Safe distribution of drinking water without disinfectant residual

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Abstract
In the Netherlands, drinking water is distributed throughout the network without a disinfectant residual. The good structural and hydraulic integrity and strict hygiene in the Netherlands, coupled with a rapid response to identify and repair these breaches, the limited protective value of a disinfectant residual and the low number of events are considered adequate protection of the safety of the consumer. This paper presents and discusses the evidence that is collected to demonstrate safe water distribution without disinfectant residual from waterborne outbreak surveillance, from incident management, from water quality analysis, from Quantitative Microbial Risk Assessment and from operational monitoring. The best available evidence is collected, representing the best state of the art, and the evidence clearly points to a high level of safety.

Keywords
Water distribution, disinfectant residual, integrity, qmra

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. 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.

Micro-organisms and micro-organism associated processes in the network can affect water quality:
- Ingress of pathogenic microbes due to loss of physical and hydraulic integrity of the network and the presence of a nearby contamination source (such as sewer lines);
- Growth of micro-organisms 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 micro-organisms can lead to:
- non-compliance with water quality standards for total coliforms, heterotrophic plate counts and Aeromonas;
- esthetical issues such as presence of invertebrates and taste and odour problems;
- corrosion of pipe materials.

In developed 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 limit microbial growth and provide a barrier against ingress of microbial contaminants. 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. The latter approach is found primarily in northern Europe, the former in most of the other developed 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. 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. Chlorine and chloramine are not effective against Cryptosporidium.
- The use of a disinfectant residual may mask the failure of the integrity of the system and ingress of microbial contamination. 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.

- 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. Also microbes in biofilm particles that slough off the wall and enter the bulk water again are more difficult to reach and inactivate.

- Disinfection is targeting the symptoms rather than the cause of the microbiological issues in the network. The cause of biofilm formation is the quality of the treated water and the materials used in the network. The cause of ingress is insufficient hydraulic and structural integrity and hygiene. 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. 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.

- 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.

THE ROAD TO DISTRIBUTION WITHOUT DISINFECTION 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), 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, 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 disappeared (from 12-22 µg/l), 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 content of the finished water was reduced with 40% (Schellart, 1986). So the chlorine dosing was stopped permanently (it was kept standby for safety 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 risk level, the utilities banned the use of post-chlorination (van Genderen, 1998).

In the 1990’s, disinfection of surface water with chlorine was replaced by ozone or membrane filtration used as primary disinfectant, except for two water treatment plants. By 2006, these two chlorine-based disinfection plants changed to UV for primary disinfection, so chlorine is not used in water treatment any longer. Important arguments were: prevent DBP formation, improve taste and odour and hence consumer satisfaction, and 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 where the water temperature is high. In several 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) is distributed without chlorination. These countries, and the EU, have no legal requirement for maintaining a disinfectant residual. Standard values 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).

**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:

A. **Structural integrity.** The structural integrity prevents ingress in places or times where the hydraulic pressure is low or absent. Structural 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 Europe this is very low (Figure 1) and a comparative study indicated that several factors contribute to this (UKWIR, 2006). The pressure in the network can be relatively low due to the flat terrain and large 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. Also the Netherlands is facing ageing networks and need to actively assess and manage network condition and integrity to prevent leakage and ingress.
Figure 1. Leakage rates in European countries (VEWIN, 2009; DVGW, 2008).

B. Hydraulic integrity. Continuous maintenance of sufficiently high pressure in the network to prevent contaminants entering the network. 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).

C. 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.

D. Strict hygiene during construction and maintenance. A national hygiene code was developed between 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 expanded (Meerkerk & Kroesbergen, 2010) and has become 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, checking, cleaning and disinfection of materials and pipes after construction or repair, personal hygiene, use of appliances such as fire hydrants. Also training, supervision and water quality monitoring to verify the efficacy of the hygiene code is described.

E. Approval system for materials and appendages. Certification of materials and appendages that are to be used in distribution networks has been developed since the start of Kiwa at 1948. All materials have to be approved according to the national acceptance scheme.

EVIDENCE OF SAFE DISTRIBUTION WITHOUT DISINFECTANT RESIDUAL
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 projects focused on the evaluation of the evidence that distribution without disinfectant residual offers sufficient protection against ingress of pathogens.

Evidence from waterborne outbreaks
In the Netherlands, since 1945, three outbreaks of waterborne diseases have occurred, all connected to contamination of drinking water in the distribution network. 6 cases of typhus in Amsterdam in
1962, possibly due to sewage contamination of the network and in 1981 in Rotterdam 609 cases of enteric disease of multiple aetiology because of waste water inflow from a marine vessel by a cross connection with the drinking water network (Huisman and Nobel, 1981). At that time, water was still distributed with a (low) disinfectant residual. In 2001 an outbreak of gastroenteritis 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). Approx. 500 people experienced symptoms. Because of this outbreak, the use of dual reticulation systems was largely banned in The Netherlands.

Comparing the documented outbreaks in The Netherlands to 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 from 1990-2004 there were 86 recorded outbreaks (roughly 6 per year or 0.01 outbreaks per million consumers per year). Though many differences in water supply and surveillance system make a direct comparison difficult, they outbreak statistics certainly do not suggest that distribution of drinking water without a disinfectant residual increases the risk of a waterborne outbreak.

**Evidence from contamination events**

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. 50 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, with 9 events affecting over 1,000 consumers and a total affected population of 185,000. 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) and the level of contamination, described by the concentration of *E. coli*/thermotolerant coliforms detected (figure 2).

![Figure 2. *E. coli* concentrations per 100 ml in water samples during 50 faecal contamination events.](image-url)
Only 3 of 50 events were reported to have occurred in wells or (groundwater) treatment plants, whereas 37 events occurred in distribution systems. 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. Of the unknown causes, most were not recorded well 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 a result of mains operations. Isolation and flushing were the primary responses to prevent the spread and 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 warranted.

What do these events mean for the consumer? The average annual probability of a Dutch consumer 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 exposure of consumers to 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 highest. Assuming surface water as contamination source yielded a 95-precentile risk of infection per event of 0.16, when sewage was assumed as source this was 0.013; 12-fold lower, because in the sewage data the average Campylobacter-to-thermotolerant coliform ratio was 12-fold lower than in the surface water data. 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 microbiological contamination.

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 records 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. Structural and hydraulic integrity and strict hygiene are preventative measures, while a
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 & Calderon, 2001, Anderson & Bohan, 2001). Hence, the good structural and hydraulic integrity and strict hygiene in the Netherlands, coupled with a rapid response to identify and repair these breaches, the limited protective value of a disinfectant residual and the low number of events 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.

**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. In a European study, 3 years of statutory monitoring data from the Netherlands, were compared to the data from France and Germany (Table 1, Hambsch et al., 2007). Overall, the percentage of samples containing *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 *E. coli* positive samples (up to 0.23%). Also, the data from France indicated that the no further deterioration of the water quality takes place in the network, while the German and Dutch data do.

<table>
<thead>
<tr>
<th>Represented # of consumers (million)</th>
<th>Germany</th>
<th>France</th>
<th>Netherlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water volume (million m³)</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>
<tr>
<td>Leaving works with <em>E. coli</em></td>
<td>0.005%</td>
<td>0.3%</td>
<td>0.04%</td>
</tr>
<tr>
<td>Distribution system with <em>E. coli</em></td>
<td>0.1%</td>
<td>0.3%</td>
<td>0.09%</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 large volumes of distributed water (10-200 L) than the normal 100 ml were sampled and analysed to increase the sensitivity of detection. 356 samples were collected in the United Kingdom, Germany and the Netherlands. None of these large volume samples showed the presence of *E. coli*. 
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, properties 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 4. Operational data on distribution networks (based on OFWAT, 2008).

<table>
<thead>
<tr>
<th>Country</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></td>
</tr>
<tr>
<td>Australia</td>
<td></td>
<td>4.4</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Portugal</td>
<td>67</td>
<td>7.0</td>
<td>0.4 (&gt;12 hr)</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>629*</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Netherlands</td>
<td>70**</td>
<td>1.6</td>
<td>***</td>
<td></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

SYNOPSIS
The collected evidence indicates 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. Under these conditions disinfectant residuals, with DBP formation and taste and odour problems, are not needed to enhance the safety of the water network.

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. 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.

- Improved monitoring by combining sentinel sensors with rapid microbiological assays
- Improved use of operational monitoring
- Improved microbial monitoring
- Epidemiology to assess safety
- QMRA to improve science-based management

These need to be developed further and incorporated in our water distribution network management

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