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Safe distribution without a disinfectant residual

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5.1 INTRODUCTION

5.1.1 Safe distribution of water: to disinfect or not to disinfect?

Drinking water is transported from the treatment works to the consumers’ tap in a distribution network of pipes and reservoirs. In situations with high raw water quality and/or extensive multiple barrier treatment to produce high quality drinking water, this water should maintain its’ high quality during transport.

Microorganisms and microorganism associated processes in the network can affect water quality:
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- Ingress of pathogenic microbes due to loss of physical and hydraulical integrity of the network and the presence of a nearby contamination source (such as sewer lines);
- Growth of microorganisms in the distribution network, some of which may be opportunistic pathogens, such as *Legionella pneumophila*, non-tuberculous mycobacteria, *Pseudomonas aeruginosa*, *Acanthamoeba*, *Naegleria fowleri* and others.

These issues not only affect water quality but may also pose a health risk to the consumer. In addition, growth of non-pathogenic microorganisms can lead to (see chapter 1):
- non-compliance with water quality standards for total coliforms, heterotrophic plate counts;
- esthetical issues such as presence of invertebrates and taste and odour problems;
- corrosion of pipe materials.

In affluent nations, there are two principal approaches to control the microbial water quality in the distribution network. The first approach is to maintain a disinfectant residual in the water during distribution to provide a barrier against ingress of microbial contaminants and limit microbial growth. The second approach is to control the risk of ingress through strict maintenance of the physical and hydraulic integrity of the network and to control the growth of microbes by distributing biologically stable water and using materials that do not leach nutrients. In the latter approach, drinking water is distributed without the presence of a disinfectant residual. This approach is found in some European countries, the former in most of the other affluent nations.

The different approaches have been the subject of debate that amalgamated in the late nineties (Trussel, 1999, van der Kooij et al 1999a, 1999b, Haas, 1999, LeChevallier, 1999). In these debates, arguments pro and con distribution with a disinfectant residual are highlighted. The most important arguments for the use of a disinfectant residual are:
- The presence of a residual disinfectant reduces the risk of microbial contaminants that may enter the distribution network. With the increasing complexity of the distribution network, the costs of the network and the open nature and aging of the infrastructure a residual disinfectant is necessary to inactivate microbial pathogens that may enter the network through cross-connections, mains breaks, repairs and leaks. Also for smaller systems with limited resources, a disinfectant residual is a relatively simple and cheap solution to improve the microbial safety.
- The presence of a residual disinfectant controls the growth of microorganisms in the network. It limits non-compliance with microbial water quality standards such as total coliforms and heterotrophic plate counts.
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counts. It is also argued that limiting the amount of nutrients in the water and materials is difficult and would require substantial investments in additional treatment (LeChevallier, 1999) and focus on carbon-sources alone may not be enough (Haas, 1999). Also, most networks now in use have been installed in the past decades with the materials of that time and a control strategy should also consider this situation.

- The presence of a residual disinfectant may serve as sentinel for a breach of integrity of the system. When a distribution network is monitored with a consistent sampling strategy (or even on-line sensors) a reduced disinfectant residual concentration may signal that a contamination event has occurred.

The most important arguments against the use of a disinfectant residual are:

- Disinfectants react with organic and inorganic compounds in the water and this creates disinfection by-products (DBP) in small quantities. DBP formation depends on many factors, but DBP such as trihalomethanes (THM) are found in the vast majority of cases of chlorination. More than 600 DBP have been identified (Richardson et al., 2008). Several (groups of) by-products have been associated with illnesses in humans. Some of the DBP (bromate, NDMA, benzaldehyde) show carcinogenic activity in long-term animal studies and several others are classified as possible carcinogens. A large body of epidemiological literature is accumulated over the years and meta-analyses have been conducted to assess the health risk of DBP. Lifetime exposure to chlorinated drinking water is associated with bladder cancer with a risk level of approximately 1 in 1000 (Hrudey & Charrois, 2012). For colon and rectal cancer and also for reproductive health outcomes results are less univocal. A recent review (Nieuwenhuijsen, 2009) indicated that there appears to be some evidence for an association between exposure to DBPs, specifically THMs, and congenital health, particularly in relation to the health effects little for gestational age/intrauterine growth retardation and, to a lesser extent, pre-term delivery, but evidence for relationships with other outcomes such as low birth weight, stillbirth, congenital anomalies and semen quality is inconclusive and inconsistent.

- The reaction of disinfectants with organic compounds in the water may also yield compounds, such as halogenated phenols and anisoles that give rise to taste and odour complaints by consumers. Taste and odour complaints are the most frequent cause of consumer complaints and consumers have a negative opinion about chlorinous taste and odour, both in terms of aesthetics and safety (Crozes et al., 2007).

- The sensitivity of pathogens to the disinfectants used in the network differs. The disinfectants used are effective against bacterial pathogens, less so against viruses and even less so against parasitic protozoa (Payment, 1999,
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EPA, 2012). Chlorine and chloramine are not effective against Cryptosporidium. (LeChevallier & Au, 2004).
- The use of a disinfectant residual may mask the failure of the integrity of the system and ingress of microbial contamination (Craun & Calderon, 2001). Water quality testing for coliforms or E. coli that are very sensitive to chlorine may indicate that the water is not contaminated, while infectious pathogens that are more resistant may be present in the water. This is of particular importance in samples taken after repairs and maintenance.
- Disinfectant residuals are not very effective against microbes in biofilms on pipe walls or sediment. The disinfectants react with the biofilm matrix but do not reach the microbes (LeChevallier et al., 1988). Also microbes in biofilm particles that slough of the wall and enter the bulk water again are more difficult to reach and inactivate (Behnke et al., 2011).
- Disinfection is targeting the symptoms rather than the cause of the microbiological issues in the network. The cause of ingress is insufficient hydraulic and structural integrity and hygiene. The cause of biofilm formation is the quality of the treated water and the materials used in the network. Targeting the cause is more effective and is also not sensitive to failures in the disinfection.
- In many settings, disinfectant residuals are not maintained throughout the entire network. That means that only a part of the network and consumers is protected by the presence of a residual and part is not (Payment, 1999, Gauthier et al., 2001). In such settings, disinfectant residuals may even enhance regrowth as they react with the organic compounds in the water and produce compounds that are more readily biodegradable (Skadsen, 1993; Zang and DiGiano, 2002).
- The use of toxic chemicals such as chlorine and chlorine dioxide requires production and may require transportation of these chemicals with a risk of accidents and spills.

Looking at the pros and cons there is no simple answer to the question whether a disinfectant residual in the distribution network is necessary/beneficial for health and a wholesome drinking water quality. The answer certainly depends on the context, such as the quality of the water entering the network, hydraulic and structural integrity of the network and the ability to apply proper hygiene. In the context of drinking water supply in the Netherlands, the answer is no. The next paragraphs describe the history and rationale of this answer and the consequences for safeguarding drinking water safety, with the emphasis on protection of the distribution network against ingress of faecal contamination. Protection against regrowth is discussed in other chapters in this book.
5.1.2 The road to distribution without disinfectant residual in the Netherlands

In the 1970’s, chlorination was applied in the Netherlands, particularly in surface water treatment. After the discovery of DBP of chlorination in the water of Rotterdam Water Works (Rook, 1974, Bellar et al., 1974), a significant effort started to reduce the use of chlorine in water treatment. The reduction of chlorine use or replacement of chlorine was promoted: “the amount of chlorine to be added should, however, not be more than is absolutely necessary” (Kiwa, 1978), but not without recognizing the significance of disinfection for public health “until...techniques have been found to be at least equivalent to chlorination, chlorine must from a public health viewpoint continue to be used as a disinfectant for potable water". In the late seventies, the amount of chlorine used in water treatment in the Netherlands was reduced significantly by limiting break-point chlorination and transport chlorination at low temperatures and using lower doses in summer (Kruithof, 1986a,b). Also, post-treatment disinfection was re-examined and was shown to be an important contributor to the presence of THMs in the network. Given the suggested relation between by-products of chlorination and several types of cancer and the observed mutagenicity (as seen with the Ames-test) of the water, it was recommended to reduce post-chlorination as much as possible. This meant in several water supplies that the residual was present only in the first part of the distribution network. The residual disappeared due to reaction of the disinfectant with reducing compounds in the water, biofilm, sediment and piping materials and no residual was present in the largest and more distant part of the network.

As an example, Amsterdam Water Supply started a full scale experiment in 1983 to reduce the chlorine dose stepwise and monitor what happened to the water quality in the distribution network (Schellart, 1986). It turned out that when the chlorine was reduced to zero, the mutagenicity (Ames-test) of the water disappeared, total trihalomethanes were reduced from 12-22 µg/l to below the detection limit, no coliforms or enterococci were detected in the network (before and after stopping the chlorine dosing), the heterotrophic plate counts remained as low as they were (2-5/ml) and the assimilable organic carbon (AOC) content of the finished water was reduced with 40% (Schellart, 1986). So the chlorine dosing was stopped permanently (it was kept standby for emergency disinfection). Similar developments were seen at the other surface water utilities that used a chlorine residual. And even though the concentrations of chlorination by-products were below the 10⁻⁶ lifetime cancer risk level, the utilities abandoned the use of post-chlorination (van Genderen, 1998).
In the 1990’s, disinfection of surface water with chlorine was replaced in the Netherlands by ozone or membrane filtration as primary barrier to pathogens, except for two water treatment plants. By 2006, these two chlorine-based disinfection plants changed to UV for primary disinfection, so chlorine is no longer used in water treatment in the Netherlands any longer. Important arguments for abandoning chlorine also from water treatment were: prevent DBP formation, improve taste and odour and hence consumer satisfaction, and apply sufficient disinfection, particularly of Cryptosporidium.

Today, there are two surface water utilities that use low doses of chlorine dioxide as post disinfection; not to create a residual in the network but to inactivate heterotrophic bacteria that may grow in activated carbon or sand filters in periods when the water temperature is high. In several other surface water, bank filtration and groundwater systems, UV is used for this purpose.

The Netherlands is not unique in the distribution of water without a disinfectant residual. Denmark and areas in other Nordic countries, areas of Germany (Hambsch, 1998), Luxembourg and Switzerland (Klein & Foster, 1998) distribute water without chlorination. These countries, and the EU, have no legal requirement for maintaining a disinfectant residual. Standards occur for microbial water quality and the owner of the network is obliged to ensure that the water meets these standards (with or without disinfectant residual).

5.1.3 Microbial safety in water legislation in the Netherlands

Water legislation in the Netherlands has adopted Quantitative Microbial Risk Assessment as the central approach to demonstrate the microbial safety of (surface) water supply systems (Anon, 2001, 2011). Water utilities have to monitor the presence of reference pathogens (Campylobacter, Cryptosporidium, Giardia, culturable Enteroviruses) in the source water and demonstrate the adequacy of the treatment processes to remove these pathogens to produce drinking water that has a quality that corresponds with a probability of infection of less than 1 in 10,000 persons per year. Although not identified specifically in the legislation, maintaining this high quality through the distribution network implies the same safety level applies to the water delivered to the consumer.

5.2 Good engineering practice

Good practices in construction, operation and maintenance of distribution networks is of paramount importance in protecting the water quality, both with and without a disinfectant residual in the network. When the network is in good condition and actively managed, this creates the proper conditions to consider distributing water without disinfectant residual.

The basic elements are:
Physical integrity. The physical integrity prevents ingress in places or times where the hydraulic pressure is low or absent. Physical integrity is particularly important in places such as reservoirs that are not pressurized. The Netherlands has a very low leakage rate, generally <3% (Beuken et al., 2006). Compared to leakage rates in other European countries this is very low (Figure 5.1) and a comparative study identified several factors that contribute to this (UKWIR, 2006). The pressure in the network can be relatively low due to the flat terrain and high buildings are equipped with their own pump. The majority of the network is relatively young and produced of PVC with relatively few joints and connections. Like many affluent nations, the Netherlands is facing ageing networks and need to actively assess and manage network condition and integrity to prevent leakage and ingress.

Hydraulic integrity. Continuous maintenance of sufficiently high pressure in the network to prevent contaminants entering the network is required. Pressure fluctuations and surges are minimized by variable pumps, pressure dampening devices, valve closure procedures, automated distribution control to prevent large flow fluctuations and pressure zoning in (the few) hilly areas (Smeets et al., 2009).
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- Protection against backflow. Use of break tanks before larger user-installations (industries, hospitals) and the use of backflow preventers in the water meters of house connections, where >96% of the connections are metered.
- Strict hygiene during construction and maintenance. A national hygiene code was developed by the water utilities (Nobel, 2001, van Lieverloo et al., 2002). Since then, this has become part of the quality assurance systems of the water utilities. It has recently been updated (Meerkerk & Kroesbergen, 2010) and has become an integral part of the Dutch drinking water legislation. The code lays down the principles of good hygiene during construction and maintenance and describes control measures for safe storage of materials, inspections, cleaning and disinfection of materials and pipes after construction or repair, personal hygiene and use of appliances such as fire hydrants. Also training, supervision and water quality monitoring to verify the efficacy of the hygiene code is described.
- Approval system for materials and valves and hydrants. Certification of materials and appendages that are to be used in distribution networks has been developed since the start of Kiwa in 1948. All materials have to be approved according to the national acceptance scheme.

5.3 Evidence of safe distribution without disinfectant residual

Noblesse oblige; with the absence of a disinfectant residual the water utilities have one barrier less in the distribution system and are obliged to ensure that the other barriers are in place and effective. Recognizing the difference in approach to safe distribution in the Netherlands and the United Kingdom, a collaborative research project was conducted around 2000 to evaluate the knowledge on distribution of drinking water with or without a disinfectant residual (van der Kooij et al., 2002). Both countries show a high compliance with microbial water quality standards and recognize that good engineering practice is the principal factor in protecting the distribution system against ingress. A chlorine residual appears to be a cheap way to reduce regrowth, but increases DBPs and taste and odour complaints. The UK-NL study indicated that a chlorine residual may offer at least some protection against faecal contamination of the network.

In the past decade, concerns were raised in North America and Europe over distribution system contaminations as a result of cross connections, pressure transients and maintenance works and the association with illness (Payment et al., 1991, 1997, Craun & Calderon, 2001, Karim et al., 2003, Hunter et al., 2005, Nygard et al., 2007, Besner et al., 2011, LeChevallier et al., 2011). In the joint research program of the water utilities in the Netherlands (BTO), research
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projects focused on the evaluation of the evidence that distribution without disinfectant residual offers sufficient protection against ingress of pathogens. The next paragraphs present the evidence coming from surveillance of waterborne outbreaks of disease, contamination events registered by the water utilities, water quality monitoring and operational monitoring.

5.3.1 Evidence from waterborne outbreaks

In affluent nations, outbreaks of waterborne illness are our main source of information about the burden of disease via community water supply, even though they are difficult to detect (Hunter et al., 2001). The difficulty to detect waterborne outbreaks means that the information we collect from outbreaks is an underestimation of the actual number of waterborne disease outbreaks (Ford, 1999). Moreover, sporadic cases are thought to represent a larger proportion of waterborne disease than cases related to outbreaks (Nichols, 2003) but go largely unnoticed. Such sporadic cases may be particularly the result of local contamination events in the distribution network. So, our picture is incomplete, but what is evident from outbreaks in public supplies is that harmful pathogens may spread to a large body of consumers resulting in substantial economic and health-related costs. This is illustrated by the April 1993 Cryptosporidium outbreak in Milwaukee (Mackenzie et al., 1994), where around 403,000 people suffered illness, 4,400 people were hospitalised and around 100 people died. Even though these figures have been disputed by others (Hunter and Syed, 2001), it is clear from this and many other outbreaks that the health and economic consequences can be large.

Outbreaks do not only show that the impact can be substantial, but also inform the water and health community about the events, faults and circumstances, alone or in combination, that may lead to an outbreak. The next paragraph is a brief literature review about outbreaks that were caused by an event in the distribution network, to indicate the relative significance of the network and the causes of contamination events that have been implicated in outbreaks.

Hunter (1997) reported that 15 of the 57 outbreaks in public water supplies in the UK between 1911 and 1995 were associated with contamination within the distribution network. In the Nordic countries, 18-20% of the outbreaks through drinking-water between 1975 and 1991 were associated with cross connections, both in community and private supplies (Stenström et al., 1994). In the European project MICRORISK, outbreaks through public water supplies in Europe between 1990-2004 were reviewed and subjected to a fault tree analysis (Risebro et al., 2007). 86 outbreaks were reported, with a total of 72,546 cases,
of which 341 were hospitalised and 1 died. In 33% of these outbreaks, contamination during distribution was the dominant cause of the outbreak. The fault tree analysis showed that distribution system events were usually solitary events, i.e. without a related event in source or treatment. Events that have contributed to outbreaks through contamination of distribution networks were:
- cross connections/backflow
- construction or repair
- damaged/old mains
- low pressure
- cleaning of mains
- reservoir contamination

In the USA, 671 outbreaks reported in community water supplies from 1971 to 2002 were associated to distribution system deficiencies (Craun et al., 2006). Data on incidents collected by the USEPA suggest that this is an underestimation of the actual number of identified outbreaks by a factor of 3 – 4 (Reynolds et al., 2008). Figure 5.2 illustrates the type of deficiencies that were identified as cause of the contamination.

The proportion of outbreaks associated with treatment deficiencies has declined over the years, and the deficiencies in the distribution network seem to be a proportionally increasing cause of waterborne outbreaks. From 1991-2000, 25% of the outbreaks were related to a contamination in the distribution system or in household plumbing. In the period 1920-1990, this was 11-18% (Craun & Calderon, 2001). This increase of distribution deficiencies may be associated
with aging distribution networks. Why didn’t the presence of a chlorine residual prevent these outbreaks? This is largely unknown. What is suggested (Craun et al., 2006) is that many pathogens associated to these outbreaks are not likely to be killed by the low level of disinfectant residual in the network. Another trend in the US that was associated with distribution-associated outbreaks was that they affect more people than other deficiencies.

From the review of outbreaks through community drinking water supplies (Hrudey & Hrudey, 2004) it is clear that in many distribution-related outbreaks, lack of or non-compliance to adequate hygiene procedures to maintain the integrity of the network or to ensure safety during and after breaks and repairs have led to gross contamination of mains water which resulted in people falling ill and even to fatalities, such as in the Cabool and Gideon outbreaks in Missouri, USA. Hrudey & Hrudey (2004) state: “many of the most troubling cases have revealed no effort whatsoever at assuring distribution system integrity”. In other cases, outbreaks resulted from cross-connections or open connections with contamination sources.

In the Netherlands, three outbreaks of waterborne diseases have been reported since 1945. All these three outbreaks connected to contamination of drinking water in the distribution network. Six cases of typhoid in Amsterdam occurred in 1962, possibly due to sewage contamination of the drinking water network. In 1981, 609 cases of enteric disease of multiple aetiology were reported because of waste water inflow from a marine vessel by a cross connection with the drinking water network in Rotterdam (Huisman and Nobel, 1981). At that time, water was still distributed with a (low) disinfectant residual. In 2001 an outbreak of gastroenteritis, with approx. 500 people experiencing symptoms, occurred due to a cross-connection in a dual reticulation system between a “household water” (partially treated river water) pipe and the drinking water network (both without residual disinfectant) (Fernandes et al., 2007; Van Lieverloo et al., 2007b). Because of this outbreak, the use of dual reticulation systems was largely banned in the Netherlands.

Comparing the documented outbreaks in the Netherlands and the United States indicates that the number of outbreaks and disease cases in The Netherlands is low: in the period 1971-2002 there were 671 community water supply outbreaks in the US (roughly 22 outbreaks per year or 0.08 outbreaks per million consumers per year), compared to 2 (1 every 15 years or 0.004 outbreaks per million people per year) in The Netherlands. In Europe 86 outbreaks were recorded (roughly 6 per year or 0.01 outbreaks per million consumers per year) from 1990-2004. Though many differences in water supply and surveillance system make a direct comparison difficult, the outbreak
statistics certainly do not suggest that distribution of drinking water without a disinfectant residual increases the risk of a waterborne outbreak.

### 5.3.2 Evidence from contamination events

Outbreaks are the tip of the iceberg of contamination events (Craun et al., 2006) that may lead to illness among exposed consumers. Operational data from water utilities may provide a more extensive picture of contamination events that occur in the distribution network. The absence of a registered outbreak of disease cases in these contamination events does not mean that no disease cases occurred. Health surveillance is not very sensitive in picking up waterborne outbreaks of intestinal illness.

Westrell et al. (2004) used operator logs of the Gothenburg water utility to estimate the frequency and magnitude of contamination events in the distribution network. Failures in the distribution system were derived from the incidence reports between 1980 and 2000 and personnel interviews. In a few events, cross-connections with pressurised sewage pipes were detected as the cause of the contamination, but for contamination events in the periphery of the distribution system or in reservoirs, no information of the contamination source was recorded. The events in the periphery and reservoirs were caused by leakage through cracks in concrete reservoir walls or through damage during maintenance of the network.
Figure 5.3. Duration of 50 faecal contamination events reported in the Netherlands from 1994 through 2003. The start was defined as the first day that faecal indicator bacteria were detected (from detection to end) or the day the suspected cause of the event occurred (from cause to detection). The end of the event was the second day when no indicator bacteria were detected anymore in 100 ml samples. From Van Lieverloo et al., 2007b.

Figure 5.4. *E. coli* concentrations per 100 ml in water samples during 50 faecal contamination events. From Van Lieverloo et al., 2007b.

In the Netherlands, a large study was conducted to collect information about contamination events in distribution networks. Water utilities, representing the water supply to 11 million consumers, collated the information on events from the period 1994-2003 (Van Lieverloo et al., 2006, 2007b). Events were defined as repeated detection of faecal indicators. Fifty events were recorded, or (roughly) 0.4 events per million people per year, hundredfold higher than the recorded outbreaks. One event was the recorded outbreak in 2001, in the other events no increased illness incidence was noted. The estimated affected
population varied between 5 and 50,000 persons, with 9 events affecting over 1,000 consumers and a total affected population of 185,000 persons. The utilities emphasized that not all events were retrievable from the records, so this overview was an underestimation of the actual number of events. Data were compiled from the events on the duration (median 8 days, 95% 30d, Figure 5.3) and the level of contamination, described by the concentration of *E. coli*/thermotolerant coliforms detected (Figure 5.4).

The event data also provided information about the cause of the event, the suspected source of contamination and type of system failure that was involved, how the event was detected and what type of remedial actions were taken to restore safe water distribution. Table 5.1 provides a summary of the data.

Table 5.1. Characteristics of 50 faecal contamination events recorded from 1994-2003.
Only 3 of 50 events were reported to have occurred in wells or (groundwater) treatment plants, whereas 37 events occurred in distribution systems (Table 1). Over half of the reported events concerned contaminations that were detected after operations in mains (18 replacements, 8 repairs, 2 cleaning operations). In these cases, supply was commenced immediately after the operations, but not before the mains were flushed and in some cases disinfected. Standard procedure for operations is isolation of the distribution mains that were opened, until microbial safety has been verified by water quality testing. Most of the unknown causes were not well recorded as information was limited to sampling dates and concentrations of thermotolerant coliforms in laboratory databases. It is likely that the causes of these events in most cases also were also a result of mains operations. Isolation and flushing were the primary responses to prevent further spread of the contaminants and to remove the contaminants from the network. Evaluating the remedial actions of the utilities from a health perspective, more attention to issuing boiling water advisories (now issued in only 7 out of 50 events) and the use of remedial, targeted disinfection of the contaminated mains (used in only 2 out of 50 events) is advised.

What do these events mean for the consumer? The average annual probability of a consumer in the Netherlands to reside in an event-affected area is $1.7 \times 10^{-3}$. But what is the health risk of these events? Van Lieverloo et al (2007) used the event data (frequency, affected population, duration, E. coli concentration) in a Quantitative Microbial Risk Assessment (QMRA) to estimate the health risk associated with such events. This required a set of assumptions since the collected information did not disclose all the elements. One major assumption was the source of the contamination. To estimate the health risk, the information collected on duration and thermotolerant coliform concentrations had to be transformed into the exposure of consumers to faecal pathogens. To achieve such a transformation, pathogen-to-thermotolerant coliform ratios were derived from data on pathogen concentration (culturable thermotolerant Campylobacter, Cryptosporidium oocysts, Giardia cysts, culturable enteroviruses) and thermotolerant coliform concentration in sewage (Medema et al., 2001; Höller, 1988). The calculated total risk of infection was dominated by the risk of Campylobacter because the Campylobacter-to-thermotolerant coliform ratios were the highest of the investigated faecal pathogens. Assuming surface water as contamination source yielded a 95-percentile risk of infection per event of 0.16; when sewage was assumed as source the 95-percentile risk of infection was 0.013; 12-fold lower, because the data showed that in sewage the average
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Campylobacter-to-thermotolerant coliform ratio was 12-fold lower than in the surface water. In any case, the best estimate of the risk of infection during events, even if low numbers of faecal indicator bacteria are detected, appears to be substantial. This is in line with recorded waterborne outbreaks where low numbers of E. coli were detected in the water (Hrudey & Hrudey, 2004; Fernandes et al., 2006). Improvement of our ability to assess the health risk of such events can be achieved by collecting more data on the contamination level of the soil surrounding the water mains. The soil was identified as the main source of contamination in the events in the Netherlands and is the least well characterized in terms of microbial contamination (Van Lieverloo et al., 2007).

Does the occurrence, frequency, magnitude and health risk of contamination events in the network imply that a disinfectant residual is necessary? Simulation studies indicate that chlorine (but not chloramine) disinfection is an effective barrier against ingress of microbial contaminants (Propato & Uber, 2004; Teunis et al., 2010). Nevertheless, many outbreaks are reported via chlorinated systems and the epidemiological studies indicate that contamination events in chlorinated systems are associated with disease in the consumers (Payment et al., 1991, 1997, Hunter et al., 2005, Nygard et al., 2007). In the UK, the Drinking Water Inspectorate recorded between 14 and 47 microbiological contamination events per year in the period 1990-2005 (Gray, 2008). They see an increasing number of events in the network of both microbiological contamination and discolouration and associate this with the increasing remedial activities of the ageing networks. These findings illustrate that a disinfectant residual in the network is certainly not an absolute protection. This was also concluded by Van der Kooij et al. (2002). Structural and hydraulic integrity and strict hygiene are preventative measures, while a disinfectant residual is a curative measure for failures. In the absence of a disinfectant residual, the water utility relies more heavily on the preventative measures, but also has a more sensitive monitoring system to detect faecal contamination. Several enteric pathogens, particularly viruses and protozoa are (much) more resistant to chlorine and related disinfectants than indicator bacteria such as E. coli. This means that infectious pathogens may still be present in contaminated water, where the indicator bacteria for faecal contamination have been inactivated. Several outbreaks of viral and protozoal illness have been reported from water in which no E. coli was detected (Craun and Calderon 2001; Anderson and Bohan 2001). Hence, the low frequency of events in the Netherlands, coupled with a rapid response to identify and repair these breaches, the limited protective value of a disinfectant residual are considered adequate protection of the safety of the consumer. In the context of the rapid response, improvements in consumer protection by proactive issuing of boil water advisories and in certain
cases the use of targeted disinfection of the network to inactivate the contaminants is warranted.

5.3.3 Evidence from water quality monitoring

The statutory monitoring of faecal indicators by water utilities can also provide information about contamination events that occur in the distribution network. Bartram et al., 2002 accumulated the results of statutory drinking water monitoring for faecal indicator bacteria in Europe. On average, 1-2% (range 0-12%) of the drinking water samples show the presence of thermotolerant coliforms. This included countries in the (far) Eastern WHO Europe region and countries with a high proportion of small rural water supply systems. Studies from European countries with more centralized water supply systems indicate that only around 0.05-0.3% of the samples show the presence of E. coli (van der Kooij et al. 2002; Mendez et al. 2004; van Lieverloo et al. 2006, 2007; Hambsch et al. 2007). In the Netherlands, the statutory monitoring for coliforms and E. coli is used by the water utilities in the water quality index of their benchmark. The statutory monitoring shows drinking water has a very high compliance with the drinking water standards. On average there was 1 instance of incidental non-compliance with standards in 2008 for every 333 million m³ supplied in the sector (VEWIN, 2009). This is a clear indication that water without a disinfectant residual can be delivered to the consumer without contamination by cross connections or ingress. To study this in more detail, coliform and thermotolerant coliform monitoring data from 1996-1998 were collected from 8 Dutch water utilities. Table 5.2 shows the pooled data.

Table 5.2. Percentage of samples containing coliform and thermotolerant coliform; first samples and repeat samples taken the next day at the same or a nearby sampling site.

<table>
<thead>
<tr>
<th>Location</th>
<th>n</th>
<th>Coliform positive</th>
<th>Repeated coliform positive</th>
<th>Thermotolerant coliform positive</th>
<th>Repeated thermotolerant coliform positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water leaving works</td>
<td>26656</td>
<td>0.70%</td>
<td>0.086%</td>
<td>0.10%</td>
<td>0.004%</td>
</tr>
<tr>
<td>Water in reservoirs</td>
<td>6682</td>
<td>2.02%</td>
<td>0.614%</td>
<td>0.31%</td>
<td>0.030%</td>
</tr>
<tr>
<td>Water in premises</td>
<td>54741</td>
<td>0.96%</td>
<td>0.037%</td>
<td>0.31%</td>
<td>0.0037%</td>
</tr>
<tr>
<td>Total</td>
<td>88079</td>
<td>0.96%</td>
<td>0.095%</td>
<td>0.24%</td>
<td>0.0057%</td>
</tr>
</tbody>
</table>

Both coliforms and thermotolerant coliforms were detected more often in premises and reservoirs than in water leaving the works, which was an indication that ingress of faecal contamination may occur at low levels during
distribution. Repeated detection of (thermotolerant) coliforms was most frequently observed in the reservoirs. Given the residence time of water (and contaminants) in reservoirs, this is not surprising.

To try to understand what this low frequency and level of potential faecal contamination means in terms of safety, the sampling program was assumed to be representative of the occurrence of faecal contamination in the network. The thermotolerant coliform drinking water data were transformed to pathogen data, assuming sewage was the source of contamination and using concurrent data of pathogens and thermotolerant coliforms in sewage. The resulting pathogen data were used to calculate the probability of infection with enteric pathogens (van Lieverloo et al., 2003). The overall probability of infection (given the assumptions) was in the order of $10^{-6}$ per person per year, well below the $10^{-4}$ threshold. Incidents of repeated \textit{E. coli} positive samples give a high probability of infection (see previous paragraph), but are very rarely seen. Given the transient nature of contamination events and the water flow in the network, current practice of repeated sampling the following day at or around the same premises as the first positive sample was taken may not be very able to detect all incidents.

In a subsequent European study, 3 years of statutory monitoring data from the Netherlands, were compared to the data from France and Germany (Table 5.3, Hambsch et al., 2007). Overall, the percentage of samples containing \textit{E. coli} was higher in France than in Germany or the Netherlands. The French data contained a high percentage of small rural water supplies, while the German and Dutch data represented larger systems. The larger German statutory data set of all systems does include small systems and yields higher percentages of \textit{E. coli} positive samples (up to 0.23%). Also, the data from France indicated that no further deterioration of the water quality takes place in the network, while the German and Dutch data do show a higher percentage of positive samples in the distribution network compared to the water leaving the works. Comparing the data from the Netherlands from this period (2001-2003) to the previous suggests that the water quality in the network has improved (Table 5.3 vs Table 5.2).

Table 5.3. Incidence of \textit{E. coli} in tap water. From Hambsch et al., 2007

<table>
<thead>
<tr>
<th></th>
<th>Germany</th>
<th>France</th>
<th>Netherlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Represented # of consumers (million)</td>
<td>5.8</td>
<td>27.5</td>
<td>12.1</td>
</tr>
<tr>
<td>Water volume (million m(^3))</td>
<td>400 (est)</td>
<td>2680</td>
<td>820</td>
</tr>
<tr>
<td>Water supply zones</td>
<td>13</td>
<td>1960</td>
<td>125</td>
</tr>
<tr>
<td># of samples</td>
<td>42000</td>
<td>94000</td>
<td>149000</td>
</tr>
<tr>
<td>Chlorine residual</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
Although a direct comparison is hampered by the nature of the supply systems, the findings suggest that a high level of safety can be reached in the absence of a disinfectant residual. The data also indicate that water quality might be affected during distribution; compare the percentages of *E. coli* positive samples in water leaving the works and in the network in the data from Germany and the Netherlands. In the same study, much larger volumes of distributed water (10-200 L) than the normal 100 ml were sampled and analysed to increase the sensitivity of detection. A total of 356 samples were collected in the United Kingdom, Germany and the Netherlands. None of these large volume samples showed the presence of *E. coli*. The study suggested that contaminations occur infrequently and during a short period.

But what is the level of protection that may be assigned to the statutory microbiological water quality monitoring? Not all water is tested all the time; the common approach is to take grab samples from predefined premises throughout the distribution network with a certain spatial and temporal distribution. The sample volume may vary, but the most commonly volume tested for *E. coli* is 100 mL. Contamination events due to cross connections or ingress through leakage or orifices may occur throughout the system. Given the nature of the statutory monitoring, it will not be possible to detect all events that occur throughout the network and time. No information was available on the sensitivity of the statutory monitoring. We evaluated the sensitivity of a statutory monitoring system to detect an event of ingress of raw sewage into the distribution network in a simulation study (van Lieverloo et al., 2007a). The distribution network of a medium-sized city (72,000 inhabitants; 20,300 connections) was used. The network was fed with groundwater and did not contain a disinfectant residual. Contamination events were simulated, in which raw sewage entered the network with a rate of 1 l/h for a period of 16 hours. The *E. coli* concentration in raw sewage (1 $\times$ 10^6 cfu/L) was the average of a sewage monitoring survey. Twelve different points of entry were simulated: at the treatment works, in a large transport main, in a reservoir and in nine (both central and peripheral) premises throughout the network.

A hydraulic model of the network, that was calibrated against flow and pressure measurements, was used to simulate the transport of *E. coli* in the network. Immediate and complete mixing of the *E. coli* from sewage into the mains and also in the reservoirs was assumed. *E. coli* was considered to behave as a conservative contaminant, be transported by convection and no inactivation or settling occurred. The hourly *E. coli* concentration at each sampling site was

| Leaving works with *E. coli* | 0.005% | 0.3% | 0.04% |
| Distribution system with *E. coli* | 0.1% | 0.3% | 0.09% |
20 Microbial growth in drinking-water supplies

calculated for a period of 1,200 hours following the contamination event and the detection probability of the statutory monitoring program was determined. The statutory monitoring program was the actual program that the water utility used in this city. The monitoring program was designed in accordance with the EU Drinking Water Directive, but was more extensive than the minimum requirements of the Directive. It contained 47 sampling sites: one at the treatment works, two in reservoirs and 44 in premises throughout the network. The annual number of samples taken from the premises is four per site (176 in total, minimum requirement of Directive for this network: 39 check and 15 audit samples). The results of the simulations showed that the probability of detecting each of the nine contamination events throughout the network was on average 5.6% and varied from 0 - 13%. That means that on average 95% of such contamination events remain undetected by the statutory monitoring, even in the more expanded mode that was used here. This is in line with the reports of outbreaks of disease or contamination events that are reported by customer complaints rather than by water quality monitoring (Hrudey & Hrudey, 2004, Fernandes et al., 2007). The low sensitivity is primarily determined by the transient nature of the contamination event and the infrequent water quality monitoring (over space and time). This appears to reflect the actual situation of contamination events (Van Lieverloo et al., 2007b, Besner et al., 2011, LeChevallier et al., 2011).

Several options to improve the detection probability were investigated (Blokker et al., 2009). Increasing the sample volume did not increase the detection probability. Increasing the sampling frequency at the sampling sites did increase the detection probability to 10.9% and at weekly sampling (which is 13 times more frequent than the current program) the average detection probability of all events was 31%, although the standard deviation was high. Selection of sampling sites based on the residence time of the water in the system or using the gate-keeper approach did not substantially improve the detection probability. We also investigated the (hypothetical) scenario of installing on-line E. coli sensors for continuous monitoring throughout the distribution network. Sensor locations were optimized with a genetic algorithm (Weickgenannt et al., 2010). With 5 sensors, 60% of all events was detected and with 25 sensors this increased to approx. 80% (Figure 5.6).
6.3.4 Evidence from operational monitoring

The combination of physical and hydraulic integrity of the distribution network provides a double barrier against contamination of drinking water during distribution. For intrusion of contaminants to occur, both the physical and the hydraulic integrity of the network need to be lost at the same time and place, and contaminants should be present in the vicinity of the network. Loss of pressure is a breach in the protection that could result in backflow from cross-connections or intrusion of contaminants through leaks and orifices (LeChevallier et al., 2003, 2011, Besner et al., 2010). Causes of sustained pressure loss are mains breaks, repairs and power loss. Also short (seconds to minutes), transient events of low or negative pressures have been implicated as the cause of contamination of distributed drinking water. Such events can be caused by pump shutdowns but also by transmission main closures, use of hydrants, main repairs and pump power failures (Funk et al., 1992, Besner, 2010b). The contaminants may enter the distribution network through (small) leaks in pipes, leaking couplings, cross-connections, joints or seals and submerged air valves. The health risk of contamination by low pressure events was suggested in two epidemiological studies in Europe. In England, a strong association between low water pressure, as noticed by the consumer, and self-reported diarrhea was found (Hunter et al., 2005). The study was not designed to test this association (it was a case control study of sporadic cryptosporidiosis), but the authors hypothesized that 15% of intestinal illness in the community may be associated with low pressure events. In Norway, Nygard et al. (2007) studied 88 low pressure events in 7 distribution networks. The events were
caused by main breaks and planned and unplanned repairs. Consumers in affected areas had a 1.6-2.0 times increased risk of intestinal illness. The authors hypothesized that if 20% of the consumers are exposed to a low pressure event every year, this would mean that these events caused 33,000 cases of intestinal illness annually in the Norwegian population of 4.5 million; if low pressure events are more frequent the number of cases will be higher. Flushing of the pipelines and use of chlorination after a repair episode yielded a reduction of the risk of illness. Guidelines in Norway recommend chlorination of distribution networks after maintenance, loss of water pressure or both and prior to repressurizing, to protect against contamination. However, these recommendations are specified to certain predefined risk incidents, where a contamination might have occurred and are often not followed. Only one of the seven participating water utilities chlorinated routinely in all episodes of work on the distribution network.

No outbreaks have been directly associated with short pressure transients. A number of outbreaks have been associated with low pressure events, leading to backsiphonage or ingress through cross connections, including the 2001 outbreak in the Netherlands (Craun & Calderon, 2001, Fernandes et al., 2007).

In the Netherlands, unplanned interruptions of supply are recorded, especially since the introduction of this parameter in the benchmark of the water utilities, to determine the level of service to the consumer. Not only the downtime but also the characteristics and causes of the unplanned supply interruptions are recorded and pooled by all water utilities. The primary objective of these records is to estimate the life expectancy of distribution network segments, as an aid to proactive evidence-based asset management (Vloerbergh et al., 2008). At the same time, they also provide information about the frequency of events that may be associated with ingress, such as low or no pressure. The interruptions are expressed as minutes of interrupted or inadequate supply. In 2009, consumers suffered an unplanned interruption of water supply of, on average, 7.5 min (range of average time between utilities was 2-13 min). This was an increase of 32% compared to 2006, probably due, at least in part, to improved registration.

OFWAT (2008) has collected data on leakage and supply interruptions from 2006-2007 from different countries. The data are not complete and not always directly comparable, but do reflect the good structural and hydraulic integrity of the distribution network in the Netherlands (Table 5.4).
Safe distribution without disinfectant residual

Table 5.4. Operational data on distribution networks (based on OFWAT, 2008).

<table>
<thead>
<tr>
<th></th>
<th>Main bursts per 1000 km</th>
<th>Leakage m³/km/d</th>
<th>Unplanned interruptions per 1000 properties</th>
<th>Properties at risk of low pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>England/Wales</td>
<td>187</td>
<td>10.1</td>
<td>23</td>
<td>0.02%</td>
</tr>
<tr>
<td>Scotland</td>
<td>166</td>
<td>21.3</td>
<td>34</td>
<td>0.31%</td>
</tr>
<tr>
<td>Canada</td>
<td>66</td>
<td>11.9</td>
<td>21</td>
<td>No data</td>
</tr>
<tr>
<td>Australia</td>
<td>No data</td>
<td>4.4</td>
<td>50</td>
<td>No data</td>
</tr>
<tr>
<td>Portugal</td>
<td>67</td>
<td>7.0</td>
<td>0.4 (&gt;12 hr)</td>
<td>No data</td>
</tr>
<tr>
<td>USA</td>
<td>629*</td>
<td>No data</td>
<td>3</td>
<td>No data</td>
</tr>
<tr>
<td>Netherlands</td>
<td>70*</td>
<td>1.6</td>
<td>**</td>
<td>No data</td>
</tr>
</tbody>
</table>

LeChevallier et al., 2011 indicate an industry average of 23-27 breaks per 100 miles, or approx. 150 per 1000 km; ""All failures, not only main bursts; ***Unplanned interruptions in the Netherlands are, on average, 7.5 min per property per year

Researchers in Canada have monitored pressure in a distribution system of 1,600 km serving 380,000 consumers with an average water demand of 210,000 m³/d (Besner et al., 2010). Pressure dropped to below 172 kPa at the treatment plant nine times in a period of 17 months and this resulted in four measured and five suspected negative pressure events throughout the distribution network. Another 4 negative pressure events were associated with the closure of a transmission main and 10 negative pressure events were recorded at only a single location. These lasted for minutes to hours and were associated with maintenance work in the same area of the network. The authors also confirmed the presence of faecal contamination in soil and water from pipe trenches, although both frequency and level of contamination was lower than previously reported in the USA (Karim et al., 2003).

Continuous pressure monitoring data from calibrated pressure monitors are limited in The Netherlands. In a dedicated study, the pressure was monitored for 50 days continuously at three locations along a limited part of a distribution network (boulevard of Zandvoort; Blokker et al., 2010). During these 50 days, the nominal pressure was 200 – 350 kPa and at 2 moments a pressure transient occurred in the network where the pressure dropped below 1 bar for several minutes. No negative
Figure 5.6. Low pressure transient in the distribution network of Zandvoort.

Pressures were observed; the minimum pressure was 0.2 bar. The movement of the low pressure transient through the network is shown in figure 5.6. The duration of the low pressure event was short (Figure 5.7). The cause of the low pressure transients was not identified. This shows that pressure transients do occur in the network in the Netherlands. Because of the predominantly flat terrain, the network is probably less prone to negative pressures, but the evidence-base is limited.
Figure 5.7. Frequency distribution of water pressure (x, in Bar) of the 50 day monitoring at three locations in the Zandvoort distribution network. A frequency of 10^-3 in 50 day monitoring corresponds to 1.2 hours, 10^-4 to 7.2 min.

6.4 Synopsis

The collected data in the Netherlands indicate that distribution networks with a high level of structural and hydraulic integrity and hygiene and without a disinfectant residual:

- have a low frequency of outbreaks;
- have a low frequency of contamination events;
- have a low frequency of detection of faecal indicator bacteria (while this system is more sensitive in non-disinfected waters);
- experience low but no negative pressure transients (based on limited data);
- have low leakage rates;
- have low rates/times of unplanned interruptions.

This demonstrates the advantages of the focus on structural and hydraulic integrity and hygiene.

Is this sufficient proof of safety? The best available evidence is collected, representing the best state of the art, and the evidence clearly points to a high level of safety. Under these conditions disinfectant residuals, with DBP formation and taste and odour problems, are not needed to enhance the safety of
the water network. It is clear that in drinking water distribution networks, unsafety is more easily demonstrated than safety. The network is complex, open and underground and with our best efforts we currently monitor water quality, condition and integrity in a fraction of the network, both in space and in time. Are there ways to improve the assessment of the safety? New technologies and concepts emerge in the area of smart networks that may substantially improve our ability to assess the safety of the network.

5.5 Outlook

5.5.1 Improved microbiological monitoring

The statutory monitoring of *E. coli* aims to verify the effectiveness of the measures to prevent contamination of the distribution network. Water utilities and health authorities use the level of compliance with the statutory monitoring of *E. coli* as an indication of the level of protection of the distribution network.

The level of protection that may be assigned to the statutory monitoring depends on the ability of the statutory monitoring to detect a faecal contamination event. Given the transient nature of contamination events and the results of our studies that showed a low recovery efficiency of the current grab sampling approach (see 5.3.3), we designed a continuous monitoring study to optimize the detection probability of events. Sampling sites were selected and tested for adequate placement with the genetic algorithm. The study uses continuous membrane filtration samplers that are installed on the tap and sample water 24 hours per day at a low flow to filter 10 – 100 l water. This study is currently in progress.

Rethinking of the sampling strategy upon detecting *E. coli* in the network, using the knowledge of the water (and contaminant) transport in the network between the first positive sample and the next samples, is also recommended.

5.5.2 Improved monitoring by combining sentinel sensors with rapid microbiological assays

The ability to monitor continuously for faecal contamination at dedicated sites in the network would mean a large improvement in the ability to demonstrate drinking water safety and due diligence. There are currently developments in monitoring stations for *E. coli* (Zibuschka *et al.*, 2010, Brown *et al.*, 2010, van de Vossenberg *et al.*, 2010) that indicate that this next generation of monitoring is becoming achievable, although true online monitoring of *E. coli* on many sites in the network is still “a bridge too far”. In the meantime, water utilities are
exploring the application of non-microbiological sensor systems (turbidity, refractive light index and others) that are able to monitor online and are cheap and robust enough to install throughout the network (Storey et al., 2011, de Graaf et al., 2012). This is driven initially from the perspective of water security, but the developments are equally useful for water safety. The combination of sentinel sensors for detection of anomalies in the network and rapid, on site confirmation of a faecal contamination, is achievable given the current status of technology. Similarly, there are recent developments in the area of sensor placement strategies based on (improved) network modelling. This approach should also be applied to optimize the current (grab) sampling programs.

5.5.2 Improved use of operational monitoring

The application of operational monitoring to aid the assessment of safety has been explored. Improved national registration of distribution system deficiencies (Vloerbergh et al., 2008) provides opportunities to upgrade the safety assessment even further. The first step is to extract information from this register (which is currently focused on the condition of network elements) that is indicative of contamination events.

In parallel, Geographical Information Systems are employed to evaluate the risk of main breaks for the surrounding area. This technology can also be used to identify spots in the network that are vulnerable to contamination, because of the presence of contamination sources, soil types, groundwater levels and pipe characteristics and condition etc.

5.5.4 Epidemiology to assess safety

Several epidemiological studies have been conducted in chlorinated systems in Canada (Payment et al., 1991, 1997) Australia (Hellard et al., 2001) and the USA (Colford et al., 2005) to determine the health burden associated with drinking water. The Canadian studies found a significant contribution of drinking water to intestinal illness in the population, and a link with events in the distribution network was suggested. No epidemiological study has been conducted in non-chlorinated systems to determine if there is a measurable contribution of drinking water to the intestinal illness in the community. Given the high background prevalence of intestinal illness, such a study requires a large population. An epidemiological study focused on the health effects of repairs and maintenance in the distribution network, in analogy with the Norwegian study, (Nygard et al., 2007), is more appropriate.
5.5.5 QMRA to improve science-based management

The Netherlands has incorporated QMRA in the drinking water legislation. Currently, QMRA is used to determine the safety of the surface water treatment systems. QMRA models have also been developed for intrusion of pathogens in the distribution network (McInnis, 2004, van Lieverloo et al., 2007b, Teunis et al., 2010, LeChevallier et al., 2011, Besner et al., 2011). These QMRA models do suggest that contamination events do amount to a high probability of infection in the affected consumers. This, in combination with the detection probability of contamination events of the current statutory monitoring programs for E.coli, is a strong incentive for QMRA-based safety management of the distribution network. The current state of knowledge implies that such a QMRA requires several assumptions. Key factors are the pathways of entry and the occurrence of pathogens in the material that enters the network via these pathways. The evidence from the Norwegian (Nygard et al., 2007) and the Canadian study (Besner et al., 2010) indicate that repair and maintenance work render the network vulnerable to ingress and may be associated with illness. Collection of information about the occurrence of pathogens in the trenches during repair and maintenance of the network, the amount of material and pathogens that can enter the network and the efficacy of the remedial actions (flushing, chlorination) in the Dutch setting is therefore recommended to evaluate the level of protection that is offered by current network operation practices.

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References

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Microbial growth in drinking-water supplies


Safe distribution without disinfectant residual


