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Research article

On-line detection of *Escherichia coli* intrusion in a pilot-scale drinking water distribution system

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ABSTRACT

Improvements in microbial drinking water quality monitoring are needed for the better control of drinking water distribution systems and for public health protection. Conventional water quality monitoring programmes are not always able to detect a microbial contamination of drinking water. In the drinking water production chain, in addition to the vulnerability of source waters, the distribution networks are prone to contamination. In this study, a pilot-scale drinking-water distribution network with an on-line monitoring system was utilized for detecting bacterial intrusion.

During the experimental *Escherichia coli* intrusions, the contaminant was measured by applying a set of on-line sensors for electric conductivity (EC), pH, temperature (T), turbidity, UV-absorbance at 254 nm (UVAS SC) and with a device for particle counting. Monitored parameters were compared with the measured *E. coli* counts using the integral calculations of the detected peaks. EC measurement gave the strongest signal compared with the measured baseline during the *E. coli* intrusion. Integral calculations showed that the peaks in the EC, pH, T, turbidity and UVAS SC data were detected corresponding to the time predicted. However, the pH and temperature peaks detected were barely above the measured baseline and could easily be mixed with the background noise. The results indicate that on-line monitoring can be utilized for the rapid detection of microbial contaminants in the drinking water distribution system although the peak interpretation has to be performed carefully to avoid being mixed up with normal variations in the measurement data.

1. Introduction

Bacteria, fungi and yeasts are systematically found in drinking water distribution networks. The distribution networks are not comprised as inert systems supplying drinking water for large areas, but rather are referred to as biological and chemical reactors that interact with the distributed water (Berry et al., 2006; Gauthier et al., 1999; Lautenschlager et al., 2013). Accidental microbial contaminations in drinking water distribution, such as cross-connections of potable water sources with sewage pipelines, have gained attention (Lahti and Hiisvirta, 1995; Laine et al., 2011). In addition to the cross-connections, intrusions are common reasons for microbial contaminations (Breitenmoser et al., 2011; Jakopanec et al., 2008; Kuusi et al., 2005; Vestergaard et al., 2007). Intrusions in the distribution systems may hamper the water quality over several days. If the contamination is not detected soon enough to start corrective measures, the attack rates of waterborne illness among water consumers can be high. Further, during heavy precipitation or snow melts, contaminating agents are being washed into creeks, rivers, streams, lakes, or vulnerable groundwater aquifers. When these waters are used as sources of drinking water and the water is not treated adequately, impurities may end up in the drinking water.

Monitoring programmes under the EU Drinking Water Directive are designed such that a total of 48 microbiological, chemical and indicator parameters must be monitored and tested regularly (EU, 1998). Unfortunately, the standard monitoring programmes have only a low probability of detecting faecal contamination (van

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Lieverloo et al., 2007). Since drinking water contamination may cause serious public health consequences, the need to improve methods for monitoring drinking water quality in the distribution systems is evident (Hall et al., 2007; Storey et al., 2011). Subsequently, tools are needed for the definitive confirmation of the presence of contaminants in the drinking water using analytical instruments. The desired monitoring techniques include rapid on-line methods with the ability to detect a microbial contamination of water. Also concentration techniques are needed for increasing the chances of detection and identification of the microbial contaminant in the drinking water. There is also an increasing interest in utilizing the physical characteristics of microorganisms as a mean to detect them (Sherchan, 2013). However, during the water contamination events, there are usually other impurities in water than just microbial contaminants (e.g. lake or sewage water) and hence observing the overall water quality deterioration might offer a solution better than the attempts to detect a certain microbe alone.

Previous studies have shown that on-line measurements could be a solution to detecting harmful events that affect drinking-water microbial quality (Mustonen et al., 2008; Plummer and Long, 2007). Indeed, it has been shown in laboratory experiments that certain optical measurements, such as the measurement of absorbance, turbidity and particle count, have the potential to detect high bacteria concentrations in drinking water (Ikonen et al., 2013). Impurities in the drinking water have been detected in simulated experimental conditions using different physico-chemical parameters, such as the measurements of free chlorine, total organic carbon (TOC), oxidation reduction potential (ORP), EC, and chloride (Hall et al., 2007). In one study (Helbling and VanBriesen, 2008), it was concluded that changes in measuring residual chlorine were proportional to the amount of fed *Escherichia coli* and *Mycobacterium aurum* bacteria, even though *E. coli* bacterial numbers were not detectable at the level of under 10^5 CFU/mL. Fass et al. (1996) found that 1–50% of injected bacterial adsorbed within a few hours to the indigenous bacterial biofilm. The feasibility of on-line measurements in the assessment of the drinking water quality is largely dependent on the remote monitoring and interpretation of the real-time data (Rosen and Bartrand, 2013; Storey et al., 2011). Further this data needs to be implemented on management strategies by responsible stakeholders (Lee et al., 2012). Recently data processing research have used e.g.clustering to find correlation between the sensors data and contamination events have used e.g. clustering (Perelman and Ostfeld, 2011).

The spectrum of microbial agents that cause waterborne illness is wide, including pathogens such as noroviruses, *Cambylobacter* spp., *Cryptosporidium* spp., and *Giardia* spp. (Craun, 1986; Mac Kenzie et al., 1994; Maunula et al., 2009; Pitkänen, 2013). However, instead of pathogens, indicator bacteria are used for water quality monitoring. *E. coli* is the most commonly used faecal bacteria indicating a recent faecal contamination of drinking water by sewage or animal feces. Standardized culturing methods are commonly used for detecting *E. coli* from drinking water. More advanced water quality sensors such as Hach GuardianBlue (Hach Company, Colorado, USA) event detection system, the BioSentry technology (JMAR Technologies Inc, SanDiego, USA), the S::CAN spectrolyser technology (scan Messtechnik GmbH, Vienna, Austria), and the GE 5310 (GE Infrastructure, Colorado, USA) online total organic carbon (TOC) unit have also been tested with different concentrations of *E. coli* bacteria (10^3–10^6 CFU/mL) (Miles et al., 2011). The presence study focused on detecting the water quality changes caused by a specific *E. coli* concentration (10^6 CFU/mL) and was made as intrusion type. The transportation of *E. coli* has been studied before in the distribution systems with counts of 1.5 x 10^6 CFU/ml (Fass et al., 1996). In this study, the efficiency of the on-line monitoring techniques for detecting *E. coli* intrusion was tested in a pilot-scale drinking-water distribution system. The on-line measurements of electric conductivity (EC), particle counting, pH, temperature (T), turbidity, UV-absorbance at 254 (UVAS SC), water flow, and water pressure were used for detecting injected *E. coli* during contamination events. After the *E. coli* contaminant was funneled through the pilot system, the efficiency of shock chlorination to decontaminate the distribution system was explored.

2. Materials and methods

2.1. The pilot-scale drinking water distribution system

The water of the City of Kuopio, Finland, was used in the experiments to test the on-line monitoring devices for their capacity to detect the intrusion of *E. coli* bacteria in the pilot-scale drinking-water network. The water originates from two raw water sources: Hietasalo and Jänneniemi. The pilot system used in the experiments is located at the laboratory of Savonia University of Applied Sciences, Kuopio, Finland, which is located five kilometers from the waterworks. Tap water was collected into a 1.5 m^3 stainless steel reservoir before pumping through stainless steel pipes to the pilot distribution network. Prior to the present study, the pilot-scale distribution network described by Lehtola et al. (2004) was reconstructed with an additional pipeline to form a continuous network of pipes. The construction of the pilot distribution network and the locations of the on-line meters in the network are shown in Fig. 1. The pilot distribution network consisted of three levels that were circulating around the study hall. The pipe material was a composite (polyethylene-aluminum-polyethylene) plastic. Level 1 and 2 were 100 m long, each with an inner diameter of Ø 41 mm, while Level 3 had a length of 200 m with an inner diameter Ø 12 mm. The system included a set of on-line measurements: eight temperature sensors (ST21, Bürkert, Ingelfingen, Germany), two EC sensors (Transmitter 8225, Bürkert, Ingelfingen, Germany), two pH sensors (Durafet III electrode, Honeywell, Metropolis, IL, USA), and two turbidity meters (1720E Low-range, Hach-Lange, Loveland, USA). On-line particle measurement (S4031, PAMAS, Rutesheim, Germany) was transferable and could be attached to any valve. In addition, there was a sensor measuring UV-absorbance at 254 nm (UVAS plus SC; here as UVAS SC, Hach-Lange, Düsseldorf, Germany), two flow meters (Transmitter 8055, Ingelfingen, Bürkert, Germany), and six pressure meters (Sitrans P, Siemens, München, Germany).

Biofilm collectors were built as the components of the pilot-scale drinking water distribution system. There were six biofilm collectors that consisted of 3–4 parallel 20 cm long pieces of composite plastic pipes with ball valves at both ends, situating on Level 3 of the distribution system. The parallel collectors were connected in-line and installed as part of the system.

2.2. Baseline monitoring

Prior to the simulated contamination events, baseline information about water temperature, pH and EC were measured (pH/cond 340i-meter, WTW, Weilhem, Germany), and free and total chlorine concentrations were determined (Micro 1000 photometer, Palintest, Gateshed UK) in the laboratory from the water samples during the one-month period. Water samples were taken from the water tank and four sampling points from the distribution network system (Fig. 1). The heterotrophic plate count (HPC) was analysed at the laboratory on Reasoner's 2 Agar medium (R2A) (Reasoner and Geldreich, 1985), with an incubation time of 7 days at 22 ± 2 °C. A sample for total microbial count (TMC) was stored at 4 °C in 2% formaldehyde before being stained with DAPI (4′, 6-diamidino-2-