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OVERVIEW OF MICROBIAL RISKS IN WATER DISTRIBUTION NETWORKS AND THEIR HEALTH CONSEQUENCES: QUANTIFICATION, MODELLING, TRENDS AND FUTURE IMPLICATIONS

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Abstract. The water distribution network (WDN) is usually the final physical barrier preventing contamination of the drinking water before it reaches consumers. Because the WDN is at the end of the supply chain, and often with limited online water quality monitoring, the probability of an incident to be detected and remediated in time is low. Microbial risks that can affect the distribution network are: intrusion, cross-connections and backflows, inadequate management of reservoirs, improper main pipe repair/maintenance work, and biofilms. Epidemiological investigations have proven that these risks have been sources of waterborne outbreaks. Increasingly since the 1990s, studies have also indicated that the contribution of these risks to the endemic level of disease is not negligible. To address the increasing health risks associated to WDNs, researchers have developed tools for risk quantification and risk management. This review aims to present the recent advancements in the field involving epidemiological investigations, use of quantitative microbial risk assessment (QMRA) for modelling, risk mitigation and decision-support. Increasing the awareness of the progress achieved, but also of the limitations and challenges faced, will aid in accelerating the implementation of QMRA tools for WDN risk management and as a decision-support tool.

Keywords: *microbial risk, water distribution network, waterborne outbreak, gastrointestinal illness, QMRA*

Introduction

The provisioning of safe drinking water is the main goal for any water supplier. Drinking water is considered safe when it does not represent a health risk to the consumers (WHO 2011). The water distribution network is usually the final physical barrier preventing contamination of the drinking water before it reaches the consumers (Risebro et al. 2007). Since the distribution network is at the end of the supply chain, it is less probable that an incident can be detected and remediated in time. Therefore, maintaining the integrity of the network is essential in preventing contamination of the treated water delivered to consumers.

The National Research Council (2006) divides the integrity of the distribution network into three components: physical, hydraulic and water quality. Physical integrity refers to the ability of the distribution system to act as a physical barrier against external contamination. The physical integrity can be lost if, for example, there are cross-connections with non-potable water pipes or due to cracks and holes in the pipes. Hydraulic integrity is the capacity of the system to maintain adequate flow, pressure and water age. Certain events, e.g., pump shutdown and main breaks, can affect the hydraulic integrity of the system. Water quality integrity deals with internal chemical processes inside the pipes that can lead to a deterioration of the drinking water quality. An example of water quality integrity breach is the complete decay of the disinfectant residual. For a contamination event to occur, it is expected that both physical and the hydraulic integrity are lost (Ercumen et al. 2014).

Deficiencies in the distribution network that lead to contamination of the drinking water poses a serious health risk to consumers. Cases where failures in the distribution network have been linked with waterborne disease outbreaks are well documented (Craun et al. 2010; Guzman-Herrador et al. 2015; Hrudey and Hrudey 2004; Schuster et al. 2005). Studies on the distribution network's contribution to background level gastrointestinal illness (GI), on the other hand, have had mixed results (Colford et al. 2005; Hellard et al. 2001; Hunter et al. 2005; Malm et al. 2013; Nygard et al. 2007; Payment et al. 1991; Payment et al. 1997; Säve-Söderbergh et al. 2017a). However, there is evidence that malfunctioning distribution networks in general, as well as specific system deficiencies (i.e., pipe breaks, water outages and inadequate residual disinfectant), increase the risk of endemic GI (Ercumen et al. 2014).

In the United States, both the total number of reported outbreaks and number of outbreaks caused by distribution system failures have decreased; on the other hand, the proportion of outbreaks caused by distribution network deficiencies has increased (from approximately 30% between 1971-1974 to almost 60% between 2001-2002) (National Research Council 2006). In a study of the factors that caused waterborne disease outbreaks in water supply systems of the European Union it was found that distribution system deficiencies contributed in 31% of the outbreaks (Risebro et al. 2007). In the

Nordic countries, approximately 10% of all reported outbreaks are due to distribution network deficiencies (Guzman-Herrador et al. 2015). In Sweden, though, the reported proportion is much higher since 34% of outbreaks with known causes are associated with the distribution network (Malm et al. 2010). This highlights that the distribution network has a significant contribution to the burden of disease of waterborne origin.

Distinct kinds of models have been used to study the microbial risks and their consequences in the distribution network. Computational fluid dynamics (CFD) models have been developed to simulate intrusion events and to study the level of contamination that can enter into the system (Mansour-Rezaei and Naser 2013; Mansour-Rezaei et al. 2013; Mora-Rodríguez et al. 2014). Quantitative microbial risk assessment models have been used in conjunction with hydraulic models to quantify the consequences of different microbial risks (Blokker et al. 2014; Teunis et al. 2010b; Yang et al. 2011). Most of these models have important limitations that restrict their use, e.g., uncertainties in the input data, assumptions made about the conditions in the distribution network (turbulent flow, instantaneous mixing, etc.) (Besner et al. 2011). However, they are useful for evaluating and assessing risk reducing measures that can be chosen to manage the specific risks addressed in the model.

Reviews for the specific risk of intrusion already exist (Besner et al. 2011; Islam et al. 2015). Broader reviews also exist (National Research Council 2006; WHO 2014); however, these reviews do not include recent advancements in the field. Therefore, we performed an extensive literature review of the available research on microbial risks in the distribution network to provide a more accessible and updated depository to experts in the field of drinking water engineering that would like to inform themselves about the current state-of-the-art, with a special focus on health-related aspects of microbial risk. This review focuses on centralized drinking water distribution networks within mainly four areas: (i) associated microbial risks, (ii) studies of the influence of the distribution network in the burden of disease, (iii) models available to quantify the microbial risks and their consequence on health, and (iv) discussions and suggestions for future research.

Microbial risks in the distribution network

The main events associated with the water distribution network that could potentially cause microbial contamination of the drinking water include cross-connections and backflows; unhygienic practices during installation, rehabilitation and repair of water mains; improper management of reservoirs/storages; combination of adverse pressure and physical breaches (i.e., intrusion) events; and biofilms (National Research Council 2005). Most of these events have been identified as the causes of waterborne disease outbreaks (Hrudey and Hrudey 2004; Hrudey and Hrudey 2007; Risebro et al. 2007). Additionally, there is evidence that these events also contribute to the endemic level of GI in the population (Säve-

Söderbergh et al. 2017a)

Cross-connections imply points in the distribution network where non-potable water elements can come into contact with the drinking water (USEPA 2002). When the pressure in the non-potable water source is greater than in the distribution system and there are inadequate cross-connections controls present (e.g., absence of backflow prevention valve), a backflow can occur (WHO 2014). Cross-connections are considered one of the most serious public health risks in the distribution network (National Research Council 2006; WHO 2014).

Routines exist to ensure correct hygienic procedures during installation, rehabilitation and repair of water mains, in addition to properly inspecting reservoirs/storages (Säve-Söderbergh et al. 2013; WHO 2011, 2014). However, contamination can occur if these routines are not carried out (e.g., inadequately disinfecting newly laid pipes, lacking an inspection routine for reservoirs). Unhygienic practices during installation, rehabilitation and repair of water mains; and improper management of reservoirs/storages were considered high priority issues based on their potential health risks (National Research Council 2005).

Intrusion has had different definitions since the term was first introduced by Kirmeyer et al. (2001). For the purpose of this review, intrusion will be defined as in Besner et al. (2011), i.e., contamination of the drinking water due to adverse pressure conditions and physical breaches in the system. In order for microbial contamination to occur from intrusion, three conditions are necessary: presence of pathogens surrounding the distribution system *(source)*; occurrence of pressure transients or low-pressure events *(adverse pressure conditions)*; and deteriorated physical conditions of the pipes *(physical breach)* (Hooper et al. 2008; Lindley and Buchberger 2002). Intrusion was considered a medium priority issue by the National Research Council (2005); however, awareness has increased substantially since then (Besner et al. 2011).

Biofilms are a complex collection of microorganisms, extracellular polymeric substances, organic and inorganic matter (Kauppinen et al. 2012). They are known to serve as potential reservoirs for pathogens inside the distribution system (Berry et al. 2006; Nocker et al. 2014; Wingender and Flemming 2011). Pathogenic organisms that manage to intrude the distribution network (e.g., via intrusion of contaminated water surrounding the pipes) can become attached to biofilms and, afterward, become detached through erosion due to the water flowing. Pathogens that can be found in biofilms include *Cryptosporidium* oocysts (Angles et al. 2007; Howe et al. 2002); enteric viruses (Skraber et al. 2005; Storey and Ashbolt 2003); opportunistic pathogens (Farkas et al. 2012; Pryor et al. 2004) and bacterial pathogens (September et al. 2007; Wingender 2011). Biofilms were classified as a medium priority issue due to their lesser health risks than other known issues (National Research Council 2005).

Influence of the distribution network on waterborne diseases

Contamination of the drinking water can pose a serious health risk to consumers, either by causing (detected) outbreaks of waterborne diseases or contributing to the endemic level of (undetected) disease in the population (Braeye et al. 2015). The effect of contamination in the distribution network is usually expressed in relation to the amount of people experiencing GI.

Waterborne Disease Outbreaks

Deficiencies in the drinking water distribution network are known to contribute to waterborne disease outbreaks (Craun et al. 2010; Guzman-Herrador et al. 2015; Hrudey and Hrudey 2004; Schuster et al. 2005). In a retrospective survey of waterborne outbreaks in Canada, the distribution network was considered to have contributed in 18% of the cases as a cause (Wilson et al. 2009). Broken pipes (7%) and post-treatment contamination (11%) were the two main contributing factors, while cross-connections were not considered as a cause in any of the outbreaks reported. In Sweden, 27 (34%) waterborne outbreaks were reported between 1980-2007 due to distribution network deficiencies (Malm et al. 2010). The most common deficiencies included cross-connections (n=5), reservoir contamination (n=4) and backflows (n=4). Descriptions of selected outbreaks from peer-reviewed articles are consecutively presented in this section to illustrate the distinct mechanisms of failure that lead to contamination in the distribution network (defined in the previous section) and possible consequences.

Swerdlow et al. (1992) investigated the extent of an *E. coli 0157:H7* outbreak in Cabool, Missouri during the period December 1989 to January 1990. There were 243 cases of diarrhea, 32 hospitalizations and 4 deaths. Geldreich et al. (1992) carried out additional sampling and investigated the involvement of the water distribution network causing the outbreak. The authors used a distribution network model to identify how the water flowed and the possible contaminant transport in the system. This was the first time this model was used for an outbreak investigation (Geldreich et al. 1992). It was theorized that unhygienic practices while replacing 43 water meters and repairing two main breaks caused the entry of the contaminants into the distribution network (Swerdlow et al. 1992).

A cohort study carried out in the Norwegian town of Røros confirmed a campylobacteriosis outbreak in 2007 (Jakopanec et al. 2008). Approximately 1 500 people were infected with *Campylobacter* and the investigation concluded that the consumption of tap water increased the risk of illness for the consumers. Potential mechanisms for the contamination of the drinking water were identified: at least two low-pressure events were documented around the time of the outbreak and in the vicinity of a dairy and slaughterhouse.

Laine et al. (2011) reported on the largest waterborne outbreak in Finland, which occurred in Nokia in November - December 2007. A cross-connection allowed effluent water from the wastewater treatment plant to enter the distribution system (Maunula et al. 2009). Pathogens were detected in patient stool samples, and in water samples taken from the drinking water distribution network and the wastewater effluent. *Campylobacter*, norovirus and *Giardia* were considered the main causative agents (Laine et al. 2011; Maunula et al. 2009; Rimhanen-Finne et al. 2010). The excess cases of illness due to the outbreak were estimated at 6 500.

A *Salmonella* outbreak occurred in Alamosa, Colorado, USA in March-April of 2008 (Falco and Williams 2009). The outbreak investigation reported about 440 cases of GI and one death. The authors proposed the main pathway for the pathogen was a storage reservoir that supplied the entire town. The storage reservoir was, according to Falco and Williams (2009), in poor conditions, with visible cracks and holes in the structure.

A viral gastroenteritis outbreak was identified in Podgorica, Montenegro in August – September 2008, with 1 700 reported cases of gastroenteritis and an estimation of 10 000 to 15 000 inhabitants being affected (Werber et al. 2009). Norovirus was identified as the most likely causative pathogen, however the authors acknowledged that other agents could not be dismissed (e.g., rotavirus). It was suspected that a series of pump failures caused low pressures inside the distribution system, allowing contaminated water to enter into the network.

Another retrospective cohort study was performed in Hemiksem, Belgium in 2010 by Braeye et al. (2015). High amounts of faecal indicators were detected in the tap water and multiple pathogens (i.e.., norovirus GI and GII, *Giardia lamblia*, rotavirus and *Campylobacter*) were detected in stool samples collected from residents seeking medical attention. The source of the contamination was hypothesized to be intrusion of river water into the network while firefighters were extinguishing a fire. The water used for firefighting was collected from a pressurised storage unit, which was supplied from two hydrants connected to the distribution system and from a surface water pump unit. A low-pressure event in the distribution network could have permitted the intrusion of the river water being collected in the unit into the system and transported to the consumers.

Endemic Level of Gastrointestinal Illness

Results from studies linking the consumption of tap water to GI, on the other hand, have had mixed results. Some studies have found that tap water contributes significantly to the endemic level of GI, while other studies have not shown such association. In the following section we select relevant studies of contribution of the distribution network to the endemic level of GI that will be briefly described to highlight these contrasting results (summarized in Table 1).

A randomized, unblinded trial was performed in a suburban area of Montréal, Canada to determine the relationship between consuming drinking water and GI illness incidence (Payment et al. 1991). In total, 607 households were enrolled, with 299 families in the filtered water group and 308 in the unfiltered water group. Commercial reverse-osmosis devices were installed in the filtered water households and one person per household was selected to note any incident of GI symptoms during a 15-month period. Between 32.8% and 35% of the excess cases of GI during the studied period was found to be linked to the consumption of drinking water from the tap.

Payment et al. (1997) re-evaluated the incidence of GI due to drinking water in the same study area in Montreal as the previous study by Payment et al. (1991). Participants were divided into four groups: unmodified tap water, tap water with a purge valve, bottled treatment plant water and purified bottled water. 350 families per group were followed for a period of 16 months. The authors determined that tap water consumption contributed between 14%-19% of excess cases of GI. The fraction increased when only evaluating the age group 2-5 years, where the attributable fraction was between 17%-40%.

In Australia, Hellard et al. (2001) conducted a randomized, blinded, controlled trial in a system with high quality source water. Six hundred households were randomly assigned an active (real) treatment device or a sham devise. Participants reported any GI symptoms in a health diary for 68 weeks. The authors found no evidence of an increased incidence of GI between users of the active and sham device, therefore concluding that waterborne pathogens did not contribute significantly to GI in the studied system.

Nygard et al. (2004) carried out an ecological study to investigate associations between potential risk factors related to water and incidence of campylobacteriosis in Sweden. The study found an association between longer distribution network pipes and increased risk of *Campylobacter* infection. Two mechanisms were considered as main contributors: intrusion of contaminated water during low pressure events and presence of cross-connections. According to the authors, the positive association between incidence of *Campylobacter* infection and distribution pipe length indicated that contamination in the distribution system may be a more significant factor of campylobacteriosis in Sweden than previously thought.

A questionnaire-based study conducted in England and Wales found a very strong association between pressure loss events and GI (Hunter et al. 2005). The majority of the pressure loss events were attributed to breaks of water mains. According to the authors, up to 15% of the cases of GI in the United Kingdom could be associated with drinking tap water contaminated during loss of pressure events in the distribution system.

Colford et al. (2005) performed a randomized, controlled, triple-blinded trial in Iowa, USA using combined filtration/UV units in a well-managed system with challenged source water. 1 296 persons distributed in 456 households participated in the study, which was divided in two cycles. During the first cycle, one group was randomly allocated an active device and the other group a sham device for 6 months; afterwards, each group switched to the opposite device for another 6 months. The study did not find any significant difference in GI among the groups when switching from the active device to the sham device or vice versa.

Nygard et al. (2007) carried out a cohort study in seven urban areas in Norway supplied by large waterworks. The main objective was to assess the relationship between main breaks or maintenance work that generated a pressure loss event in the system and GI among consumers affected by the event. Low pressure events (n=88) were recorded in the study where 1159 households were interviewed (612 exposed to the event and 547 unexposed). The attributable fraction of GI illness due to main breaks or maintenance work was 37%. Chlorination and flushing were found to reduce the risk

Tinker et al. (2009) studied the relationship between the average water residence time in the distribution network and visits to the emergency department for GI illnesses in Atlanta, USA. The residence time was calculated using two hydraulic models from two of the largest utilities that serve the city. The authors found that people living in areas with long residence times ($t \geq$ 90th percentile estimated residence times) were more likely to visit the hospital with GI symptoms than the residents of areas with intermediate (t = 11th to 89th percentile) or short residence times ($t \leq$ 10th percentile) In a subsequent study, Tinker et al. (2010) studied drinking water turbidity and emergency visits for GI illness in the same city and including four more water treatment plants. In this study, no relationship could be found between turbidity after treatment and emergency department visits.

Malm et al. (2013) studied the relationship between disturbances in the drinking water supply system and frequency of calls to report GI to the Health Call Centre in the city of Gothenburg, Sweden. More than 55 000 calls were recorded during the period 2007-2010, of which 13.5% were due to GI. In this study it was concluded that there was no statistically significant variation of calls to report GI during or after disturbances in the distribution system or at the treatment plant.

Säve-Söderbergh et al. (2017a) carried out a study in five Swedish municipalities, of varying sizes, to determine the contribution of incidents in the distribution network to risk of GI. The study took into account demographics, seasonal variation, source water, incidents in the network, mitigation measures performed after the incident. Questionnaires were sent to water suppliers to report incidents where at least 20 households were affected. Households (n = 3238) were interviewed 1-2 weeks after a reported incident to find out if any household member had fallen ill. The authors found an

increased risk for vomiting and acute gastrointestinal illness (AGI) but not for GI. The risk was elevated even after flushing the newly laid pipes.

Economic costs of waterborne diseases

Globally, waterborne GI represents a significant economic and health burden to society. Waterborne disease outbreaks cause considerable losses in productivity and medical costs (Corso et al. 2003; Lindberg et al. 2011; National Research Council 2006; USEPA 2007). Since distribution network deficiencies can lead to waterborne disease outbreaks, a portion of these costs can be directly attributed to these deficiencies.

In two of the outbreaks described in the previous section, their costs associated with them were estimated using different methodologies (see Table 2). Huovinen et al. (2013) calculated the total excess healthcare costs incurred due to the Nokia outbreak in Finland 2007 to be EUR 354 000. Moreover, the indirect costs (i.e., sick leaves and lost workdays) in the public sector alone were estimated to be in the range of EUR 1.8 – 2.1 million (Halonen et al. 2012). The *Salmonella* outbreak in Alamosa, Colorado, USA 2008 was estimated to have caused expenses totalling USD 2.6 million (≈EUR 2.4 million) [range: USD 1.1 – 7.8 million] (Ailes et al. 2013). This amount included healthcare costs, business losses, and outbreak response costs, among others. One unforeseen consequence of the outbreak was the loss of trust among the consumers of the public water supply, though this was not represented monetarily in the cost estimate.

In addition to outbreaks, some authors have tried to monetize the disease burden related to the endemic level of disease. Payment (1997) estimated the annual cost of water related disease in Canada to be in the range of USD 309 – 900 million (≈EUR 330 – 975 million). According to Hunter et al. (2005), the contribution of low-pressure events in the distribution network to the cost of illness in the United Kingdom could be over GBP 100 million [≈EUR 115 million] (15% of the total annual cost of diarrheal disease). Edelstein et al. (2016) estimated the total annual cost for AGI in Sweden to be more than EUR 1 billion (95% CI: EUR 754 – 1 257 million); of which EUR 150 to 400 million could theoretically be associated to distribution network deficiencies (using a range of incidence rates available from studies in Sweden and abroad).

Modelling tools to quantify risk and potential health effects

A wide array of models have been developed to quantify microbial risks in the network, especially pathogen intrusion. CFD models have been developed to more accurately describe intrusion rates in the network (Collins and Boxall 2013; Mansour-Rezaei and Naser 2013; Mora-Rodríguez et al. 2014; Mora-Rodríguez et al. 2012; Yang et al. 2016), and to model intrusion and contaminant transport in the network (Mansour-Rezaei et al. 2013). An extension to the EPANET model, called EPANET-MSX, was developed to simulate the interaction of multiple species in the distribution network

(Shang et al. 2008). The extension allows for more complex scenarios to be evaluated, for example, interaction between pathogen and disinfection residual, biofilms, etc. Recent developments also enable the possibility of modelling multispecies interactions in dynamic hydraulic conditions (Seyoum and Tanyimboh 2017). An extensive review on modelling of contaminant intrusion in the distribution network can be found in Islam et al. (2015).

Additionally, different risk assessment approaches can be used to identify and estimate risk levels in distribution networks. Qualitative assessments, such as sanitary surveys or risk matrixes, require few resources, are simple to use and can provide reasonable estimates of risk. Semi-quantitative assessments, such as more-detailed risk matrixes, can provide more comprehensive assessments of the hazards in the network. Moreover, quantitative methods can be used to explicitly quantify health risks, e.g., in terms of annual risk of infection for consumers (Petterson and Ashbolt, 2016). One of the most used frameworks for quantification of health effects of microbial risks is the quantitative microbial risk assessment (QMRA). This methodology has been used in varying contexts, including North America (Petterson and Ashbolt 2016; Tfaily et al. 2015), Europe (Petterson and Ashbolt 2016; Schijven et al. 2011) and developing regions (Petterson 2016).

A QMRA consists of four basic steps (WHO 2016):

- Problem formulation: the scope and purpose of the assessment is determined at this stage. Hazards, exposure pathways and health outcomes are investigated;
- Exposure assessment includes quantifying pathogen sources, magnitude and frequency of the exposure for the different scenarios being analysed;
- Health effects assessment involves estimating the health impact from the identified hazards and the population of the study (e.g., drinking water consumers);
- Risk characterization combines the exposure and health effects assessments to quantify the risk of infection. This can be represented as number of consumers infected per year, DALYs. A sensitivity analysis can also be performed in this step to determine which parameters influence the most the QMRA results.

It is important to note that in order to perform a valid assessment, uncertainties must be taken into account in each step, otherwise the results will not be representative of reality (Bouwknegt et al. 2014). These uncertainties could be due to different reasons such as: natural variability of pathogen concentrations and limitations in the detection methods (Ramírez-Castillo et al. 2015), water consumption behavior of the population (volume, times, etc.) (Roche et al. 2012), choice of dose-response model (Van Abel et al. 2017), among others.

A QMRA model can be used to estimate the risk of infection after a contamination event in the distribution network, the expected number of illnesses, maximum number of illness existing at a given time and upper confidence intervals for infection risks (Haas et al. 2014). Additionally, other models can be combined with the QMRA to obtain more accurate probabilities of infection, e.g., hydraulic model to simulate transient pressure events, quality models to simulate interaction between disinfection residual and inactivation, among others (Blokker et al. 2014; Teunis et al. 2010b; Yang et al. 2011). Table 3 summarizes the QMRA models done for the distribution network. A conceptual QMRA model for intrusion has been developed (Besner et al. 2011), as well as a simplistic approach for quantifying infection risk for *Legionella* (Storey et al. 2004). Mena et al. (2008) used an experimental study to evaluate the infection risk of a sewage cross-connection and compared it to an actual outbreak case. Brief descriptions of studies performed with QMRA to evaluate the risk of microbial contamination in the distribution network and its consequences are presented in the following paragraphs.

Using faecal indicator information, van Lieverloo et al. (2007) estimated possible pathogen concentrations and calculated the risk of infection to consumers in areas affected by a contamination event. Pathogen to faecal indicator ratios were calculated for three common contamination sources: sewage, surface water and soil/shallow groundwater surrounding the pipes. The authors determined that the risks of infection might be considerable, but were also highly uncertain. This uncertainty limited the applicability of the method using faecal indicators to estimate infection risks during contamination events.

Teunis et al. (2010b) studied the health effects of virus intrusion in the distribution network. A combination of Monte Carlo simulations for initial virus concentrations, hydraulic modelling of water flow and contaminant transport, and dose-response model were used for estimating the infection risk. The most influential parameters in this model were the combination of a pressure event occurring simultaneously as the user consuming water. Another important parameter was the duration of the pressure transient event.

Yang et al. (2011) evaluated the different factors influencing the risk of norovirus infection from a pressure transient event to propose mitigation strategies to address this risk. The factors considered in this study included virus concentrations located in the vicinity of the distribution pipes, presence of a disinfectant residual, the sizes of the leak orifices, the duration and the number of nodes drawing negative pressures. In their model, the most sensitive factor was the duration of the negative pressure. Therefore, the most important risk mitigation strategy would be an optimized pressure management to control negative pressure transients. Additional measures that were beneficial to reduce the risk of infection included maintaining free chlorine residual of at least 0.2 mg/l and prioritizing cross connection and leak detection in vulnerable areas.

Blokker et al. (2014) used a QMRA model, coupled with a hydraulic model, to estimate the risk of infection after a main break repair. Previously, the model was used to calculate the risk of enteric virus infection during an intrusion event (Teunis et al. 2010b; Yang et al. 2011). However, the assumption that the tap water consumers consumed the full volume of water in a single instance was modified to include ingestions at different times during the day. The authors concluded that the infection rate was highly influenced by the initial concentration of the contamination; and to a lesser extent, but still relevant, by the time of consumption.

A more detailed main break repair scenario and evaluation of mitigation measures was done subsequently by Yang et al. (2015) and Blokker et al. (2018). Yang et al. (2015) used a simplified version of an intrusion model developed previously (Teunis et al. 2010b) to investigate the effect of flushing and disinfection after repairing a water main. This study found that virus was the pathogen group with highest infection risk after a main break, and that a combination of flushing and disinfection (free chlorine) would be needed to achieve an acceptable risk level (according to National Research Council (2006) this would be equal to an infection risk of to 1 x 10^{-4}).

Discussion

Waterborne Disease Outbreaks

Outbreak investigations have methodological limitations which can influence or limit the usefulness of the results (Hrudey and Hrudey 2007). One of these limitations is related to finding evidence of the relationship between drinking water and disease. Using the level of strength of epidemiological and microbiological evidence, Schuster et al. (2005) categorized Canadian waterborne outbreaks in: definitely waterborne, probably waterborne and possibly waterborne. Of the 99 outbreaks in public water systems identified in this study, 40% did not have adequate epidemiological proof for being the cause of the outbreak. For semi-public and private systems, the proportion without adequate evidence was higher (80% and 76% respectively). Using a similar three-tier classification scheme proposed by Tillett et al. (1998), only 18% of the outbreaks in the Nordic countries could be strongly associated to drinking water, while the same proportion had no known level of association (Guzman-Herrador et al. 2015). Most of the outbreaks in the unknown category had a small number of cases reported. This reflects the limitations of outbreak investigations to find conclusive proof of the contribution of the contamination event in the water supply system to the outbreak, especially when the size of the outbreak is not large enough. Furthermore, Craun and Frost (2002) found evidence of bias during an outbreak investigation, which led to a misclassification of the association between drinking water and disease. The circumstances for the misclassification were not unique to this outbreak investigation; hence, health officials conducting studies during an outbreak should be aware of possible issues that could affect their results, e.g., range of the confidence interval for associations and statistical

significance, recall bias of questionnaires and effect of the publicity of the outbreak in the population (Craun et al. 2001). Taking these measures into account, in turn, could lead to more reliable results from outbreak investigations.

Endemic Level of Gastrointestinal Illness

As previously mentioned, the results from studies linking distribution network deficiencies to endemic level of GI have had mixed results. The cause for the conflicting results reached in these studies has not been conclusively established (National Research Council 2006). Most studies do not have enough information on the drinking water systems to determine the exact causes for an increase in the risk of GI. Sinclair and Fairley (2000) recommended precaution when interpreting results from epidemiological studies due to their methodological limitations. Bylund et al. (2017) found that many epidemiological studies lack statistical robustness and local variations between the systems studied hinder generalizing the results. Nonetheless, recent evidence suggests that malfunctioning distribution networks, as well as specific system deficiencies (i.e., pipe breaks, water outages and inadequate residual disinfectant), increase the risk of endemic GI (Ercumen et al. 2014). Providing more detailed descriptions of system parameters (e.g., extent of leaks and cracks, better characterization of the faecal contamination surrounding the pipes, etc.) could improve the interpretation and comparison of the results in the future studies. Additionally, Payment et al. (1997) was the only study to distinguish the effect of contamination in the distribution network on GI incidence from other sources of contamination at the source or treatment plant. Using similar design methods could also improve the interpretation of future studies.

QMRA model

QMRA models have been used by water suppliers to perform risk assessments for their raw water source and treatment plants (Petterson and Ashbolt 2016; Schijven et al. 2011). For example, QMRA was used to evaluate the performance of 17 water treatment plants in Canada, calculating risk estimates using different approaches (Tfaily et al. 2015). So far, QMRA models used by water suppliers at a water supply system level do not include the distribution network. The models presented in the previous section could be seen as first attempts at bridging this gap. The following section will highlight important limitations that restrict their current applicability.

A thorough description of the parameters used to create a QMRA model, the assumptions made for each and limitations to take into account, is available in Besner et al. (2011). This conceptual model has been developed specifically for intrusion, nonetheless, the limitations presented are valid for other microbial risk models that use similar parameters for their risk estimations. One common assumption for calculating intrusion volumes is the use of the orifice equation ($Q = \frac{\pi}{4} C_d d^2 \sqrt{2g\Delta H}$; where Q is the intrusion volume, C_d is the discharge coefficient, d is the orifice diameter, g is the gravitational acceleration and ΔH is the difference between external and internal pressure head). A limitation of this

equation is that it does not take into account the soil media surrounding the pipes (Yang et al. 2014; Yang et al. 2016). Experimental tests for intrusion reported that the volume of soil water intrusion would be lower than the estimated with the orifice equation; this equation would provide an estimate of the maximum volume of intrusion (Collins and Boxall 2013; Fox et al. 2016). Hence, the risk of exposure due to intrusion would most likely be lower than the models' predictions.

Dose-response models are currently available for relevant waterborne pathogens: *Campylobacter* (Teunis et al. 2005; Teunis et al. 1999); *Salmonella* (Teunis et al. 1999; Teunis et al. 2010a); *E. coli O157:H7* (Teunis et al. 2004; Teunis et al. 2008b); adenovirus (Teunis et al. 2016); norovirus (Messner et al. 2014; Teunis et al. 2008a); *Cryptosporidium* (Teunis et al. 1999; Teunis et al. 2002); and *Giardia* (Teunis et al. 1996; Zmirou-Navier et al. 2006). These models have mainly been developed using healthy, adult individuals; which might underrepresent the risk of infection in a population with more susceptible individuals (i.e., children, elderly, pregnant women and immunocompromised individuals) (Gerba et al. 1996; Nwachuku and Gerba 2004). Choosing the appropriate dose-response model will also have an impact in the risk estimate calculated with QMRA (Van Abel et al. 2017). Therefore, careful considerations are necessary when deciding which dose-response models to use and the implications carried.

Another assumption in QMRA models is the consumption pattern of individuals (Hynds et al. 2012; Roche et al. 2012; Säve-Söderbergh et al. 2017b; Van Abel et al. 2014). Some models assume the person consumes water once per day (Teunis et al. 2010b; Yang et al. 2011). However, it has been shown that the probability of infection is higher if the consumption pattern is modified to include the possibility of consuming water at different times throughout the day (Van Abel et al. 2014). This has been addressed in the model used by Blokker et al. (2018); although it could also be relevant to consider consumption of alternative water sources when carrying out risk assessments (Jones et al. 2007; Roche et al. 2012). An additional layer of simulation could be considered for the consumption pattern: the impact on consumption due to alerts issued by water suppliers during a contamination event (Zechman 2011). Changes in the consumer demand could affect the hydraulic conditions in the distribution network, influencing the contaminant transport inside the system and, hence, the exposure to the contaminant (Rasekh et al. 2014; Shafiee and Zechman 2013). On the other hand, QMRA models are already quite complex, requiring a large amounts of input data with limited availability. Therefore, adding another layer of complexity seems excessive at this stage of development of distribution network QMRA models. Nevertheless, it could be useful to consider after a mature version of a QMRA tool for the distribution network exists.

Microbial risks in the distribution network

Knowledge about the distinct microbial risks in the distribution network are at different levels of certainty, with research on intrusion being carried out extensively compared to other risks. Potential sources of contamination surrounding the pipe network have been characterized to some extent (Besner et al. 2010; Karim et al. 2003); yet these characterization studies have only been carried out in North America. Pressure monitoring of distribution networks using pressure loggers have recorded adverse pressure events in the system (Besner et al. 2010; Gullick et al. 2005; Gullick et al. 2004). Recent experiments have studied contaminant intrusion during a pressure transient in a laboratory setting (Fontanazza et al. 2015; Fox et al. 2014; Fox et al. 2016). These experiments have confirmed long-held views about the risk of intrusion into the distribution network during adverse pressure conditions. On the other hand, the level of association of biofilms to waterborne disease and its role harbouring pathogens after a contamination event (e.g., intrusion) is not well-understood (Fox et al. 2016; Messner et al. 2006) and must be addressed in future research. This could be especially significant during waterborne outbreak crises, since abnormally large amount of pathogens are present for some duration of time in the system.

Studies such as Nygard et al. (2007) and Van Abel (2014) are helpful in informing the estimation of risk associated with the distribution network and ageing infrastructure. However, more work is needed to better characterize the distribution network risk. There is minimal data on the prevalence of enteric pathogens in water sources, which is essential to carry out a QMRA (Murphy et al. 2014). Improved modelling capabilities, such as the creation of better water quality models (Yang and Boccelli 2016), represent an opportunity to increase the usefulness of the models as decision support tools.

Events in the distribution network can represent a health risk to consumers to varying degrees. Most of the health risks associated with deficiencies in the system can be controlled if proper management of the network is carried out. Hence, health risks to the consumers can be minimized by implementing appropriate methods of risk management, such as Water Safety Plans (Dunn et al. 2014; WHO 2011, 2014) or control strategies for the distribution network (Kirmeyer et al. 2014). Adapting methods from other risk schemes could also prove beneficial in mitigating microbial risks in the distribution network, e.g., risk-based economic decision model (Bergion et al. 2018); sociotechnical risk assessments (Busby et al. 2016; Rasekh and Brumbelow 2014; Rasekh et al. 2014; Shafiee and Berglund 2017; Shafiee and Zechman 2013; Vicente and Christoffersen 2006; Woo and Vicente 2003).

McInnis (2004) and Teunis et al. (2010b) developed similar risk-based frameworks to evaluate the risk reduction for intrusion achieved by implementing different mitigation measures. This was also done for main breaks and repairs

(Blokker et al. 2018; Yang et al. 2015) These types of frameworks can be useful to aid water supply operators in managing their networks and can be used to complement WSPs. However, information about the economic aspect of risk-reducing measures is needed if the QMRA framework is to be implemented in a strategic renewal planning context.

Conclusion

Epidemiological investigations have shown that the distribution network can cause waterborne outbreaks and, in some respect, indicate a contribution to the endemic level of disease in the population. To complement epidemiological data, models can be used to estimate site-specific risks. QMRA models have been developed to calculate risk estimates for specific distribution networks; hence, they can be used to aid water suppliers in areas such as renewal planning and normal operation of their network. In order to develop a comprehensive microbial risk management framework, limitations of QMRA models need to be addressed with better input data and increased understanding of other microbial risks, e.g., role of biofilms during a waterborne outbreak. Additionally, monetization of health effects is crucial, where QMRA can be very useful for decision support in the management of distribution networks.

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Table 1. Selected epidemiological studies that have addressed the contribution of tap water to endemic level of disease.

Study	Location	Study design	Blinding	Size of the study*	Follow-up period	Results†	Attributable Risk
Payment et al (1991)	Canada	Cluster Randomized Controlled Trial	No	607 / 2 408	12 months	IRR = 1.5 (p <0.01)	≈35% excess GI in the tap water group compared to control
Payment et al (1997)	Canada	Cluster Randomized Controlled Trial	No	1 369 / 5 253	16 months	IRR = 1.15 (p <0.01)	14% - 19% excess risk of GI; 17% - 40% in children 2-5 years old
Hellard et al (2001)	Australia	Cluster Randomized Controlled Trial	Yes	600 / 2 811	12 months	IRR = 0.99 [0.85 - 1.10]	No association found
Nygård et al (2004)	Sweden	Ecological	n.a.	-- / 7 280	n.a.	1. IRR = 1.11 [1.08 – 1.15] 2. IRR = 1.12 [1.08 – 1.16] 3. IRR = 1.13 [1.09 – 1.17]‡	Significant association of length of pipe directly proportional to increased risk of infection
Colford et al (2005)	United States	Cluster Randomized Controlled Trial	Yes	456 / 1 296	12 months	IRR = 0.98 [0.87-1.10]	No association found
Hunter et al (2005)	United Kingdom	Case-control	n.a.	-- / 427	n.a.	OR = 12.5 [3.5 - 44.7]	Significant association between low pressure event and disease (p <0.01)
Nygård et al (2007)	Norway	Cohort	n.a.	1 159 / --	n.a.	IRR = 1.58 [1.1 - 2.3]	Attributable fraction of 37% one week after exposure
Tinker et al. (2009)§	United States	Ecological	n.a.	-- / 1 700 000	n.a.	1. OR = 1.00 [0.96 - 1.03] 2. OR = 0.99 [0.96 - 1.03] 3. OR = 1.07 [1.03 - 1.10] 4. OR = 1.05 [1.02 - 1.08]‖	Slight association directly proportional to the residence time and increased risk of disease
Malm et al (2013)	Sweden	Ecological	n.a.	-- / 500 000	n.a.	SIR = 1.08 [0.86 - 1.32]	No association found due to low pressure events
Säve-Söderbergh et al. (2017a)	Sweden	Cohort	n.a.	3 238 / 7431	n.a.	GI: OR = 1.1 [0.9 - 1.5] AGI: OR = 2.0 [1.2 – 3.3] Vomiting: OR = 1.9 [1.2 – 3.0]	Significant association for AGI and vomiting

*Sample size is given by No. of households / No. of individuals
†IRR: Incidence Risk Ratio. OR: Odds Ratio. SIR: Standardized Infection Ratio.

‡Result 1 is from univariate analysis; results 2 and 3 are from multivariate analyses
§Included more water suppliers in a subsequent study Tinker et al. 2010
‖(1)OR between intermediate and short residence times and utility 1, (2) OR between intermediate and short residence times and utility 2, (3) OR between intermediate and long residence times and utility 1, (4) OR between intermediate and long residence times and utility 2

Table 2. Economic costs of waterborne disease outbreaks associated to the distribution network.

Study	Outbreak location, year	No. of cases	Total Economic cost of outbreak [MEUR]	Cost of outbreak per person infected [EUR/person]	Economic impact assessed
Halonen et al, 2012; Huovinen et al, 2013	Nokia, Finland 2007	6 500	2.3 [2.15 – 2.45]	354 (331 – 377)	Total excess healthcare costs, in addition to sick leaves and lost workdays
Ailes et al, 2013	Alamosa, Colorado 2008	440	2.3 [1.03 – 7.28]	5 227 (2 341 – 16 546)	Healthcare costs, lost productivity, business losses, outbreak response costs

Table 3. QMRA performed for distribution networks

Study	Network site	Risk event	Pathogen	Methodology
McInnis 2004	City in North America	Intrusion	Giardia, faecal streptococci	QMRA coupled with hydraulic modelling. QMRA modelling
Storey et al. 2004	Sweden	Biofilm	Legionella	Detachment of Legionella was determined experimentally, as well as disinfection data. Monte Carlo simulations were used for risk characterization
van Lieverloo et al. 2007	Netherlands	Multiple contamination events	Giardia, Campylobacter, Cryptosporidium and enterovirus	QMRA coupled with hydraulic modelling. QMRA coupled with hydraulic modelling.
Mena et al. 2008	United States	Cross-connection	Salmonella	Used a distribution network simulator to estimate transport of contaminated water and Monte Carlo simulations for risk characterization
Teunis et al. 2010b*	United States	Intrusion	Rotavirus, norovirus	QMRA coupled with hydraulic modelling. Used commercial software to do surge modelling, EPANET-MSX for water quality modelling coupled with Monte Carlo simulations for risk characterization
Blokker et al. 2018†	Netherlands	Main repair	Giardia, Campylobacter, Cryptosporidium and enterovirus	QMRA coupled with hydraulic modelling. Used EPANET to simulate transport of contaminated water, SIMDEUM for consumption patterns, and Monte Carlo simulations for risk characterization
Yang et al. 2015	United States	Main repair	Norovirus, E. coli O157, Cryptosporidium	QMRA coupled with hydraulic modelling. Simplified model from Teunis et al. 2010b

*Complemented by Yang et al 2011.
†Originally developed in Blokker et al. 2014