Water Research 96 (2016) 148–154

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Evaluation of exposure scenarios on intentional microbiological contamination in a drinking water distribution network

Jack Schijven [a, b, *], Jean Marie Forêt [c], Jurgen Chardon [a], Peter Teunis [a, d], Martijn Bouwknegt [a], Ben Tangena [a]

[a] National Institute for Public Health and the Environment (RIVM), PO Box 1, Bilthoven, The Netherlands
[b] Faculty of Geosciences, Utrecht University, The Netherlands
[c] UReason, Drie Akersstraat 1, Delft, The Netherlands
[d] Center for Global Safe WASH, Rollins School of Public Health, Emory University, Atlanta GA, USA

ARTICLE INFO

Article history:
Received 29 December 2015
Received in revised form
25 February 2016
Accepted 24 March 2016
Available online 26 March 2016

Keywords:
Drinking water distribution network
Pathogen contamination
QMRA
Tooth brushing
Shower model

ABSTRACT

Drinking water distribution networks are vulnerable to accidental or intentional contamination events. The objective of this study was to investigate the effects of seeding duration and concentration, exposure pathway (ingestion via drinking of water and tooth brushing and inhalation by taking a shower) and pathogen infectivity on exposure and infection risk in the case of an intentional pathogenic contamination in a drinking water distribution network. Seeding of a pathogen for 10 min and 120 min, and subsequent spreading through a drinking water distribution network were simulated. For exposure via drinking, actual data on drinking events and volumes were used. Ingestion of a small volume of water by tooth brushing twice a day by every person in the network was assumed. Inhalation of contaminated aerosol droplets took place when taking a shower. Infection risks were estimated for pathogens with low ($r = 0.0001$) and high ($r = 0.1$) infectivity. In the served population (48 000 persons) and within 24 h, about 1400 persons were exposed to the pathogen by ingestion of water in the 10-min seeding scenario and about 3400 persons in the 120-min scenario. The numbers of exposed persons via tooth brushing were about the same as via drinking of water. Showering caused (inhalation) exposure in about 450 persons in the 10-min scenario and about 1500 in the 120-min scenario. Regardless of pathogen infectivity, if the seeding concentration is 10^6 pathogens per litre or more, infection risks are close to one. Exposure by taking a shower is of relevance if the pathogen is highly infectious via inhalation. A longer duration of the seeding of a pathogen increases the probability of exposure.

1. Introduction

Drinking water systems are vulnerable to accidental or intentional contamination events (Clark and Deininger, 2000). The water industry must assume that water resources are at risk and develop a preparedness plan for monitoring, communication, and decontamination in the event that an intentional attack on the water supply occurs (Rose, 2002). In the case of a contamination event in the drinking water distribution network, a quick assessment of the situation as well as proper response actions are required. Such an assessment requires knowledge of the behaviour of contaminants in the network and the resulting public health effects as the basis for appropriate measures for protection of the consumers and mitigation of the effects; measures are to be conducted by operators of the water utility.

In order to determine the impact of a contamination event and to evaluate control measures, the decision support system NETSIM has been developed (Tangena et al., 2013). NETSIM can be used in an off-line modus where various contamination scenarios can be analysed, providing insight in possible outcomes and the effects of interventions. Scenarios to evaluate various contamination events are defined in consultation with chemical and microbiological experts, security experts and operators. The scenarios differ in the type of the contaminant (fate in drinking water, toxicological or pathogenic properties), the event, quantity, pace and place of introduction, the exposure path (oral, inhalation, dermal) and the control measures (opening and/or closing valves, draining off or

* Corresponding author. National Institute for Public Health and the Environment (RIVM), PO Box 1, Bilthoven, The Netherlands.
E-mail address: Jack.Schijven@rivm.nl (J. Schijven).

http://dx.doi.org/10.1016/j.watres.2016.03.057
0043-1354/

stop pumping). In that way, a library of contamination scenarios may be constructed. NETSIM uses EPANET-MSX (version 2, US Environmental Protection Agency, Cincinnati, Ohio) for calculating the distribution of a contamination throughout a drinking water distribution network. For a few microbial pathogens, it is able to conduct a Quantitative Microbial Risk Assessment (QMRA) from the exposure to the pathogenic contamination via drinking water consumption.

There are a few published studies using Quantitative Microbial Risk Assessment (QMRA) to assess the health risk associated pathogen transport in a drinking water distribution network. LeChevallier et al. (2003), Teunis et al. (2010) and Yang et al. (2011) used a risk model for predicting intrusion of rotavirus and norovirus from sewage into a drinking water distribution network due to pressure events. Blokker et al. (2014) developed a QMRA model for contamination events after mains repairs. The risk calculations were conducted for enterovirus, *Campylobacter*, *Cryptosporidium* and *Giardia*.

Risk of infection is determined by the dose (number of pathogenic microorganisms to which one is exposed) and the infectivity of the pathogen (Teunis et al., 1999). The amount and duration of seeding a pathogenic microorganism in a drinking water distribution network and the way the contamination subsequently spreads throughout the distribution network are major factors determining how many persons may be exposed to the pathogen. The size of the network (number of connections) and the location of the seeding determine this too. Ingestion or inhalation of unboiled drinking water and the coincidence of ingestion or inhalation with the presence of the pathogen in the water determine exposure (Teunis et al., 2010). Yang et al. (2011) simulated negative pressure events in a drinking water distribution network with a duration of 1 s–17 min. A longer duration increased the amount of sewage entering the system (in the case of leakages that allow this kind of intrusion) and the probability of a person's water consumption coinciding with the concentration peak of viruses from the intruding sewage.

So far, Quantitative Microbial Risk Assessment (QMRA) of a microbial contamination in the drinking water distribution network has relied on the daily drinking water usage as function of time (includes washing, toilet use, etc.) for determining the time points of drinking a glass of water (Blokker et al., 2014; Davis and Janke, 2009). Here, we use actual data on drinking time points. Tooth brushing is an activity that most people exert twice a day, even when they never drink unheated tap water, and whereby they ingest a small amount of tap water. Tooth brushing may therefore be a highly vulnerable event in the case of an intentional contamination of the drinking water distribution network. Another exposure pathway may be inhalation of contaminated aerosol droplets when taking a shower. QMRAs for exposure to Legionella when taking a shower or a bath have been conducted (Azuma et al., 2013; Schoen and Ashbolt, 2011; Storey et al., 2004). To our knowledge, QMRA for exposure to an intentionally introduced pathogen in the drinking water network via tooth brushing or taking a shower has not yet been reported in literature.

The objective of this study was to investigate the effects of seeding duration and concentration, exposure pathway (ingestion and inhalation) and pathogen infectivity on exposure and infection risk in the case of an intentional pathogenic contamination in a drinking water distribution network.

2. Method

2.1. Model drinking water distribution network

NETSIM is a decision support system (Tangena et al., 2013) that interfaces with EPANET-MSX (version 2, US Environmental Protection Agency, Cincinnati, Ohio). EPANET-MSX performs extended period simulation of hydraulic and water quality behaviour within pressurized pipe networks consisting of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs.

Daily drinking water usage (Bakker et al., 2013) determines the water flow in the network. The contamination is advected with the water flow. Dispersion is not considered. In reservoirs in the network, complete instantaneous mixing takes place. NETSIM has an interactive dashboard that facilitates definition and running of simulations of contaminant transport in the network. NETSIM also enables simulation of control measures, such as flushing of contaminated pipes, shutting off pumps and opening or closing valves. For the purposes of the current study, a model drinking water distribution network of a Dutch town (anonymous) consisting of 11,533 nodes, 5 reservoirs, 9954 mains and 2021 valves was implemented in NETSIM. The total water demand of the network is 2.9×10^6 m^3/year. In the area live 48,000 persons (20,000 connections, a node may encompass several connections). The numbers of persons per node were derived from the daily total drinking water demand at each node. NETSIM-MSX captures simulation results from EPANET-MSX for post-processing. For a defined simulation period, EPANET calculates contaminant concentrations for each node and simulation time step. All concentration-time profiles are stored in a csv-file (comma separated values), except for the nodes where the contaminant did not pass. Another csv-file contains the numbers of persons per node.

2.2. Scenarios

Five scenarios simulated deliberate microbial contamination. In the first two scenarios, a suspension of a pathogenic microorganism was seeded (or injected) at time 0:00 a.m. at a node from which water may reach the whole network. The concentration in the water of the network at the node where pathogens were seeded was set equal to one, implying normalized concentration levels at the nodes. Using normalised concentrations (C_t/C_0), allows generating scenarios with different seeding concentrations (C_0) using the same output from NETSIM. Transport of the contamination was considered to be conservative, *i.e*. die-off and interaction with the pipe surfaces were not included. Chlorine disinfection was not considered, because it is not applied in the Dutch drinking water production. In the first scenario, the duration of seeding the suspension was 10 min. In the second scenario, the seeding duration was 120 min. The simulation period was 24 h with 10 min time steps. The effect of seeding time was investigated by adding three scenarios with a seeding duration of 10 min and seeding times of 3:00 a.m., 06:00 a.m. and 10:00 a.m. For risk calculations, the default seeding concentration was set to 10^6 pathogens per litre. The effect of seeding concentration on the infection risk was investigated for the first 10-min seeding scenario with a seeding concentration range of 1–10^7 pathogens per litre in decimal steps.

Post-processing of the network simulations consisted of estimating infection risk from exposure to microbial contamination in the network by means of a Quantitative Microbial Risk Assessment (QMRA). For QMRA, the csv-files were imported into a Mathematica notebook (version 10.3.1.0, Wolfram Inc., Champaign, Illinois). QMRA entailed estimating exposure to the microbial contamination from consuming contaminated unboiled drinking water, and from inhaling contaminated aerosol droplets when taking a shower and subsequent risk of infection. The QMRA requires data on drinking water consumption and tooth brushing (times and volumes), taking a shower (times, duration, frequency), and dose response date as is explained in detail in the following sections.