge, Denmark</td>
<td>140</td>
<td>5,802</td>
<td>Campylobacter, E. coli and norovirus</td>
<td>Technical and human error at sewage treatment work allowed partially filtered wastewater to enter the drinking water system</td>
<td>Vestergaard et al. (2007)</td>
</tr>
<tr>
<td>2007</td>
<td>Nokia, Finland</td>
<td>8,453</td>
<td>30,016</td>
<td>Norovirus, Campylobacter and Giardia</td>
<td>Drinking water network contaminated by treated sewage effluent</td>
<td>Laine et al. (2010)</td>
</tr>
<tr>
<td>2007</td>
<td>Västerås, Sweden</td>
<td>400</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Leaked sewage into drinking water network during maintenance work on a pipeline</td>
<td>Nilsson (2008)</td>
</tr>
<tr>
<td>2008</td>
<td>Zurich, Switzerland</td>
<td>126</td>
<td>2,000</td>
<td>Campylobacter and norovirus</td>
<td>Input of highly pressurised washwater from sewage plant into the drinking water system</td>
<td>Breitenmoser et al. (2011)</td>
</tr>
<tr>
<td>2008</td>
<td>Northampton, UK</td>
<td>&gt;422</td>
<td>250,000</td>
<td>Cryptosporidium</td>
<td>Dead rabbit found in a tank containing drinking water at the treatment works</td>
<td>Smith et al. (2010), Chalmers (2012)</td>
</tr>
</tbody>
</table>
Table 4 | continued

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

Figure 1 | The number of events of WBOs and the number of cases of illnesses among the consumers.
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 rotavirus 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 (Aström 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 (Coulibaly & 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.

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