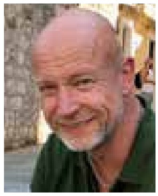
SOLVING INCIDENTS WITH CONTAMINATED DRINKING WATER USING HYDRAULIC MODELLING

HYDRAULISK MODELLERING EFFEKTIVT FÖR ATT SPÅRA KÄLLAN UNDER DRICKSVATTENKRISEN





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Abstract

During 2017, two incidents with coliform bacteria in the drinking water occurred in Lund, South Sweden. Boil water advisories were issued and the extensive work began to limit the affected areas, find the sources of contamination and restore the network to normal conditions. During both incidents, hydraulic mod-el-ling was used as part of the trace methodology for detection of the sources of the microbiological contamina-tions. This proved to be an essential tool in which the theoretical distributions from different source scenarios were compared to the results from water analysis. The model was also used to reduce the areas with boil water advisories. In incident no 1, the coliform bacteria were typed as Erwinia spp. Lab results later showed that the recovered source of contamination consisted of wheat flour; which had been put in the pipe during an installation work four months earlier. In incident no 2, the source also consisted of organic matter (paper napkin) left in a pipe after an installation work. The coliforms found on the organic matter were typed as Serratia spp.

Sammanfattning

Under våren 2017 hanterades i Lund med omnejd två incidenter med koliforma bakterier i dricksvattnet. I båda fallen utfärdades kokrekommendationer. Omfattande arbete inleddes med att identifiera de berörda delarna av ledningsnätet, hitta kontamineringskällorna och återställa dricksvattenkvaliteten i nätet. Vid båda incidenterna användes hydraulisk modellering för att spåra kontaminieringskällorna. Detta visade sig – i kombination med vattenprov – vara ett effektivt verktyg för att testa olika teorier och scenarier kopplade till kon-tamineringen. Modellen kunde också användas för att efterhand minska de områden som var förlagda med kok-ningsrekommendation. Vid den första incidenten kunde de koliforma bakterierna typas till Erwinia spp. Förore-ningskällan visade sig vara en klump med vetemjöl – mjölet hade fyra månader tidigare förts in i ledningen i syfte att suga upp vatten vid ett svetsarbete och sedan utgjort en god tillväxtmiljö för koliforma bakterier. Vid den andra incidenten typades de koliforma bakterierna till Serratia spp. Tillväxtmiljön var även här av organisk natur, en eller flera pappershanddukar som lämnats kvar i en ledning vid ett ledningsarbete.

Keywords: Boil water advisory; Contamination; EPANET; Hydraulic modelling; Trace methodology

INTRODUCTION

Contamination of the drinking water is one of the most problematic situations that can occur in a city. Immediate action must be taken to locate the contaminant in the drinking water system in order to prevent epidemics. In Sweden, boil water advisories are periodically issued as a result of bacterial outbreaks in drinking water. Based on two real events, the emphasis of this paper is to highlight the applicability of hydraulic modelling as part of the trace methodology for detec-tion of contaminations in the distribution system. This is a methodology described in literature (Preis & Ostfeld, 2007; Liu et al., 2011; Bazargan-Lari, 2014) but for reasonable causes it is not so common with examples of hydraulic modelling being used during real incidents. In Lund, the joint municipal authority VA SYD successfully tested it twice.

VA SYD supplies half a million people in South Sweden with drinking water, including the 100,000 citizens of Lund and the regional university hospital in the city. During the period of March to June 2017, two incidents with increased levels of coliform bacteria in the drinking wa-ter occurred in Lund. In both situations, use of the hydraulic model of the city's water distribu-tion system was crucial to locate the sources of contamination; to decrease the areas with boil water advisories and to accelerate the processes of resetting the network to normal conditions.

METHOD

The methodology in this section describes the approach used by VA SYD during the two inci-dents.

The hydraulic model

The model describes the water distribution system; including main pipes, valves, pumps and reservoirs; and is calibrated during a regular consumption week (Possling et al., 2014). It is not an online model, but continuously updated to reflect the current operating conditions. It is gener-ally used for e.g. testing of operational measures, master planning, fire flow analysis and for capacity management by generating information of flow, pressure and flow direction. The model is developed in cooperation between VA SYD and the consultant company DHI Sverige AB (DHI). The software used for the model is MIKE URBAN; a GIS integrated program with EPANET as the hydraulic analysis engine (DHI, 2017).

Events that could open up for contamination

In a pressurized drinking water system there are usually a few possible ways for a contaminant to enter the distribution system (Save-Soderbergh et al., 2017):

- Leakage into reservoirs and water towers with free water surfaces
- Pipe breakage
- Maintenance/installation work on the pipe network
- Water hammers
- Sudden pressure loss, e.g. due to power failure
- Cross connections from higher pressure systems, e.g. pressurized sewage systems
- Sabotage
- Abnormalities/problems with the different processes in the water treatment plant
- Abnormal bacterial growth can also occur given improved conditions for bacteria, such as:
- Stagnation due to pipe sections with zero demand
- Supply of organic matter
- Increased water temperatures

During the incidents it was crucial to go through data in the monitoring system to find anomalies in the operational events and to have access to an updated list of all ongoing or recently finished maintenance or installation works, thereby being able to model the locations of these as probable sources of contamination.

Usage of hydraulic modelling during the incidents

Finding sample points.

Water samples were be taken in both taps and fire hydrants. The sample points were selected based on modelling results and in order not to miss a more diffuse spread or the possibility that the origin of the contaminant was more than one.

Free or trap possible causes of contamination.
In the EPANET based MIKE URBAN water distribution model it is possible to insert a contaminant anywhere in the distribution system to see how it propagates throughout the network over time. Using this tool, it was possible to disclaim e.g. reservoirs as being the host of a source of contamination and to disclaim installation works that have recently been performed. Furthermore, an iterative approach could be applied to prove or not to prove experience-based guesses of where the contaminant could be located.

Systematic reduction the area with boil water advisory.
It was possible to simulate how the water with high concentration of coliform bacteria spread throughout the network, and conse-quently what areas that were not affected. The area with boil water advisory could thereby be systematically reduced. Water samples verified the model results before the restrictions were lifted.

Optimizing the flushing of the network.
After isolating the source, a procedure recommended by VAKA (Swedish National Water Catastrophe Group) was applied. This includes ten turno-vers in the entire area followed by two subsequent clean water samples. Hydraulic modelling was used to determine the turnover time given normal water consumption. This was done esti-mating that the water in the area with boil water advisory was contaminated to an extent of 100%, then simulating flushing and consumption to a theoretical extent of 0% contaminated wa-ter. As a result, it was possible to see which parts of the network that had the longest turnover time and thereby identify where to flush to shorten the total turnover time. The longest turnover time was thereafter multiplied with 10 to get the required time for 10 turnovers.

Optimizing the status of valves.
Modelling made it possible to, in advance, foresee the hydrau-lic effects of valve management. Before a valve was closed or opened, the model could confirm whether or not the operation would give the desired effect. Together with flushing, the closing or opening of valves could keep the area with boil water advisory as small as possible and en-sure delivery of potable incoming water to critical consumers, e.g. the hospital.

RESULTS AND DISCUSSION

This section aims to describe the efforts made to find the causes of contaminations in Lund, as well as to discuss the advantages and disadvantages of hydraulic modelling as a tool in trace methodology.

Incident no 1

On March 9 2017, increased levels of coliform bacteria were detected and confirmed from one of the regular sampling sites in central Lund (Figure 1). Further samples verified the previous result. As a consequence, a boil water advisory was issued for the entire city of Lund. Step by step, the area could be limited to the central part of the city although still affecting the university hospital and 20,000 habitants.

Results from analyzed water samples from the public network between March 7 and March 15 indicated levels of coliform bacteria ranging from <1 to 25 cfu/100 ml. More than 700 water samples were analyzed from both taps and fire hydrants. The concentrations in the same sampling point fluctuated around the threshold value for when water is regarded as unfit due to the standard set by the Swedish National Food Agency (10 cfu/100 ml). In all samples, except for one, the coliforms were identified as Erwinia spp; coliforms that are usually considered as plant pathogens and thrive in soil and surface waters (Bottone & Schneierson, 1972). During the period with boil water advisory, illness did not increase in the area (based on statistics from 1177 (medical advisory) and daily reports from the medical Officer at the hospital).

Less than 24 h after the boil water advisory had been issued for the entire city of Lund, the southernmost pressure zone was found to be clean. Gradually, the contamination was traced to an area around the regional university hospital. The hospital area is supplied with water from three main pipes and under normal conditions water will pass

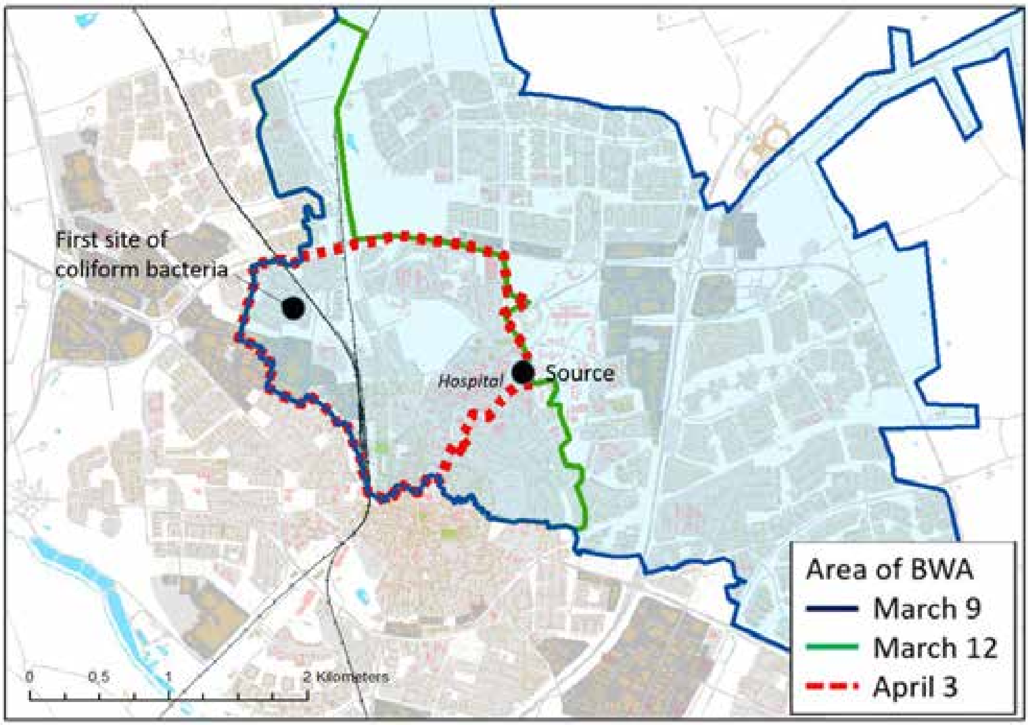

Figure 1. *The different areas with boil water advisory in Lund during incident no 1, with the exception of the firstly announced area including the whole city. Also shown in Figure 1 is the location of the firstly detected bacteria as well as the location of the source of contamination. The light blue color represent the pressure zone in which the contaminated sample was found.*

through the hospital network back to the public network. Laboratory results of water from the hospital network showed levels of bacteria (typed Erwinia spp.) many times higher than in the public network. The hospital network was therefore isolated so that water could not transit back to the public distribution system. The water in the public network then immediately showed decreasing levels of coliform bacteria and reached potable levels in a few days.

On March 21 the boil water advisory was lifted with the exception of the hospital area. Unfortunately, a backlash came two days later with raised concentrations of coliforms in sampling points just west of the hospital area. On March 24, a boil water advisory was again issued for the same area as previously (Figure 1, green encirclement). Either there was an additional source or the assumption that the hospital area acted as the source of pollution was incorrect. In the vicinity of the hospital, an installation work performed three months earlier again aroused interest. An inverted siphon had been put in to enable the installation of a new district heating pipe. Hydraulic modelling showed a spread pattern that resembled the results from the water samples perfectly (Figure 2).

Early on in the investigations this site had been disclaimed as onsite VA SYD personnel reported that the installation work had been performed under proper hygienic conditions, thereby it was considered as an unlikely source of contamination. Re-examining the installation work, analyses showed that drinking water entering the inverted siphon was clean and that water leaving the siphon was contaminated with high concentrations of coliform bacteria typed Erwinia spp. The source had been found and as the contaminated pipe was taken out of operation the levels of bacteria rapidly decreased in the area with boil water advisory. The restrictions were finally lifted on April 10.

To find out why the siphon acted as the host of the contaminant a filming and pigging procedure was initiated. The film showed a white blob in the pipe (Figure 3). The white blob, with the size of an orange, was recovered when the pipe was poly-pigged and could later be identified as wheat flour with growth of Erwinia spp. As for the origin of the wheat flour, the main hypothesis is that it was inserted during the installation work to absorb excess water when welding the new polyethylene pipe with electrofusion fittings to the existing polyethylene pipe.

Incident no 2

Three months after the first incident, water analysis of another regular sample showed increased levels of coliform bacteria in the distribution system. This time the outbreak originated in the north-eastern district in Lund. A boil water advisory was announced for nine days.

When the first laboratory results showed presence of coliform bacteria, VA SYD initiated flushing in hydrants in parts of the area with low turnover time, which led to propagation of coliform bacteria to earlier non-contaminated parts. This move together with modelling and closing of valves contributed to the identification of the source, but on the other hand, bacteria were spread. This states the importance of having a theory of the contaminants origin before flushing; de-scribed by Liu et al. (2012); i.e. knowledge about the release history of a contaminant is essen-tial in order to reduce the exposure. To be able to perform accurate flushing, it is necessary to have knowledge about the contaminants location, start time, duration and mass flow rate (Preis & Ostfeld, 2007).

Given the spread pattern of the coliforms when flushing the network, the modelling results as well as the results from the drinking water analyses came to the conclusion that the contaminant was located in one of the main pipes in the north part of the area. When identified, the contami-nated pipe was filmed, flushed and pigged. When pig-

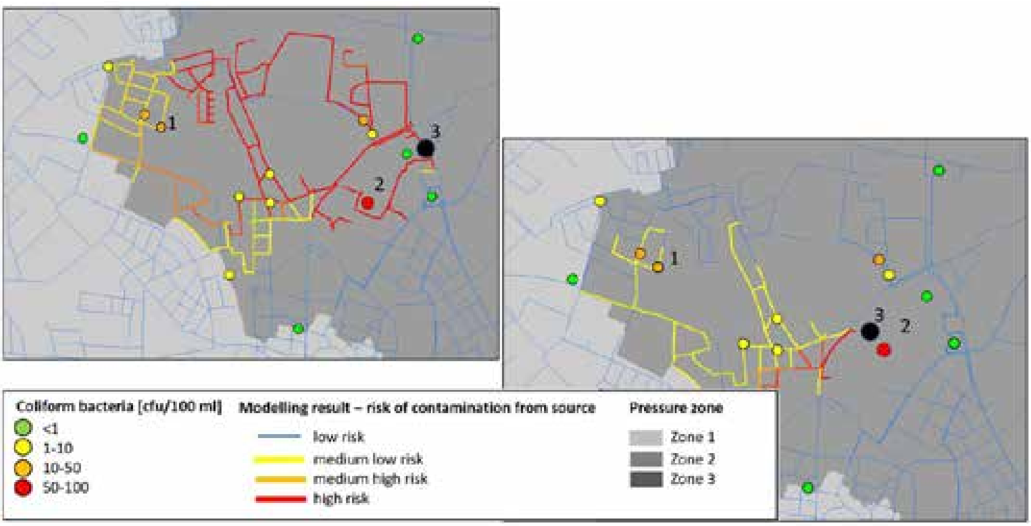

Figure 2. *Laboratory results for water samples during the period of March 7 to March 15. The lines represent modelling results of the propagation of a contamination from a potential source. The first site of coliform bacteria is marked (1). The highest level of coliform bacteria was detected within the hospital area (2) but the hospital area did not perfectly well correspond with the distribution pattern of the pollutant (right picture). Instead, the modelling results from another potential source correlated with the results of the analyzed water samples (left picture).*

Figure 3. *To the left: The white blob (later identified as wheat flour) in incident no 1 was about the size of an orange. The black chips are pieces of the cut PE-pipe. To the right: The blob from incident no 2, later identified as growth of bacteria and fungus around a paper napkin.*

ging the pipe, a blob of probable organic origin was caught (Figure 3). Examinations of the blob using microscopy with phase contrast and Fourier Transform Infrared Spectroscopy (FTIR) indicated fungus and bacterial growth on a paper napkin (Werker & Bengtsson, 2018). Typing of the bacteria indicated Seratia spp.

Hydraulic modelling versus water samples – focus on the hospital area in incident no 1

As shown in Figure 2 the concentrations of coliforms in samples taken within the hospital network were many times higher than in the rest of the network. This in combination with the rea-sonable hydraulic location of the hospital led to the erroneous conclusion that the source of the bacteria was located within the hospital area. The conclusion was drawn despite the fact that some water analysis results did not correlate with the model results (Figure 2). It was simply assumed that the model was wrong which ultimately prolonged the time with boil water adviso-ry.

The situation in incident no 1 can be interpreted as a practical experience of what is theoretically described and hydraulically modelled by Liu et al. (2011); the different possible solutions to where the sources of contamination (the source nodes) are located tend to concentrate in the vicinity of the exact location of the source. Furthermore, it is not always the correct solution that gets the highest rank in means of prediction error values; and it is worth the effort of examine probable solutions with lower rank in the area of interest (Liu et al., 2011). The lesson learned from the hospital situation is to keep searching for different source locations although a probable source of contamination has been identified.

Lessons learned

Hydraulic modelling served as a useful tool in especially three main areas:

Reducing the number of sample points and limiting the area with boil water advisory.

The number of sample points could be limited as the modelling results supported the empirical evaluations of which areas that could not be reached by contaminated water. Since restrictions in drinking water usage causes stress on the society it is of great public interest to be able to lift them. The method of reducing the number of sample points, based on modelling results, was developed during incident no 1 and used with confidence during incident no 2, reducing the time and cost consuming work of sampling and analyzing drinking water from numerous locations.

Serving as a complement to drinking water analyses.
The results from the water analyses gave snapshots of the concentrations in the very moment that the samplings were done. Using the trace modelling result as a background provided a stability when working with the origin and spread of the coliform bacteria, even though the actual concentrations fluctuated. The contribution of hydraulic modelling as a stable decision basis is also mentioned by Liu et al. (2011).

Identifying the source instead of disposing it.
The intention of solving the problem at hand can often reduce the chances of finding the explanation to the contamination; flushing the network in order to exchange the polluted water and adding chlorine compounds to decrease the concentra-tions of bacteria. Usage of hydraulic modelling contributes to the possibilities of finding the source. In order to resolve the situation permanently it is often crucial to locate the source (Liu et al., 2011). In situations where the flushing possibilities are restricted, this becomes critical.

Possibilities, restrictions and areas of development
The two incidents in Lund were of equivalent origin; abnormal growth of coliform bacteria on organic material on a certain location in the distribution system. Would modelling be as useful if the spread was more diffuse or if there were more than one source? Other authors e.g. Bazagan-Lari (2013) suggest multi injection source contamination as an area of further research.

A different scenario is when the habitants suddenly get disease symptoms that is (yet) not linked to the drinking water. If the illness can be geographically defined, it could possibly be compared to the patterns of drinking water distribution in the actual area. An area of development is closer cooperation with the health authorities that continuously map illness on a geographical basis.

Absolutely crucial to the viability of hydraulic modelling in situations regarding contaminated drinking water is, that the model itself is reliable. An unreliable model could in worst case indicate spread images that are not correct and that increase instead of decrease the possibilities of solving the problem. The usage of hydraulic modelling during the incidents in Lund also stressed the importance of developing protocols for modelling of scenarios with contaminated water. The experience acquired by VA SYD personnel suggest:

- Systematically modelling saves time. Start with disclaiming the main pipes and other parts of the distribution system that affect large part of the network.
- Knowledge about all works are essential and wide time span must be taken into account. The origin of the pollutants in the two incidents were installation works executed months before the outbreaks emerged.
- Keep searching for different source locations although a probable location has been identified.
- Water samples should be taken in fire hydrants instead of in taps in order to match the model accurately.

It is a prerequisite that the users can interpret the results correctly and set up the adequate scenarios. It is also crucial that the model itself is reliable.

To facilitate the operational work more measurement equipment will be installed in the network. VA SYD will divide the larger pressure zones into smaller DMAs (District Metering Areas). The DMA flow data can be used to verify the model in the network finding deviations caused by e.g. closed valves or increased local consumption. The DMAs will also discover leakage in an early stage which will reduce the risk of contamination due to acute water leaks. A future ambition is to have an online model that is connected to the monitoring system and automatically updated to correspond to reality. This would increase the accuracy of the water quality model results.

CONCLUSIONS

During the two incidents with contaminated drinking water in Lund, hydraulic modelling turned out to be an effective tool as part of the trace methodology for detection of microbiological contaminations in the drinking water distribution system. The benefits were substantially:

- Speeding up the trace process
- Reducing the number of water sample points and limit the area with boil water advisory
- Serving as a complement to drinking water analyses and representing a stable decision basis
- Optimizing and predicting the effects of the flushing and valve management
- Increasing the likelihood of identifying the source of contamination in order to solve the problem permanently

It was regarded as essential to get to the root of the problem causing the contaminations, in order to prevent the situations from reoccurring.

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