

Reduction of Infection Risk by Automated Rapid Detection of Faecal Contamination of Drinking Water Distribution Systems

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ABSTRACT

Water companies may perform a quantitative microbial risk assessment to verify that the produced water is safe to drink. However, in the drinking water distribution system (DWDS) a faecal contamination may occur when the integrity of the system is broken. Therefore a similar verification of water safety during distribution is desirable, however challenging due to the complexity and extent of the network. Currently verification consists of regulatory 100 ml samples for E.coli and enterococci analyses at the consumer tap. The drawbacks are that not all contaminations are detected and analysis results take 24 to 48 hours, before action can be taken.

Automated analysers that take a sample and analyse it on location within a few hours are now available and can act as online sensors for faecal contamination. This allows a much faster response when a contamination is detected. In this study a hydraulic model was run with many contamination scenario's and sensor networks to quantify the resulting exposure of consumes to pathogens. The resulting infection risk was then determined with a previously developed QMRA model for distribution systems. It was shown that a boil water notice within hours instead of days can significantly reduce the infection risk. Next to reducing infection risk, these automated analysers can help to better assess infection risk levels and enable more flexibility in network maintenance.

Keywords: Faecal Contamination; Infection Risk; Sensoring.

1 INTRODUCTION

The quality of the drinking water that leaves the water treatment works (WTW) is well known. In the Netherlands the water companies perform a quantitative microbial risk assessment (QMRA) for faecal contamination of the water, and then take measures to ensure that the water from the WTW does not lead to more than 1 per 10,000 infections per year [1]. In the drinking water distribution system (DWDS) the water may be contaminated when the integrity of the system is broken [2]. Therefore verification of water safety during distribution is desirable, however challenging due to the complexity and extent of the network. A QMRA of the DWDS showed the most important contamination pathways and the measures needed to keep the infection risk low [3]. Over the past 35 years only one known outbreak by contaminated drinking water occurred in the Netherlands.. In 2001 an accidental cross connection between the drinking water distribution system and a grey water distribution system, intended for flushing toilets, washing cloths and watering gardens in a new residential area occurred [2].

Currently regulatory 100 ml samples for *E.coli* and *enterococci* analyses from the DWDS in the Netherlands are randomly taken over the year and the supply area. Samples are also taken after pipe maintenance to verify that the standard practice of operating a DWDS such as flushing and hygienic working procedures for pipe maintenance suffice [3]. In the Netherlands these samples are typically taken 12-24 hours after the maintenance work is completed, which includes flushing the affected pipe section of the system. Approximately 0,00000015% of the total amount of distributed water is thus tested. Due to this limited coverage and the low probability of contamination, most or all samples are negative, thus providing little insight into the actual water safety during distribution. Samples are taken to the labs where analysis takes 24-48 hours for cultivation. If a sample is positive for faecal contamination a repeat sample is taken and the result takes another 1-2 days. The response time between the occurrence and the detection of a contamination, and subsequently the issuing of a boil water notice depends to a great extent on the analysis time.

Automated analysers that take a sample and analyse it on location within a few hours are now available and can act as semi-continuous online sensors for faecal contamination. This allows for a much faster response when a contamination is detected. A boil water notice within hours instead of days may actually reduce the infection risk. The extent of the infection risk and the risk reduction will depend on the type of contamination, characterised by the location, time, duration and concentration of the faecal contamination, and the type of sensor network, characterised by the type of sensor, the number of sensors, the location, sampling frequency and the time of analysis. Where studies on sensors in the DWDS usually focus on detection likelihood [4], this paper describes a modelling approach to quantify the potential effect of automated *E.coli* analysers on the infection risk. Also, some more qualitative effects will be discussed.

2 METHODS

In a previous research project a QMRA model for faecal contamination during maintenance of the DWDS was developed [3]. This QMRA model is based on a hydraulic network model, and the result is the number of infections in a network. The model was adjusted in two ways. A first adjustment allowed for also taking into account contamination scenarios during normal operation. A second adjustment was the introduction of semi-continuous sensors at specified locations that could detect the contamination, and then allow for a boil water notice within a given time after detection to reduce the consumption of unboiled water and thus reduce infection risk.

A hydraulic model was run with many contamination scenario's and sensor networks, and the infection risk was then determined with the adjusted QMRA. This adjusted QMRA model takes into account the variability in contamination scenarios, characterised by the location, time, duration and concentration of the faecal contamination, and in flows through the DWDS, in consumption of drinking water, and in dose response relations. The adjusted QMRA model also takes into account the variability in sensor networks, characterised by the type of sensor, the number of sensors, the sensor locations, sampling frequency and the time of analysis. *Campylobacter* was used as the pathogenic micro-organism in the model as it is highly infectious and known to be relevant for drinking water in the Netherlands [1]. As in the previous study, the Zandvoort boulevard network was again used as a model area [3].

The study entailed the following steps:

1. 5,000 different contamination scenarios with variation in start location (1 of 316 potential nodes in the network), de start time (at 0:00, 3:00, 6:00, 9:00, 12:00, 15:00, 18:00, 21:00) and the duration (between 0 and 24 hours). All contaminations had the same concentration of 1 *Campylobacter* per litre.
2. For all 5,000 contamination scenarios, 100 consumption scenarios (time of consumption, number of intakes, volume per intake) were applied and the infection risk was determined as the median number of infected people for these 100 consumption scenarios.
3. For each of the 5,000 contamination scenarios it was determined if the sensor configuration (1-8, Table 1) would detect it at least twice with any of the sensors, to allow for a verification measurement. Then after a certain response time after the verification detection, 100% of the people connected to the network were assumed to stop drinking unboiled water. The infection risk was then determined as in step 2.

The sensor locations (Figure 1) were optimised for probability of detection, using a neural networks approach [5]. A monitoring interval of 4 hours for sampling and analysis was assumed. A second detection by on of the sensors is required to confirm the contamination before a boil water notice is issued. This would take another 4 hours at maximum.

Table 1. Definition of sensor configurations.

Configuration	Number of sensors	Sensor locations	Optimization criterion for location	Analysis time (h)	Number of verifications	Response time issuing boil water notice (h)
0 (base)	0	x	x	x	x	x
1	2	264154	Detection likelihood	4	1	1
2		207802		4	2	1
3				1	1	0
4	3	264154	Detection likelihood	4	1	1
5		263927		4	2	1
6		264147		1	1	0
7	2	264147 252536	Detection time, 12 h assumed for verification and response	4	1	1
8	2	N0193775 N0193902	Detection time, 3 h assumed for verification and response	4	1	1

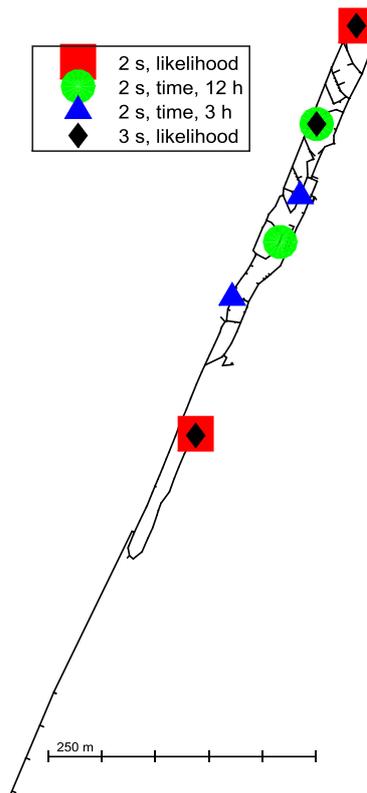


Figure 1. Sensor locations: red squares are sensor configuration 1,2,3; green circles are sensor configuration 7; blue triangles are sensor configuration 8; black diamonds are sensor configuration 4-6.

3 RESULTS AND DISCUSSION

3.1 Effect of automated *E.coli* analysers on infection risk

Figure 2 shows the potential reduction of the infection risk in the modelled area of Zandvoort when two sensors are present (sensor configuration 1) compared to the situation without sensors. In this sensor configuration the average risk of infection is reduced by 25% compared to current practice of sampling at the tap. Especially the contamination scenarios with a high infection risk (because it happens upstream from many customers, or because it had a long duration or occurred at a critical time of the day) would benefit from the sensors and subsequent boil water notice. More than 50% risk reduction can be seen for those high risk contamination scenarios. Sensors with faster analysis (less time between sample and detection) or issuing a boil water notice after the first positive sample will further reduce the infection risk.

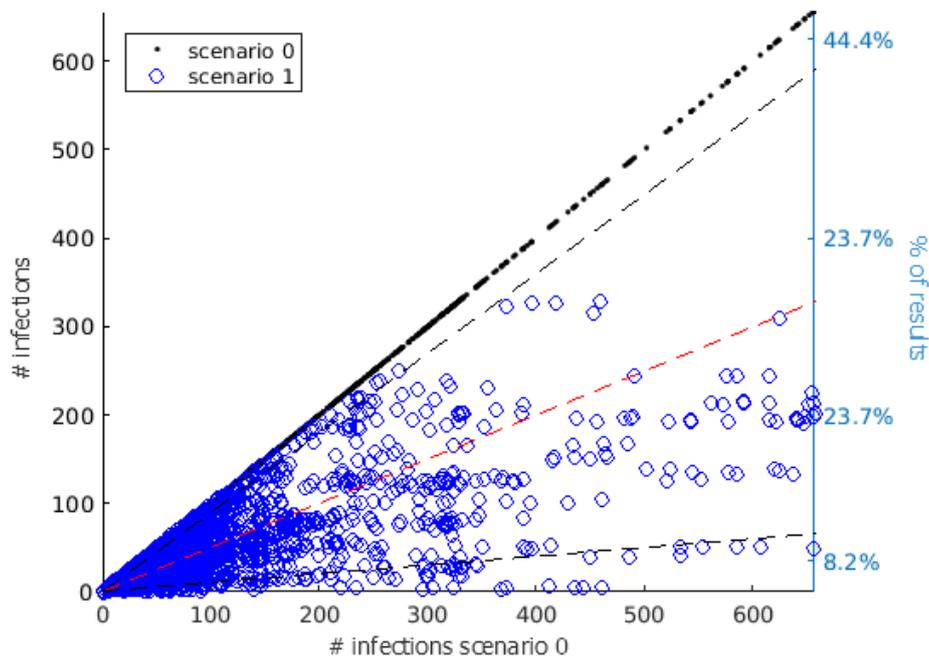


Figure 2. Number of infections per contamination scenario on the horizontal axis versus that of sensor configuration 0 (no sensors, in black) and sensor configuration 1 (with analysis time of 4 hours, one confirmation takes another 4 hours and 1 hour to issue the boil water notice, in blue). The black dotted lines indicate 10% and 90% reduction, the red dotted line the 50% reduction.

3.2 Sensitivity analysis risk reduction

The variation in the contamination scenarios and sensor configurations allows for a sensitivity analysis. By comparing the distribution of the 5,000 contamination scenarios to that of the 50 worst contamination scenarios (highest infection numbers) and the most effectively reduces ones (highest absolute reduction of infection numbers with infection configuration 1), it is possible to make some remarks on sensor effectiveness:

- Time of contamination start (0:00, 3:00, 6:00, 9:00, 12:00, 15:00, 18:00, 21:00) is equally distributed over the 5,000 contamination scenarios. In the 50 worst cases the night hours and especially the early morning (6:00) are overly present; in the 50 highest reductions the 6:00 and 21:00 scenarios are overly present. This means that sensors are most effective for the more serious contaminations that take place in the early morning, and boil water notice typically is issued during the daytime and evening.
- The contamination duration (0-4, 4-8, 8-12, 12-16, 16-20, 20-24 h) is equally distributed over the 5,000 contamination scenarios. In the 50 worst cases the more than 16 hours are overly present; in the 50 highest reductions the same effect is seen. This means that sensors are most effective for the more serious contaminations that have a long duration. For short contaminations where the contamination is gone before the verification measurement and boil water notice are issued, there is a limited effect of sensors, but also a limited risk involved, in terms of number of infections.
- Location of contamination is not equally distributed over the 5,000 contamination scenarios, as too many nodes were a potential location. In the 50 worst cases only upstream

locations close to the network inlet are found, with sensor configuration 1 resulting in 70% infection risk reduction. Sensor locations downstream of those contamination locations would sooner or later detect the contamination. This would mean detection likelihood is high, but the time to detection in combination with the response time determine the reduction of the infection risk.

Also a sensitivity analysis was done with respect to sensor configuration.

- It was shown that configurations with faster analysis, less verification needed and faster response times have a larger potential infection risk reduction; e.g. a 25% average risk reduction in sensor configuration 1 and 45% average risk reduction in sensor configuration 3. Note that “less verification” is only possible if this would not lead to too many false alarms.
- The number of sensors in this relatively small network had a limited effect; viz. a 25% average risk reduction in sensor configuration 1 (2 sensors) and 30% average risk reduction in sensor configuration 4 (3 sensors).
- The sensor location optimization criterion in this relatively small network had a limited effect; viz. a 25% average risk reduction in sensor configuration 1 (optimized for detection likelihood) and 25%, respectively 11% average risk reduction in sensor configuration 7 and 8 (optimized for detection time with different assumptions for response times).

3.3 Qualitative effects of automated *E.coli* analysers

The QMRA for faecal contamination during DWDS maintenance [3] concluded that it was not possible to quantify the infection risk as there were on the one hand far too few measurements done in the network and the detection likelihood was low due to sampling time and location, and on the other hand there were far too many uncertainties in the estimation of contamination pathways, contamination likelihood, contamination concentrations etc. Automated *E.coli* analysers can help in better quantifying the risk as more measurements are taken, and measurement locations can be optimized. However, in order to ensure a maximum of 1 in 10,000 infection risk, at least 50 perfect sensors (i.e. never fail, take 6 samples per day, 365 days per year, and very sensitive, 0 false positives and 0 false negatives) are required per supply area. The current risk level is believed to be very low, and the need for risk reduction measures is not clear. However, automated *E.coli* analysers in combination with a boil water notice can significantly reduce the risk when contamination occurs, or verify a much higher level of water safety approaching the health target for QMRA of produced drinking water in the absence of contamination events. The amount of risk reduction depends on the sensor locations, number of required verification measurements, time of analysis and the contamination location, start time and duration. Especially the high infection risk scenarios can benefit from these sensors. Also, these type of sensors in combination with hydraulic modelling may help to map the affected area, identify the contamination source location, thus allow faster removal of the contamination source, effective flushing of the system and confirmation of effectiveness of cleaning actions.

Additionally to the modelled stationary placement, these automated *E.coli* analysers could be placed temporarily after maintenance and flushing to verify that contamination is absent. Thus a boil water

notice can be issued as a standard practice, and within 4 to 8 hours the notice can be retracted. This would lead to substantial risk reduction since the connected households are no longer exposed during the current two days of analysis time. Meanwhile the customer burden would be acceptable as customers generally already receive warnings for discoloured water after maintenance and there usually is no contamination. Faster analysis also allows sooner opening of the isolation valves, restoring normal network conditions and allowing maintenance on the rest of the network. Semi-continuous measurements after maintenance are expected to better detect contaminations, contributing to a better quality control of the maintenance on the DWDS.

Preferably the automated *E.coli* analysers would be connected directly to the pipe section, eliminating the need to get access to customers taps and the risk of false positives due to contamination of the plumbing system or tap.

4 CONCLUSIONS

In the current situation of very low risk of faecal contamination of the DWDS and the limited water testing the infection risk at the tap cannot be verified to the same level as the produced drinking water. Automated *E.coli* analysers can act as semi-continuous online *E.coli* sensors, and by thus collecting more data on strategic locations a lower level of risk (or a higher level of safety) can be verified. At the same time, these sensors in combination with a quick issuing of a boil water notice, can significantly reduce infection risk in case of a contamination event. These findings will help water companies in their decision on whether to adopt this innovation, taking into account not only the increased safety, but also cost, logistics, planning and image.

References

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