WATER RESEARCH 54 (2014) 254–261

Available online at www.sciencedirect.com

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Health risk assessment for splash parks that use rainwater as source water

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ARTICLE INFO

Article history:
Received 21 October 2013
Received in revised form
30 January 2014
Accepted 2 February 2014
Available online 12 February 2014

Keywords:
Interactive splash park
Fountain
Risk of infection
Exposure
QMRA
Rainwater

ABSTRACT

In the Netherlands, rainwater becomes more and more popular as an economic and environmentally sustainable water source for splash parks, however, the associated public health risk and underlying risk factors are unknown. Since splash parks have been associated with outbreaks of infectious diseases, a quantitative microbial risk assessment was performed using *Legionella pneumophila* as a target pathogen to quantify the risk of infection for exposure due to inhalation and *Campylobacter jejuni* for ingestion. Data for *L. pneumophila* and *C. jejuni* concentrations in rainfall generated surface runoff from streets were extracted from literature. Data for exposure were obtained by observing 604 people at splash parks, of whom 259 were children. Exposure volumes were estimated using data from literature to determine the volume of exposure through inhalation at 0.394 μL/min (95% CI-range 0.0446–1.27 μL/min), hand-to-mouth contact at 22.6 μL/min, (95% CI-range 2.02–81.0 μL/min), ingestion of water droplets at 94.4 μL/min (95% CI-range 5.1–279 μL/min) and ingestion of mouthfuls of water at $21.5 \cdot 10^3$ μL/min (95% CI-range $1.17 \cdot 10^3$ –$67.0 \cdot 10^3$ μL/min). The corresponding risk of infection for the mean exposure duration of 3.5 min was $9.3 \cdot 10^{-5}$ (95% CI-range 0–$2.4 \cdot 10^{-4}$) for inhalation of *L. pneumophila* and $3.6 \cdot 10^{-2}$ (95% CI-range 0–$5.3 \cdot 10^{-1}$) for ingestion of *C. jejuni*. This study provided a methodology to quantify exposure volumes using observations on site. We estimated that using rainwater as source water for splash parks may pose a health risk, however, further detailed quantitative microbial analysis is required to confirm this finding. Furthermore we give insight into the effect of water quality standards, which may limit infection risks from exposure at splash parks.

Abbreviations: QMRA, Quantitative Microbial Risk Assessment; C, concentrations of pathogenic micro-organisms; V, individual exposure volume; D, ingested dose of pathogenic micro-organisms; CFU, Colony Forming Unit; MPN, Most Probable Number; CI, Confidence Interval; *r*, infectivity parameter of the exponential dose–response model; α,β, infectivity parameters of the hypergeometric dose–response model; P_{inf}, Risk of infection.

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0043-1354/$ – see front matter
http://dx.doi.org/10.1016/j.watres.2014.02.010

1. Introduction

Splash parks are often located in shopping areas or play grounds. They are popular features that encourage many children to play with water. Splash parks use water that is typically stored in an underground reservoir or surge chamber and is sprayed into the air; after it hits the ground, it flows back to the reservoir through floor drains. Although almost all splash parks incorporate some form of disinfection, many show poor water quality through poor design or poor maintenance (Kebabjian, 2003). Thus, splash parks have been associated with outbreaks of infectious diseases, including *Legionella* (Hlady et al., 1993; Palmore et al., 2009; Haupt et al., 2012; Correia et al., 2001), *Cryptosporidium* and *Giardia* (Eisenstein et al., 2008; Anonymous, 2000, 1999), *Shigella* (Fleming et al., 2000; Bancroft et al., 2010), *Salmonella* (Andión Campos, 1995; Molinero et al., 1998; Usera et al., 1995), *Leptospira* (Cacciapuoti et al., 1987), and noroviruses (Hoebe et al., 2004).

People may be exposed to waterborne pathogens in splash park through inhalation, ingestion and dermal contact. Inhalation of aerosols causes deposition of water in the respiratory tract (Heyder et al., 1986) and may cause allergic reactions (Douwes et al., 2003). If pathogens are present in water of splash parks, inhalation may cause infectious diseases such as pneumonia due to *Legionella pneumophila* (Fields et al., 2002). Ingestion of water, whether intended (by swallowing mouthfuls of water) or unintended (through getting water droplets in the mouth or through hand-to-mouth contact) can cause gastroenteritis though infection with enteric pathogens such as norovirus, rotavirus, *Campylobacter*, *Giardia* or *Cryptosporidium*, and may cause other severe illnesses such as hemolytic uremic syndrome (Keene et al., 1994) or Gullain-Barré syndrome (McCarthy and Giesecke, 2001). Finally, dermal contact (skin and mucous membranes of nose, ears and eyes in contact with the water) can result in infections such as wound infections due to *Aeromonas hydrophila* (Semel and Trenholme, 1990), otitis externa due to *Pseudomonas aeruginosa* (Van Asperen et al., 1995), or conjunctivitis due to adenoviruses (Crabtree et al., 1997).

Quantitative microbial risk assessment (QMRA) is a tool to quantify health risks and to get insight into measures that can prevent outbreaks (World Health Organization, 2011). A QMRA requires information on the concentration of pathogens in the matrix, the fate and behavior of pathogens, the volume of water to which people were exposed, and the dose–response relation for the pathogen.

Because harvested rainwater has been widely regarded as a sustainable source for water (re)use in urban areas and for recreational purposes, it is often used as a source water of splash parks (De Man et al., 2014b). Pathogens may be present in rainwater dependent on weather conditions such as rainfall intensity and temperature (Schets et al., 2010; Kaushik et al., 2012). Furthermore, the atmospheric deposition of airborne microorganisms (Evans et al., 2006), the (rooftop) runoff of fecal depositions of birds and other mammals (Ahmed et al., 2012; Fewtrell and Kay, 2007), and the growth or decay of micro-organisms in collected rainwater may influence the presence of pathogens in rainwater (Ahmed et al., 2014). Pathogens may also be introduced into water of splash parks by people, dogs, birds and other animals upon contact with the water (Hoebe et al., 2004).

To be able to quantify the public health risk of splash parks that use rainwater as their source water, an exposure assessment was performed using field observations. The generated exposure data were used to determine exposure volumes and infection risks for inhalation and ingestion by a QMRA approach. The QMRA was performed with Monte Carlo simulations to provide a range of uncertainties in infection risks.

2. Methods

2.1. *Hazard identification*

People are exposed to the water of urban splash parks through ingestion, inhalation and dermal contact. To estimate the public health risks, these exposure routes were used to choose model organisms that (I) were pathogens of concern in situations where people were exposed to water, (II) were present in rainwater and (III) showed a dose–response relation. Based on these criteria, *L. pneumophila* was chosen to model inhalation and *Campylobacter jejuni* for ingestion. These pathogens were preferred above other pathogens such as *Giardia*, *Cryptosporidium* or *Salmonella* because *L. pneumophila* and *C. jejuni* may be present in high concentrations in rainwater, combined with a high pathogenicity and environmental survival, thus posing a potential health risk. For dermal contact, no dose–response relationship is available and therefore this exposure route could not be considered.

Legionella spp. are found in a wide range of water environments and can proliferate at temperatures above 25 °C (World Health Organization, 2011). *Legionella* was assumed not to proliferate in the water of splash parks because the water temperature is generally below 25 °C in the Netherlands (Zuurman, personal communication). Data on *Legionella* concentrations in splash parks are lacking, and therefore we assumed that its concentration was equal to concentrations found in rainwater samples on roads. Reservoirs of splash parks were filled with such rainwater runoff at several locations in the Netherlands (Zuurman, personal communication). *L. pneumophila* was found in rainwater by several studies using PCR (Ahmed et al., 2008, 2010) and data about cultured *L. pneumophila* in rainwater on roads were previously reported by Sakamoto et al. (2009) and recently by Van Heijnsbergen et al. (submitted for publication) who used the method described by Schalk et al. (2012). Counts and tested volumes of these data were used to fit a gamma distribution for the concentration of *L. pneumophila* in water of splash parks using the method of Schijven et al. (2011).

Campylobacter is an enteric pathogen that occurs in a variety of environments, such as food and water (World Health Organization, 2011). The presence of *C. jejuni* in rainwater was confirmed by several studies (Fewtrell and Kay, 2007) and also by using PCR (Ahmed et al., 2010). A study by De Man et al. (2014a) showed that culturable *C. jejuni* was present in rainfall generated overland flow; these data were used to fit a gamma distribution for the concentration of *C. jejuni* in water of splash parks. *C. jejuni* may also contaminate the source water of splash parks through the activities of people, birds and other animals while a water feature is in operation. Because there is no information about such contaminations, these were not included as part of the current study.

Almost all splash parks incorporated some form of disinfection. Nevertheless, many splash parks exhibited poor water quality resulting from poor design and/or poor maintenance (Kebabjian, 2003). Furthermore, as De Man et al. (2014a,b,c) showed, disinfection of rainwater at splash parks is ineffective in reducing pathogen concentrations. Therefore disinfection was not included in this study.

2.2. Exposure assessment

Exposure volumes (μL/min) were quantified for inhalation and for ingestion. The volume of ingestion due to hand-to-mouth-contact with wet hands per minute (Q_{HM}) was calculated using:

$$Q_{HM} = h \times A \times f_{HM} \quad (1)$$

where h represented the film thickness of water on hands (mm), A the skin-surface area of the hand that touched the mouth (mm^2) and f_{HM} the frequency of hand-to- mouth contact (n per min). The volume of ingestion of droplets of water in the mouth (Q_D) was determined using:

$$Q_D = V_D \times f_D \quad (2)$$

where V_D represented the volume of water droplets (μL) and f_D the frequency of splashing water droplets in someone mouth (*n* per min). The volume of ingestion due to drinking mouthfuls of water per minute (Q_m) was determined using:

$$Q_M = V_M \times f_M \quad (3)$$

where V_M represented the volume of a mouthful of water (μL) and f_M the frequency that people take a mouthful of water (*n* per min). The inhaled volume of water per minute during the visit of the splash park was determined using:

$$Q_I = IR \times VIWS \quad (4)$$

where IR represented the inhalation rate of air (m^3/min) and VIWS the fraction of inhalable water spray (μL water/m^{3}air).

Values of model parameters were considered to be uncertain, therefore an uncertainty analysis was carried out through Monte Carlo simulations. Model parameters were explained by various types of distributions. To determine the volume distributions according to Equations (1)–(4), from each of these distributions, 10^6 values were randomly drawn using Mathematica version 9.0 (Wolfram Research).

Film thickness of water on hands, *h* [mm]. The film thickness of liquids on skin was represented by the amount of material that remains on the skin after contact with a liquid. A value for h was estimated in an experiment by U.S. EPA (2011) as the amount of liquid retained on the skin (g/mm^2) divided by the density of the liquid (g/mm^3) used. This showed a range of 2.34×10^{-2} to 1.97×10^{-2} mm for retention of water on the skin after initial contact with water. The uncertainty of h was considered to be uniformly distributed within this range.

Skin-surface area of the hand that was mouthed, *A* [mm^2]. Most frequently, a finger or a part of a finger is mouthed by children (U.S. EPA, 2011). The average surface area of child's finger is reported to be 2000 mm^2 (U.S. EPA, 2011). Therefore, the uncertainty of A was assumed to be uniformly distributed between 100 and 2000 mm^2 of a hand for children (U.S. EPA, 2011).

The frequency of hand-to-mouth contact f_{HM} [min^{-1}]. Freeman et al. (2001) gathered hand-to-mouth frequency data of 102 children. Boys were observed to have hand- to-mouth contact of 1.7 (0–5.6) times per hour, girls 2.3 (0–6.2) times per hour. Because data on the variability of hand-to-mouth contact for boys and girls and its uncertainty have not been reported and were unavailable upon request, we assumed the uncertainty of f_{HM} could be described by a Gamma Distribution. The gamma (α,β) distribution models the time required for α events to occur, given that the events occur randomly in a Poisson process with a mean time between events of β (Vose, 2008). Therefore, the uncertainty of f_{HM} was assumed to be gamma distributed with $\alpha = 2$ and $\beta = 0.5$.

Volume of a droplet, V_D [μL]. Children who make each other wet cause droplets of water to be ingested by themselves or other children. These water droplets were assumed to be spherical and to have a diameter that varied between 1 and 10 mm, to reflect the range in inhalable droplet sizes. The volume of a water droplet was determined by $4/3\pi r^3$, thus the volume of water of one droplet varied between 0.5 μL and 524 μL, for which a uniform distribution was assumed in absence of data on a more specific distribution.

Frequency of getting droplets of water in the mouth f_D [min^{-1}]. The frequency of getting a splash of water in the mouth was determined using onsite observations. The number of times that an individual received a splash of water in their face was counted, assuming that per moment of splashing one droplet was ingested by that person. Using the total duration of exposure of a person, a gamma distribution was fitted for the frequency of getting droplets of water in the mouth as described previously in this paragraph.

Volume of a mouthful of water V_M [μL]. The volume of a mouthful of water V_M was estimated by Schets, Schijven et al. (2011). The mean volume of a mouthful of water for a child was described by a Gamma distribution with $\alpha = 4.72$ and $\beta = 5300$ and used as such in this study.

Frequency of taking a mouthful of water f_M [min^{-1}]. The frequency of taking a mouthful of water was also determined using observations on site. The number of times that a person leans over a fountain to take a mouthful of water was counted assuming that each time, one mouthful was ingested. Using the total duration of exposure of a person, a gamma distribution for the frequency of taking a mouthful of water was fitted as described previously.

Inhalation Rate, IR [m^3/min]. The inhalation rate (*IR*) is dependent on the intensity of people's activity. *IR* for children varied between $1.01 \cdot 10^{-2}$ m^3/min for light activities and $6.24 \cdot 10^{-2}$ m^3/min for high intensity activities. For adults, it varied between $1.03 \cdot 10^{-2}$ and $7.77 \cdot 10^{-2}$ m^3/min (U.S. EPA, 2011).

Volume of inhalable water spray, VIWS [μL water/m^3 air]. The fraction of inhalable water spray (VIWS) per m^3 was extracted from a study of De Man et al. (2014b). The

Table 1 – Results of observations: number of people observed per category of exposure.

	Having wet hands	Having wet face	Drinking mouthfuls of water	Being present within 2 m of water spray
Children	198	65	8	257
Adults	192	31	2	347

concentration of inhalable endotoxin in air near splash parks varied from 7.2 to 19 endotoxin units (EU)/m^3, while the concentration of endotoxins in water varied from 9 to 2799 EU/mL. That study showed a significant linear relation between the EU in water and air ($R^2 = 0.645$). The volume of inhalable aerosols per cubic meter (*VIWS*) was estimated by maximum likelihood using beta regression (Espinheira et al., 2008, 2004). The parameters α and β for a Beta (α, β) distribution were re-parameterized with a mean dilution factor μ and a precision parameter φ according to $\alpha = \mu\varphi$ and $\beta = (1-\mu)\varphi$. The values for μ and φ were estimated by maximum likelihood. The uncertainty distribution for μ was obtained by Markov Chain Monte Carlo sampling from the likelihood function with the Metropolis-Hästings algorithm (Gilks et al., 1996).

Field observations to collect quantitative data on the behavior of splash park visitors were performed at two splash parks in urban centers on five days in June 2010 from 12:00AM until 4:00PM. During these observations, distinction was made between the different routes of exposure: 1) having wet hands, 2) having a wet face, 3) drinking mouthfuls of water and, 4) being present within 2 m of the water spray. Field observations were used to quantify several exposure model parameters (see Table 2).

Exposure through ingestion was mainly the case for children who interacted with water. Therefore, exposure through ingestion was only calculated for children. This choice was also made because there was a lack of information for model parameters *A*, f_{HM}, f_D and f_M for adults. Exposure through inhalation was calculated for children as well as for adults, because adults were exposed through inhalation while chaperoning their children.

2.3. *Dose response*

The dose *D* of exposure to the model organisms *L. pneumophila* and *C. jejuni* was calculated by multiplication of the concentration distribution *C* (numbers of pathogens per liter) and total exposure volume *V* (liter). The distribution for *V* for ingestion was calculated by:

$$V_{Ingestion} = (Q_{HM} + Q_D + Q_M)t \quad (5)$$

where *t* was the duration of exposure according to the field observations and Q_{HM}, Q_D and Q_M were summed when relevant according to the observed routes of exposure during the field observations.

The risk of infection for inhalation due to exposure to *Legionella* was analyzed using the exponential dose–response relation

$$P_{inf} = 1 - e^{-r \cdot D} \quad (6)$$

where *r* represents an infectivity of 0.06 (Armstrong and Haas, 2007). The risk of infection for ingestion due to exposure to *Campylobacter* was analyzed using the hypergeometric dose–response relation

$$P_{inf}(D;\alpha,\beta) = 1 - {}_1F_1(\alpha, \alpha+\beta, -D) \quad (7)$$

where ${}_1F_1$ was a Kummer confluent hypergeometric function and α and β represented the beta distributed dose response parameters for *Campylobacter*. In the case of *C. jejuni*, the values for parameters α and β were 0.024 and 0.011, respectively (Teunis et al., 2005).

2.4. *Risk characterization*

The risk of infection for inhalation and ingestion was calculated as a function of the duration of exposure. Given the large range of possible concentrations of *L. pneumophila* and *C. jejuni*, a scenario analysis was performed for five scenarios with different concentrations, from 1–10^4 cfu/L water. Subsequently a sensitivity analysis was carried out to determine the effect of the model parameters on the risk of infection. It was

Table 2 – Model parameters used in the exposure assessment.

Parameter	Value or distribution of values	Source
IR, Inhalation Rate (m^3/min)		
Children	Uniform [$1.11 \cdot 10^{-2}$, $4.36 \cdot 10^{-2}$]	(U.S. EPA, 2011)
Adults	Uniform [$1.03 \cdot 10^{-2}$, $7.77 \cdot 10^{-2}$]	
VIWS, Volume of inhalable water spray, (μL/m^3)	Average: 10.8 95% Confidence Interval: 1.76–36.3	(De Man et al., 2014b)
h, Film Thickness of water on hands, (mm)	Uniform [$1.97 \cdot 10^{-2}$, $2.34 \cdot 10^{-2}$]	(U.S. EPA, 2011)
A, Surface area of the hand that is mouthed, (mm^2)	Uniform [100,2000]	(U.S. EPA, 2011)
f_{HM}, Frequency of hand-to-mouth contact, (n/min)	Gamma [2,0.5]	(Freeman et al., 2001)
f_D, Frequency of getting water droplets in the mouth (n/min)	Gamma [2.1,0.17]	Field observations
V_D, Volume of a droplet (μL)	Uniform [0.5,524]	Estimate
V_M, Volume of a mouthful of water (μL)	Gamma [4.72,5300]	(Schets, Schijven and de Roda Husman, 2011)
f_M, Frequency of taking a mouthful of water (n/min)	Gamma [1.2,0.76]	Field observations

assumed that the model parameters were independent. The effect of the value of a model parameter was calculated by varying a model parameter (within its range of uncertainty), including the uncertainties of the other parameters.

3. Results

A QMRA was performed to calculate the risk of infection inherent to exposure to splash parks using rainwater as their source. To quantify the risk of infection, *L. pneumophila* and *C. jejuni* were selected as target pathogens. The concentration of *L. pneumophila* in rainwater was described by a Gamma distribution with $r = 0.045$ and $\lambda = 26{,}000$ with an average concentration of *L. pneumophila* of 1200 cfu/l. The concentration of *C. jejuni* in rainwater was described by a Gamma distribution with $r = 0.76$ and $\lambda = 330$, the average concentration of *C. jejuni* was 250 cfu/l.

Exposure was investigated during outdoor temperatures between 20 and 23°. Six hundred and four people were observed, of whom 259 were children estimated to be below 13 years old. Significant differences ($p < 0.05$) in behavior (*i.e.* in exposure) were observed between people younger and older than 13 years (Table 1). The mean duration of a visit at an interactive water fountain was 3.5 min (range 1–120 min). No significant differences ($p > 0.05$) were observed between the duration of a visit for people younger and older than 13 years. Observations on site were used to quantify the frequency that droplets of water reached children's mouths (f_D), these data ($N = 12$ children) were fitted to a gamma distribution, resulting in parameters $r = 2.1$ and $\lambda = 0.17$. Also, the frequency with which people take a mouthful of water (f_M) was quantified ($N = 8$ children) and fitted to a gamma distribution, resulting in $r = 1.2$ and $\lambda = 0.76$ (Table 1).

The estimated mean volume of inhalation of water aerosols for children was 0.394 μL/min, (95% CI-range 0.0446–1.27 μL/min) and for adults 0.489 μL/min (95% CI-range 0.0494–1.55 μL/min). The estimated mean volume of ingestion due to hand-to-mouth-contact with wet hands for children was 22.6 μL/min, (95% CI-range 2.02–81.0 μL/min). The estimated mean volume of ingestion of water droplets that splash into children's mouths was 94.4 μL/min (95% CI-range 5.1–279 μL/min) and the mean volume of ingestion through drinking mouthfuls of water amounted $21.5\cdot10^3$ μL/min (95% CI-range $1.17\cdot10^3$–$67\cdot10^3$ μL/min) for children.

The estimated infection risk due to inhalation of *L. pneumophila* for a child was $9.3\cdot10^{-5}$ (95% CI-range 0–$2.4\cdot10^{-4}$) and for adults $1.1\cdot10^{-4}$ (95% CI-range 0–$82.8\cdot10^{-4}$) for the mean exposure duration of 3.5 min (Fig. 1). The estimated risk of infection due to ingestion of *Campylobacter* was $1.3\cdot10^{-2}$ (95% CI-range 0–$5.3\cdot10^{-2}$) for ingestion due to hand-to-mouth contact with wet hands, $4.5\cdot10^{-2}$ (95% CI-range 0–$1.9\cdot10^{-1}$) for ingestion of water droplets in the mouth and $4.7\cdot10^{-1}$ (95% CI-range $2.3\cdot10^{-2}$–$7.1\cdot10^{-1}$) for ingestion of mouthfuls of water. Based on the observational data, the estimated mean total risk of infection for children after ingestion of *Campylobacter* amounted to $3.6\cdot10^{-2}$ (95% CI-range 0–$5.3\cdot10^{-1}$) for the mean exposure duration of 3.5 min.

The sensitivity analysis showed that the risk of infection was most affected by the volume of inhalable water spray VIWS and the volume of a water droplet V_D and least affected by the volume of a mouthful of water V_m and the film thickness of water on hands h (Fig. 2). Fig. 3 shows the results of the scenario-analyses, here the risks of infection are presented for different concentrations of pathogens in the water of splash parks. It demonstrates that concentrations of *L. pneumophila* and *C.jejuni* of less than 10 cfu/l (which is equal to absence in 100 ml) would lead to a decrease in the risk of infection for both *L. pneumophila* and *C. jejuni*.

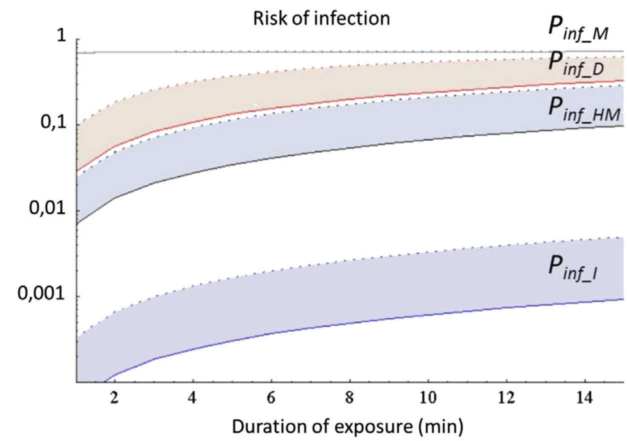

Fig. 1 – Risk of infection (mean and 95% percentile) for ingestion of mouthfuls of water P_{inf_M}, ingestion of water droplets P_{inf_D}, ingestion due to hand-to-mouth contact P_{inf_HM} and inhalation P_{inf_I} for mean concentrations of *C. jejuni* and *L. pneumophila* in rainwater that is used as source water for splash parks. (95th percentiles were shown by dotted lines).

4. Discussion

4.1. Hazard Identification

This study estimated the public health risk of splash parks that use rainwater as their source water. *L. pneumophila* and *C.*

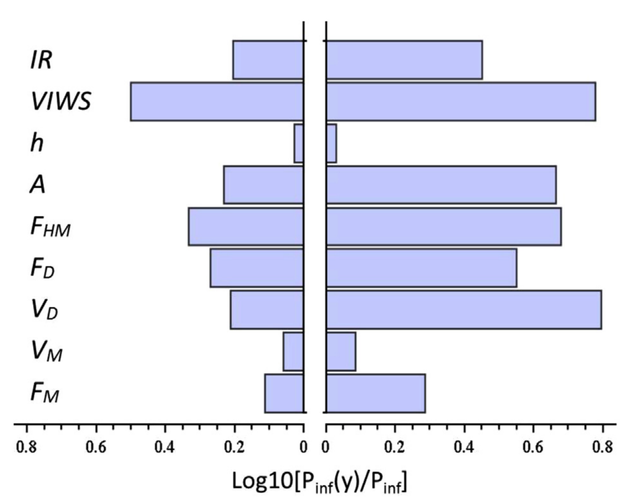

Fig. 2 – Sensitivity of P_{inf} by varying a model parameter within its range of uncertainty.

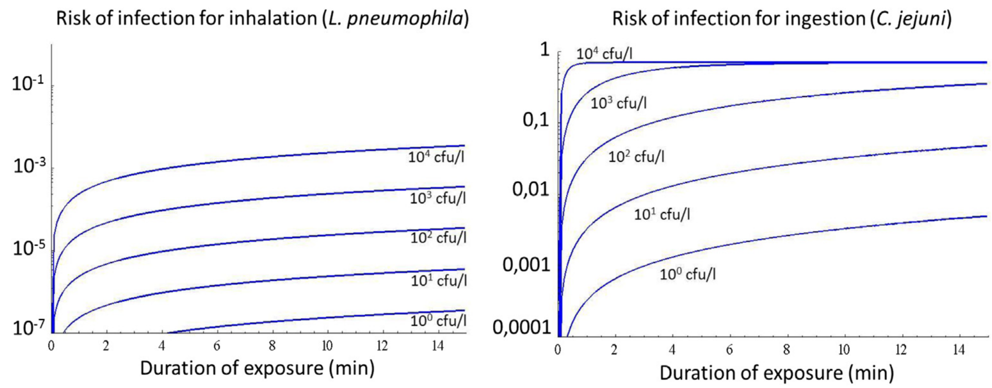

Fig. 3 – Risk of infection for inhalation and ingestion for different scenarios with respect to concentrations of pathogens in water as a function of the duration of exposure to water of a splash park.

jejuni have been chosen to determine the risk of infection for inhalation and ingestion at splash parks. The target pathogen *L. pneumophila* that is used to quantify health risks after inhalation, can grow and become more virulent at water temperatures above 25 °C. The growth of *Legionella* was not incorporated into our model, because water temperatures above 25 °C require prolonged outside temperatures of 30–35 °C (Zuurman, personal communication), which is uncommon in The Netherlands. Under optimal conditions, the concentration of *L. pneumophila* may double in 8 h (Cooling Tower Institute, 1990) and increase 3 to 4 orders of magnitude in 48–72 h (Holden et al., 1984). This is in contrast to *C. jejuni* which will not multiply at temperatures between 25 and 30 °C (Jones, 2001). Besides the investigated model parameter *C. jejuni*, other pathogens at splash parks may also cause gastro-intestinal diseases. For instance, norovirus may be introduced in water of splash parks by people who interact with the water (Hoebe et al., 2004) or bird and other animals may introduce pathogens like *Giardia* and *Cryptosporidium* (Eisenstein et al., 2008). Given the poor water quality at splash parks (De Man et al., 2014b; De Man et al., 2014a,b,c), together with the increase of water temperature on warm days also gives rise to risks of non-fecal pathogens such as *A. hydrophila* and *P. aeruginosa*. While risks posed by these pathogens deserve evaluation, the necessary dose–response data is currently lacking. And health risk from contact exposure cannot be assessed.

4.2. *Exposure Assessment*

The present study quantified exposure volumes through inhalation and ingestion, by providing insight into volumes of exposure due to inhalation, hand-to-mouth contact, splash of droplets in someone's mouth and drinking of water. The observational component of the study yielded important data that was previously missing. The methodology used in this study can be used to inform QMRA in other situations where people are exposed to water in the studied ways.

The exposure assessment for ingestion was not performed for adults, because information was missing for several model parameters (A, F_{HM}, F_D, F_M). Based on the uncertain assumption that exposure volumes of ingestion of adults were equal to children and using the data of the field observations (i.e. 55% of the people got wet hands and 9% got water droplets in their mouths) gives an exposure volume of 20 μL/min. This exposure volume was approximately one order of magnitude lower than the volume of exposure of children (707 μL/min), which supports the conclusion that children were more at risk at splash parks than adults.

In our study, we quantified infection risk as a function of exposure. The importance of exposure is endorsed by the study of Hoebe et al. (2004), who reported that the attack rate for gastrointestinal illnesses was higher for children who interacted for a longer duration with a splash park. This assumption is also supported by the outbreak of Legionellosis at the 1999 West Frisian Flower Show in The Netherlands, where a relation was found between the duration of exposure and the concentration of antibodies in titers of exposed individuals (Den Boer et al., 2002). It should be noted that the average exposure duration of 3.5 min reported in this study was short because these observations took place in an urban environment. At playgrounds and other recreational water parks, the exposure duration may increase to 0.5 h or possibly up to 2 h (Hoebe et al., 2004), which would increase the ingested or inhaled dose of pathogens and therefore the subsequent health risk. According to our model, the risk of infection would increase to $2.3 \cdot 10^{-1}$ for ingestion of *C. jejuni* and $2.8 \cdot 10^{-3}$ for inhalation of *L. pneumophila* for an exposure duration of 2 h.

4.3. *Risk assessment*

A standard for exposure to enteric pathogens by consumption of unboiled tap water in set by the Dutch Ministry of Infrastructure and Environment, stating that less than one infection per 10,000 persons per year should occur. Relating this standard to the current study results showed exceedence for *C. jejuni* and *L. pneumophila* (for the latter one, in case of exposure of adults and for exposures of children longer than 5 min). The risk of infection for ingestion of water of a splash park also exceeded the value of 0.001 pppy, which was recommended as an infection risk benchmark for the reuse of rooftop-harvested rainwater (Lim and Jiang, 2013). Furthermore, the estimated risk of infection exceeded the value of 0.01, being at the threshold at which epidemiologic studies can identify health risks (Wade et al., 2006; Ashbolt et al., 2010).

Thus, the present study shows that exposure to splash parks may pose a public health risk. This, together with the fact that outbreaks were associated with malfunctioning of disinfection systems (Kebabjian, 2003; Hoebe et al., 2004) indicates that legislation is required to minimize health risks. Water quality standards, we believe, can provide a tool for operators to monitor water quality and to make interventions when necessary. The scenario analyses (Fig. 3) provides information about the estimated effect of a reduction of *C. jejuni* or *L. pneumophila* (i.e. the effect of water quality standards) on the risk of infection determined for splash parks that use rainwater as their source water. Concentrations of *L. pneumophila* and *C.jejuni* of less than 10 cfu/l (which is equal to absence in 100 ml) would lead to a decrease in the risk of infection of 10–100 times for C. jejuni and L. pneumophila, respectively.

5. Conclusion

This study showed that exposure to splash parks that use rainwater as their source water can cause an infection risk. While at this moment, splash parks do not have to meet any criteria for water quality and/or design, this study should give rise to debates concerning the need for such guidelines. The scenario analyses gives information about infection risks for specific concentrations of pathogens in their source water. This information is valuable in terms of the insight it provides into the effect of water quality standards on public health. Furthermore, this study uses a new methodology making it possible to quantify exposure volumes using onsite observations, a methodology both practical and useful when assessing quantitative microbial risk wherever people are exposed to water.

Disclosure

The authors declare they have no competing financial interests.

Acknowledgments

The authors are grateful to Mr. R. Sakamoto who provided raw data of *Legionella* in rainwater samples. The research was funded by STOWA (Dutch Foundation for Applied Water Research), RIONED (Dutch Centre of Expertise in Sewer Management and Urban Drainage), the Municipalities of Groningen, Nijmegen, Rotterdam and Utrecht, and the Water Boards 'Noorderzijlvest', 'Hoogheemraadschap de Stichtse Rijnlanden', 'Hoogheemraadschap Delfland', 'Waterschap Hollandse Delta' and 'Hoogheemraadschap Schieland en de Krimpenerwaard'.

REFERENCES

Anonymous, 2000. Outbreak of gastroenteritis associated with an interactive water fountain at a Beachside –Florida, 1999. Morb. Mortal. Wkly. Rep. 49 (25), 565–568.

Anonymous, 1999. Outbreak of cryptosporidiosis associated with a water sprinkler fountain–Minnesota, 1997. Canada communicable disease report = Releve des maladies transmissibles au Canada 25 (2), 13–15.

Ahmed, W., Richardson, K., Sidhu, J.P.S., Jagals, P., Toze, S., 2014. Inactivation of faecal indicator bacteria in a roof-captured rainwater system under ambient meteorological conditions. J. Appl. Microbiol. 116 (1), 199–207.

Ahmed, W., Hodgers, L., Sidhu, J.P.S., Toze, S., 2012. Fecal indicators and zoonotic pathogens in household drinking water taps fed from rainwater tanks in Southeast Queensland, Australia. Appl. Environ. Microbiol. 78 (1), 219–226.

Ahmed, W., Vieritz, A., Goonetilleke, A., Gardner, T., 2010. Health risk from the use of Roof-Harvested rainwater in Southeast Queensland, Australia, as potable or nonpotable water, determined using quantitative microbial risk assessment. Appl. Environ. Microbiol. 76 (22), 7382–7391.

Ahmed, W., Huygens, F., Goonetilleke, A., Gardner, T., 2008. Real-time PCR detection of pathogenic microorganisms in roof-harvested rainwater in Southeast Queensland, Australia. Appl. Environ. Microbiol. 74 (17), 5490–5496.

Andión Campos, E., 1995. Study of a typhoid fever outbreak in Baiona (Pontevedra). Revista española de salud pública 69 (2), 233–242.

Armstrong, T.W., Haas, C.N., 2007. A quantitative microbial risk assessment model for Legionnaires' disease: animal model selection and dose-response modeling. Risk Anal. 27 (6), 1581–1596.

Ashbolt, N.J., Schoen, M.E., Soller, J.A., Roser, D.J., 2010. Predicting pathogen risks to aid beach management: the real value of quantitative microbial risk assessment (QMRA). Water Res. 44 (16), 4692–4703.

Bancroft, J.E., Keifer, S.B., Keene, W.E., 2010. Shigellosis from an interactive fountain: implications for regulation. J. Environ. Health 73 (4), 16–20.

Cacciapuoti, B., Ciceroni, L., Maffei, C., 1987. A waterborne outbreak of leptospirosis. Am. J. Epidemiol. 126 (3), 535–545.

Cooling Tower Institute, 1990. Legionnaires' disease bacteria. CTI J. 11 (1), 70–71. CTI Journal 1, 70–71.

Correia, A.M., Gonçalves, G., Reis, J., Cruz, J.M., Castro e Freitas, J.A., 2001. An outbreak of legionnaires' disease in a municipality in northern Portugal. Euro surveillance : bulletin europeen sur les maladies transmissibles = European communicable disease bulletin 6 (8), 121–124.

Crabtree, K.D., Gerba, C.P., Rose, J.B., Haas, C.N., 1997. Waterborne adenovirus: a risk assessment. Water Sci. Technol. 35 (11–12), 1–6.

De Man, H., Van Den Berg, H., Leenen, E.T.J.M., Schijven, J., Schets, F.M., Van der Vliet, J.C., Knapen, F., De Roda Husman, A.M., 2014a. Quantitative assessment of infection risk from exposure to waterborne pathogens in urban floodwater. Water Res. 48 (1), 90–99.

De Man, H., Heederik, D.J.J., Leenen, E.T.J.M., Spithoven, J.J.G., De Roda Husman, A.M., Knapen, F., 2014b. Human exposure to endotoxins and fecal indicators originating from water features. Water Res. 51, 198–205.

De Man, H., Leenen, E.T.J.M., Knapen, F., De Roda Husman, A.M., 2014c. Best water quality management practices for splash parks. J. Water Health (in press).

Den Boer, J.W., Yzerman, E.P.F., Schellekens, J., Lettinga, K.D., Boshuizen, H.C., Van Steenbergen, J.E., Bosman, A., Van Hof, S.D., Van Vliet, H.A., Peeters, M.F., Van Ketel, R.J., Speelman, P., Kool, J.L., Marina, A.E., Spaendonck, C., 2002. A large outbreak of Legionnaires' disease at a flower show, the Netherlands, 1999. Emerg. Infect. Dis. 8 (1), 37–43.

Douwes, J., Thorne, P., Pearce, N., Heederik, D., 2003. Bioaerosol health effects and exposure assessment: progress and prospects. Ann. Occup. Hyg. 47 (3), 187–200.

Eisenstein, L., Bodager, D., Ginzl, D., 2008. Outbreak of giardiasis and cryptosporidiosis associated with a neighborhood interactive water fountain-Florida, 2006. J. Environ. Health 71 (3), 18–22.
Espinheira, P.L., Ferrari, S.L.P., Cribari-Neto, F., 2008. On beta regression residuals. J. Appl. Stat. 35 (4), 407–419.
Evans, C.A., Coombes, P.J., Dunstan, R.H., 2006. Wind, rain and bacteria: the effect of weather on the microbial composition of roof-harvested rainwater. Water Res. 40 (1), 37–44.
Ferrari, S.L.P., Cribari-Neto, F., 2004. Beta regression for modelling rates and proportions. J. Appl. Stat. 31 (7), 799–815.
Fewtrell, L., Kay, D., 2007. Quantitative microbial risk assessment with respect to Campylobacter spp. in toilets flushed with harvested rainwater. Water Environ. J. 21 (4), 275–280.
Fields, B.S., Benson, R.F., Besser, R.E., 2002. Legionella and legionnaires' disease: 25 Years of investigation. Clin. Microbiol. Rev. 15 (3), 506–526.
Fleming, C.A., Caron, D., Gunn, J.E., Horine, M.S., Matyas, B.T., Barry, M.A., 2000. An outbreak of Shigella sonnei associated with a recreational spray fountain. Am. J. Public Health 90 (10), 1641–1642.
Freeman, N.C.G., Jimenez, M., Reed, K.J., Gurunathan, S., Edwards, R.D., Roy, A., Adgate, J.L., Pellizzari, E.D., Quackenboss, J., Sexton, K., Lioy, P.J., 2001. Quantitative analysis of children's microactivity patterns: the Minnesota children's pesticide exposure Study. J. Expo. Analysis Environ. Epidemiol. 11 (6), 501–509.
Gilks, W.R., Richardson, S., Spiegelhalter, D.J., 1996. Markov Chain Monte Carlo in Practice. Chapman & Hall, London, p. 486.
Haupt, T.E., Heffernan, R.T., Kazmierczak, J.J., Nehls-Lowe, H., Rheineck, B., Powell, C., Leonhardt, K.K., Chitnis, A.S., Davis, J.P., 2012. An outbreak of legionnaires disease associated with a decorative water wall fountain in a hospital. Infect. Control Hosp. Epidemiol. 33 (2), 185–191.
Heyder, J., Gebhart, J., Rudolf, G., Schiller, C.F., Stahlhofen, W., 1986. Deposition of particles in the human respiratory tract in the size range 0.005-15 μm. J. Aerosol Sci. 17 (5), 811–825.
Hlady, W.G., Mullen, R.C., Mintz, C.S., Shelton, B.G., Hopkins, R.S., Daikos, G.L., 1993. Outbreak of Legionnaire's disease linked to a decorative fountain by molecular epidemiology. Am. J. Epidemiol. 138 (8), 555–562.
Hoebe, C.J.P.A., Vennema, H., De Roda Husman, A.M., Van Duynhoven, Y.T.H.P., 2004. Norovirus outbreak among primary schoolchildren who had played in a recreational water Fountain. J. Infect. Dis. 189 (4), 699–705.
Holden, E.P., Winkler, H.H., Wood, D.O., Leinbach, E.D., 1984. Intracellular growth of Legionella pneumophila within *Acanthamoeba castellanii* Neff. Infect. Immun. 45 (1), 18–24.
Jones, K., 2001. Campylobacters in water, sewage and the environment. J. Appl. Microbiol. Symposium Suppl. 90 (30), 68S–79S.
Kaushik, R., Balasubramanian, R., de la Cruz, A.A., 2012. Influence of air quality on the composition of microbial pathogens in fresh rainwater. Appl. Environ. Microbiol. 78 (8), 2813–2818.
Kebabjian, R.S., 2003. Interactive water fountains: the potential for disaster. J. Environ. Health 66 (1), 29–30.
Keene, W.E., Mcanulty, J.M., Hoesly, F.C., Williams Jr., L.P., Hedberg, K., Oxman, G.L., Barrett, T.J., Pfaller, M.A., Fleming, D.W., 1994. A swimming-associated outbreak of hemorrhagic colitis caused by Escherichia coli O157:H7 and Shigella sonnei. N. Engl. J. Med. 331 (9), 579–584.
Lim, K., Jiang, S.C., 2013. Reevaluation of health risk benchmark for sustainable water practice through risk analysis of rooftop-harvested rainwater. Water Res. 47 (20), 7273–7286.
McCarthy, N., Giesecke, J., 2001. Incidence of Guillain-Barré syndrome following infection with Campylobacter jejuni. Am. J. Epidemiol. 153 (6), 610–614.
Molinero, M.E., Fernández, I., García-Calabuig, M.Á., Peiró, E., 1998. Investigation of an outbreak of water origin due to salmonella ohio. Enfermedades Infecc. Microbiol. Clin. 16 (5), 230–232.
Palmore, T.N., Stock, F., White, M., Bordner, M., Michelin, A., Bennett, J.E., Murray, P.R., Henderson, D.K., 2009. A cluster of cases of nosocomial legionnaires disease linked to a contaminated hospital decorative water fountain. Infect. Control Hosp. Epidemiol. 30 (8), 764–768.
Sakamoto, R., Ohno, A., Nakahara, T., Satomura, K., Iwanaga, S., Kouyama, Y., Kura, F., Kato, N., Matsubayashi, K., Okumiya, K., Yamaguchi, K., 2009. Legionella pneumophila in rainwater on roads. Emerg. Infect. Dis. 15 (8), 1295–1297.
Schalk, J.A.C., van Leeuwen, A.E.D., Lodder, W.J., de Man, H., Euser, S., den Boer, J.W., de Roda Husman, A.M., 2012. Isolation of Legionella pneumophila from pluvial floods by amoebal coculture. Appl. Environ. Microbiol. 78 (12), 4519–4521.
Schets, F.M., Schijven, J.F., de Roda Husman, A.M., 2011. Exposure assessment for swimmers in bathing waters and swimming pools. Water Res. 45 (7), 2392–2400.
Schets, F.M., Italiaander, R., Van Den Berg, H.H.J.L., De Roda Husman, A.M., 2010. Rainwater harvesting: quality assessment and utilization in The Netherlands. J. Water Health 8 (2), 224–235.
Schijven, J.F., Teunis, P.F.M., Rutjes, S.A., Bouwknegt, M., de Roda Husman, A.M., 2011. QMRAspot: a tool for quantitative microbial risk assessment from surface water to potable water. Water Res. 45 (17), 5564–5576.
Semel, J.D., Trenholme, G., 1990. Aeromonas hydrophila water-associated traumatic wound infections: a review. J. Trauma 30 (3), 324–327.
Teunis, P.F.M., van den Brandhof, W., Nauta, M., Wagenaar, J., van den Kerkhof, H., van Pelt, W., 2005. A reconsideration of the Campylobacter dose - response relation. Epidemiol. Infect. 133 (4), 583–592.
U.S. EPA, 2011. Exposure Factors Handbook, 2011 ed. EPA/600/R-09/052F.
Usera, M.A., Echeita, A., Aladuena, A., Alvarez, J., Carreno, C., Orcau, A., Planas, C., 1995. Investigation of an outbreak of typhoid fever of water origin in Catalonia (Spain) in 1994. Enfermedades Infecc. Microbiol. Clin. 13 (8), 450–454.
Van Asperen, I.A., De Rover, C.M., Schijven, J.F., Bambang Oetomo, S., Schellekens, J.F.P., Van Leeuwen, N.J., Colle, C., Havelaar, A.H., Kromhout, D., Sprenger, M.W.J., 1995. Risk of otitis externa after swimming in recreational fresh water lakes containing Pseudomonas aeruginosa. Br. Med. J. 311 (7017), 1407–1410.
Van Heijnsbergen, E., de Roda Husman, A.M., Bouwknegt, M., Docters van Leeuwen, A.E., Lodder, W.J., Bruin, J.P., Euser, S.M., Den Boer, J.W., Schalk, J.A.C., 2014. Viable *Legionella pneumophila* Bacteria Isolated from Rainwater on the Road and in Nearby Soils in the Netherlands (submitted for publication).
Vose, D., 2008. Risk Analyses, a quantitative quide. In: Anonymous (Ed.), Gamma Distribution. John Wiley & Sons, Chichester, West Sussex, England, p. 633.
Wade, T.J., Calderon, R.L., Sams, E., Beach, M., Brenner, K.P., Williams, A.H., Dufour, A.P., 2006. Rapidly measured indicators of recreational water quality are predictive of swimming-associated gastrointestinal illness. Environ. Health Perspect. 114 (1), 24–28.
World Health Organization, 2011. Guidelines for Drinking-water Quality, fourth ed. http://www.who.int/water_sanitation_health/publications/2011/dwq_guidelines/en/index.html.