Microbial risk assessment for urban pluvial flooding

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ABSTRACT
Public health risks of urban pluvial flooding have so far received little attention in technical discussions. In this paper, the results of pathogen measurements in the sewer system of Utrecht and an urban flooding experiment are presented and used in an application of Quantitative Microbial Risk Assessment, an existing risk analysis method for the quantification of infection probabilities. This method uses ingested doses of pathogenic organisms for the calculation of infection probabilities. Ingested dose estimations are based on pathogen measurements. These samples have been analysed for concentrations of *Campylobacter, Cryptosporidium* and *Giardia.* Dose-response relations from literature are used to calculate infection probabilities for flood events. The results show that mean probabilities of obtaining a *Campylobacter* or *Giardia* infection as a result of contact with urban flood water are 2.8% and 0.6% per event respectively for adults and at least 5.7% and 1.0% per event for children, respectively. Infection probabilities for *Cryptosporidium* are about 1000 times lower than for *Giardia.* The infection probabilities found indicate that the health risk of urban flooding is higher than that of swimming in recreational freshwater environments, based on a comparison to the values for 'acceptable risk' as defined by the WHO for bathing water.

KEYWORDS
Public health; risk analysis; urban flooding; waterborne disease

INTRODUCTION
In discussions on urban flood risk, the focus is mainly on the financial consequences of flood events (Ashley et al., 2005). Consequences related to public health are easily overlooked. Two important types of health consequences are: ingestion of contaminated water and physical injuries as a result of stumbling over objects under the water surface or even falling into manholes. This paper focuses on the health risk caused by the ingestion of contaminated water from overflowing sewers during urban flood events.
When combined sewer systems flood as a result of heavy rainfall, humans can come into contact with the mixture of waste- and stormwater that flows onto the surface and may contain various types of pathogens. Different contamination routes are possible; the most important route is ingestion of the flood water, as a result of playing in it, or being splashed.
This paper presents the application of a formal method for risk quantification to the case of urban flooding, to assess and quantify the health risk via the oral-fecal contamination route. The application of this method is demonstrated with data from practice. A comparison to the bathing water quality directives is used to present a framework for the magnitude of the risk.

METHOD

Several methods exist to assess health consequences of contact with diluted wastewater in urban flooding situations for man: epidemiological population studies, comparison of the flood water quality with the EU water quality directives based on WHO-guidelines, or Quantitative Microbial Risk Assessment (QMRA).
Epidemiological studies require large amounts of population disease data. The correct procedure that needs to be followed to be able to attribute disease cases to a cause are strict: an infected person has to seek medical care and a full blood and stools test has to be carried out to confirm the causative agent (Haas *et al.*, 1999). For exploratory research, epidemiological research is therefore not considered a feasible approach.

A second possible approach to assess health consequences of urban flooding is to compare flood water quality data to bathing water quality standards. The European bathing water directive defines standards for the quality of water for swimming. The directive is partially based on the WHO-guideline for safe recreational water environments. The definition for good quality in this guideline is based on concentrations of *Enterococci*: acceptable health risk for swimming in bathing waters of good quality is based on the probability of obtaining gastrointestinal convulsion (GI) and acute febrile respiratory syndrome (AFRI). The estimated health risk of swimming in water with a maximum *Enterococci* concentration of 200 CFU/100ml, is a probability of 5% of obtaining GI illness, and a probability of 1.9% of obtaining AFRI, based on large epidemiological studies. This is considered an acceptable risk for swimming in freshwater recreational environments (Kay *et al.*, 2003). The European bathing water directive quantifies microbiological quality by two bacterial parameters: *E.coli* and *Enterococci* (Table 1). The standard test for these pathogens is simple and gives relatively quick results. Comparison of the flood water quality with bathing water quality directives gives a rough indication of the health risks caused by urban flooding.

Table 1 *Water quality standard according to the EU bathing water directive.*

	Excellent quality (CFU/100 ml)	Good quality (CFU/100 ml)
Intestinal *Enterococci*	100	200
E.coli	250	500

The third method, QMRA, is a method often used for public health risk assessment related to water. This method gives quantitative results on infection probabilities for different pathogens. The method only applies for pathogens for which a dose-response relation is known, a function that describes the relation between the number of ingested pathogens and the probability of obtaining an infection from these pathogens. Most dose-response relations have been determined in volunteer studies (Teunis *et al.*, 1996).

Quantitative Microbial Risk Assessment

QMRA is applied here for the quantification of urban flood health risk, because it directly calculates infection probabilities based on pathogens concentrations found. A comparison between flood water and bathing water is used as a comparison method for the results of the QMRA, since no ‘acceptable health risk’ guidelines exist for urban flooding.
A QMRA procedure consists of four successive steps (Haas *et al.*, 1999):

1) Hazard identification;
2) Exposure assessment;
3) Dose-response relations;
4) Risk characterisation.

Infection risk has been calculated for a number of pathogens, based on the measurement of pathogen concentrations in wastewater and dose-response relations from literature. The uncertainty in the calculation results due to uncertainties in pathogen measurements and literature values is quantified using Monte-Carlo simulations.
In the hazard identification step of the QMRA for urban flooding, three different pathogens have been selected: Campylobacter, and the protozoa Cryptosporidium and Giardia. The reason for this choice is the availability of a dose-response relation, and the high occurrence of these pathogens in wastewater. All three pathogens are common causes of waterborne disease (Westrell, 2004).
The bacteria E.coli and Enterococci, common indicators of faecal pollution, have been analysed in order to make a comparison with water quality standards as a part of the risk characterisation step. Testing water for the Campylobacter, Cryptosporidium and Giardia is a more expensive and complicated process than for E.coli and Enterococci. The symptoms of disease caused by the five different pathogens are mostly gastrointestinal (table 2).

Table 2 *Pathogens studied in health risk assessment and their possible symptoms (EPA, 2003; Schaechter et al., 1999)*

Pathogen	Symptoms
Escherichia coli	Gastroenteritis, hemolytic uremic syndrome
Enterococci	Urinary tract infections, endocarditis
Campylobacter	Gastro-enteritis, Guillain-Barré syndrome
Cryptosporidium	Gastroenteritis, intestinal convulsions
Giardia	Chronic gastroenteritis

The exposure assessment is carried out for two different types of exposure: the case of a pedestrian that is splashed by passing traffic and the case of a child that is playing in the water. The extent to which they are exposed to pathogens is described by the ingested pathogen dose: when contact with the flood water occurs, a small volume is ingested, the amount of pathogens in this volume determines the dose μ:

$$\mu = \frac{c \cdot v}{d \cdot 1000} \tag{1}$$

Where: μ : dose [nr of pathogens]
c : concentration of a pathogen in water [nr of pathogens/l]
v : intake volume [ml]
d : dilution factor [-]

The concentrations of pathogens are based on values found in sampling experiments that are described in the next paragraph. The dilution factor of wastewater in urban flooding is based on expert judgment: a dilution of the wastewater with a factor 50 to 100 is estimated for urban flooding situations. A uniform distribution with a minimum of 50 and a maximum of 100 has been used as input for the Monte-Carlo simulation of infection probabilities. The ingested volumes are based on figures taken from literature (Steyn *et al.*, 2004). These values are expected to have a lognormal distribution, which is used in the Monte-Carlo simulation. The values for μ and σ, see table 3, are based on data from literature (Steyn *et al.*, 2004).

Table 3 *Estimated intake volume distributions for different exposure cases*

Exposure case	Mean intake volume (ml)	σ
Splashed pedestrians	10	10
Playing children	30	30

Dose-response relations are mathematical functions that quantify the infection probability for a given dose, based on the concept that when a pathogen manages to survive in the right location in a host, it has the possibility to multiply and cause infection. Two different survival mechanisms are possible: either the pathogens have an independent probability of survival or the different individuals influence each others survival rate.
In the first case the exponential dose-response model applies that holds for most protozoa, among which *Cryptosporidium* and *Giardia* (Teunis *et al.*, 1996; see table 4):

$$P^*_{\text{inf}} = 1 - e^{-r\mu} \tag{2}$$

Where: P^*_{inf} : probability of infection by a certain pathogen when ingesting a dose
r : probability of survival for each individual pathogen
μ : dose of the pathogen

Table 4 *Probabilities of survival for Cryptosporidium and Giardia in a human host (Teunis et al., 1996)*

Protozoan	R
Cryptosporidium	0.004005
Giardia	0.0199

In the case of conditional survival probability, the Beta-Poisson model applies, that holds for many different types of bacteria, among which Campylobacter (table 5):

$$P^*_{\text{inf}} \approx 1 - \left(1 + \frac{\mu}{\beta}\right)^{-\alpha} \tag{3}$$

Provided $\beta \gg \alpha$ (Furomoto and Mickey, 1967)

Where: P^*_{inf} : probability of infection by a certain pathogen when ingesting a dose
μ : dose of the pathogen
α, β : pathogen-specific constants describing the conditional survival probability of that pathogen

Table 5 *Constants for the survival function of Campylobacter in a human host (Teunis et al., 1996)*

Bacterium	A	β
Campylobacter	0.145	7.589

Point estimates of the infection probability are calculated using representative concentration values of *Campylobacter, Cryptosporidium* and *Giardia* found in the wastewater samples from sampling experiments. Based on histograms of the measured concentrations, probability distributions of pathogen concentrations have been defined. The input values for the *E.coli* and *Enterococci* concentrations are based on the values found in wastewater samples.
Monte-Carlo simulations in which values for the concentrations of pathogens, dilution factor and intake volumes are randomly drawn from the defined distributions give insight into the uncertainty in the calculated infection probabilities.
For the last step in the QMRA, the risk characterization, the infection probabilities are compared to infection probabilities in swimming water. Also, a comparison between pathogen concentrations in urban flood water and bathing water is made using the *E.coli* and *Enterococci* concentration measurements in wastewater.

MEASUREMENT EXPERIMENTS FOR PATHOGEN CONCENTRATIONS

Three types of field experiments have been conducted to obtain insight into pathogen concentrations in wastewater: samples have been taken from sewer systems in a spatial variation and in a temporal variation experiment and an urban flooding simulation experiment has been done as a third experiment. Details of the experiments are given in table 6. All wastewater samples are taken from the sewer system of the municipality of Utrecht.

Table 6 *Overview of experiments*

Experiment	Nr. of Experiments	Purpose of experiments	Sample analyses
Urban flooding simulation experiment	4	Study pathogen concentration variations in flood water for a representative duration of an urban flooding event (60 minutes)	*E.coli, Enterococci*
Spatial variation experiment, 6 locations with different spatial use	2	Study spatial pathogen concentration variations in wastewater samples from a sewer system (DWF)	*E.coli, Enterococci, Campylobacter, Cryptosporidium, Giardia*
Temporal variation experiments, 1 location	2	Study pathogen concentration variations in time during a weekday (DWF)	*E.coli, Enterococci*
Real urban flooding situation, Den Haag, 16 July 2007, 3 locations	1	Study pathogen concentrations in samples from a real flooding situation	*E.coli, Enterococci, Campylobacter*

The *urban flooding simulation* experiments have been carried out in a small-scale urban flooding setup, using a metal ring (Ø 0.5 m) stuck to the pavement with quick-drying cement. In each of the four simulation experiments done with this setup, the ring has been filled with diluted wastewater and samples have been drawn at t = 0, 5, 10, 15, 30, 45 and 60 minutes. One hour is considered a representative duration for urban pluvial flooding. The experiments have been done on two sampling days: October 10th and 17th 2007.

During the *spatial variation experiments* two samples have been taken from a main sewer within an interval of a few seconds, at six locations with different spatial use, within an area of 4x5 km^2. The sampling has been done twice, on October 8th and 15th 2007.

One of the locations of the spatial variation experiment, a typical residential area, has been chosen for the *temporal variation experiment*. In this experiment, every 30 minutes two samples have been drawn from the sewer from 7:00 AM to 6:00 PM. The sampling has been done twice, on October 3rd and 22nd 2007. The analysis methods that have been used to measure pathogen concentrations are summarized in table 7. The dilution series on count plates have been done in duplicate or triplicate.

Table 7 *Analysis methods for different pathogens*

Pathogen	Analysis method
E.coli	Dilution series on count plates
Enterococci	Dilution series on count plates
Campylobacter	Presence/absence test, microscopy
Cryptosporidium	Epifluorescence microscopy
Giardia	Epifluorescence microscopy

RESULTS AND DISCUSSION

Figure 1 shows an example of the measurement results for *E.coli* in one of the urban flooding simulation experiments. The pathogen concentration values show significant variations in time up to about a factor 4.

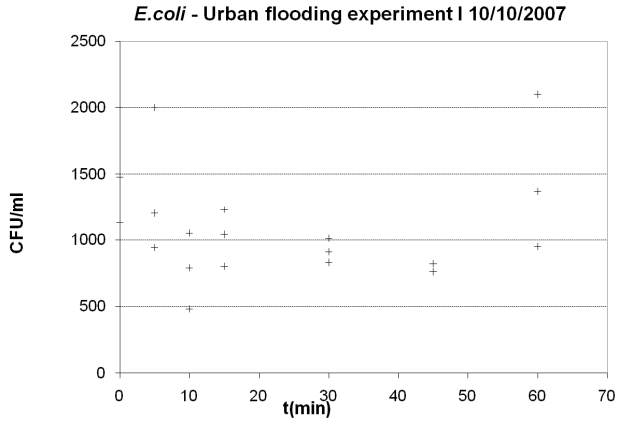

Figure 1 *Results of one of the urban flooding simulation experiments with diluted wastewater, for E.coli. The data points indicate the counts from different sample dilution series. The values show a significant variation and show no clear increase or decrease with time.*

The results of the sample analyses on *E.coli* and *Enterococci* in sewer water from 2 temporal variation experiments show a much larger variability of up to a factor 30, see figure 2.

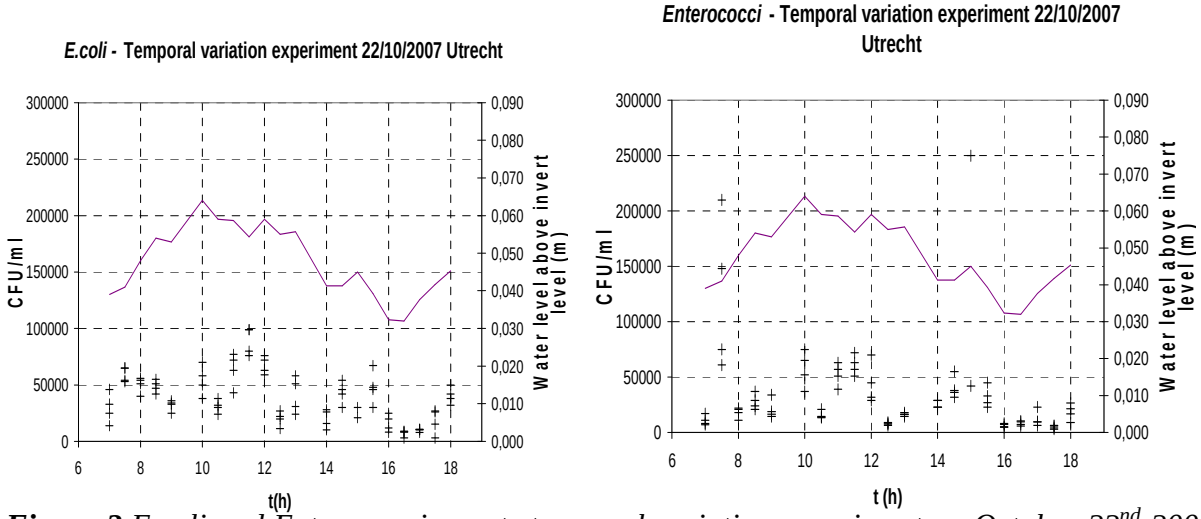

Figure 2 *E.coli and Enterococci counts temporal variation experiment on October 22nd 2007. The data point indicate the different counts from samples and dilution series, the line indicates* the water level in the sewer system

A possible cause of the pathogen concentration variability in the samples is that the pathogens in wastewater have a so-called “contagious distribution” (Jarvis, 1989): pathogens are not uniformly distributed in the wastewater but form clots and stick to suspended particles in wastewater. This is confirmed by the significant differences in concentration values that have been found in two samples taken from a sewer shortly after one another. The non-uniform distribution of pathogens also leads to differences between dilution series from one sample, and to differences within dilution series. The order of magnitude to which contagious distribution disturbs the concentration counts is estimated at a factor 5.

Another reason for large concentration variations in sewers is that the wastewater composition varies in time and in space as a result of aboveground activities (domestic activity, weather). The sampling frequency is too low to measure the variation patterns in the sewer; the samples give a snapshot indication of the wastewater composition.

Figure 3 shows the results of the spatial variation experiment for *E.coli* and *Enterococci*. *E.coli* and *Enterococci* are found in all wastewater samples. The concentrations of both pathogens show no correlation.

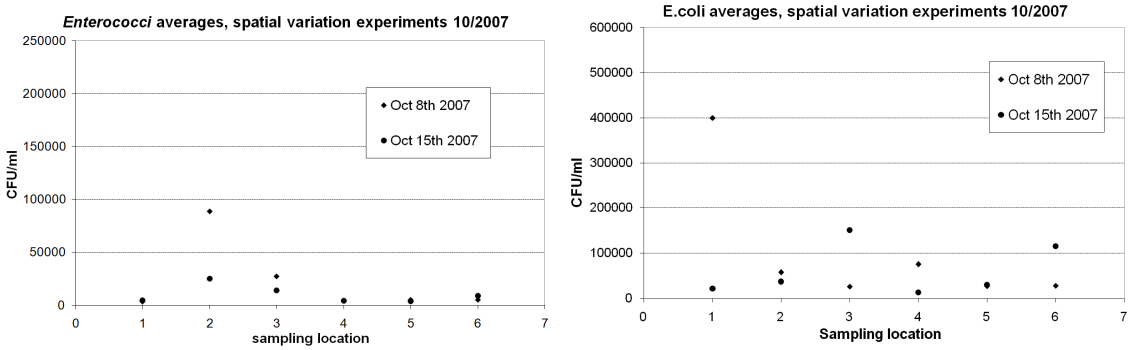

***Figure 3**: Mean concentrations of E.coli and Enterococci found on the two sampling days of the spatial variation experiments*

The results of the spatial variation experiments are summarised in table 8. *Campylobacter* is found in 25% of the samples, *Cryptosporidium* in 17% and *Giardia* in 75% of the analysed samples (table 8).

***Table 8** Pathogen concentrations in wastewater as measured in the spatial variation samples taken from the sewer of Utrecht*

	Mean (of positives)	Range	n	Positive
E.coli	77,465	7,700-570,000	24	24
Enterococci	19,985	2,600-127,00	24	24
Campylobacter (CFU/L)	16,635	2,300-24,000	12	3
Cryptosporidium (oocysts/L)	12	10-15	12	2
Giardia (cysts/L)	584	20-1,700	12	9

Based on the results of the spatial variation experiments average concentrations of *E.coli* and *Enterococci* have been calculated and these are used for risk quantification. The variation in concentration values has been used as input for the Monte Carlo simulations to calculate probability distributions of health risk.

The water and sludge samples that have been collected in the urban flooding situation in Den Haag have been analysed for *E.coli*, *Enterococci* and *Campylobacter*. The results of these analyses are shown in table 9. The pathogen concentrations in sludge are 60-100 times higher than in the water samples taken at the same location.

Table 9 *E.coli and Enterococci counts and presence/absence test results for Campylobacter as found in the urban flooding situation in Den Haag on July 16th 2007*

		E.Coli CFU/mL	*Enterococci* CFU/mL	*Campylobacter*
Sample	Location			
1	Valkenbosplein	1,000	2,100	Positive
2	Boulevard I	87	500	Positive
3	Boulevard II	700	3,700	Positive
4	Johan de Wittlaan	500	2,400	Positive
5	Valkenbosplein sediment	108,000	132,000	Positive

Risk quantification

The average measured pathogen concentrations in the spatial variation experiments and estimated dilution and intake volumes are used to quantify pathogen doses. Applying the dose-response relations from literature mean infection probabilities are calculated for *Campylobacter, Cryptosporidium and Giardia*. Table 10 shows the mean infection probabilities for pedestrians and for children. The presented values for the latter are higher due to higher estimated intake volumes; factual infection probabilities are expected to be larger than the calculated values, since the dose –response relations have been developed for adults who are normally less sensitive to pathogens than children.

Table 10 *Mean infection probabilities per urban flooding event. For a playing child the infection probabilities are higher than calculated, due to the fact that the dose-response relations used are based on healthy adults*

	Pedestrian	Playing child
Campylobacter	28.0×10^{-3}	$>57.0 \times 10^{-3}$
Cryptosporidium	10.4×10^{-6}	$>13.6 \times 10^{-6}$
Giardia	5.8×10^{-3}	$>9.6 \times 10^{-3}$

The measured *E.coli* and *Enterococci* values have been used to define probability distributions of these pathogens. The distributions have been used as input for Monte-Carlo simulations in @Risk software (10,000 iterations), along with estimated probability distributions for a wastewater dilution factor in urban flooding situations.

Monte-Carlo simulations in @Risk (10,000 iterations) with estimated probability distributions for *E.coli* and *Enterococci* concentrations in wastewater and for dilution volumes of wastewater in urban flooding situations are made to calculate pathogen concentration probability distributions in urban flooding water as shown in figure 4.

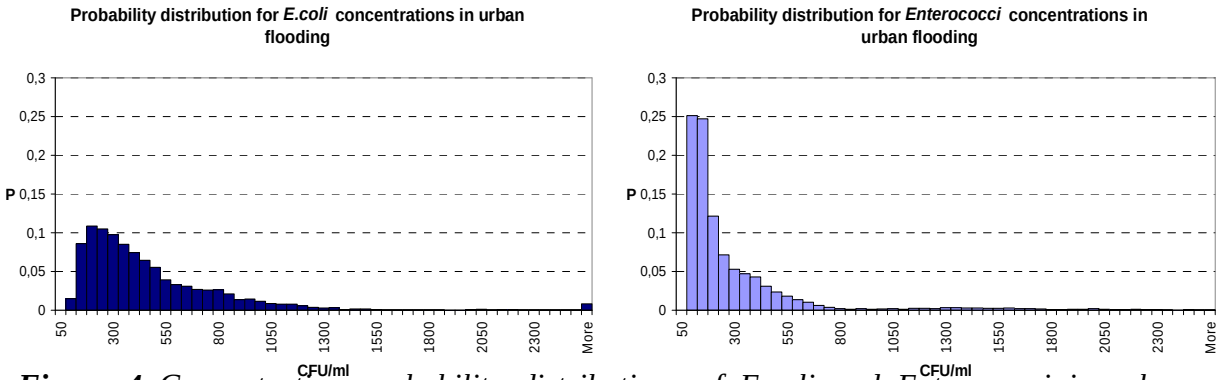

Figure 4 *Concentration probability distributions of E.coli and Enterococci in urban flooding events*

When comparing the results in table 9 with the concentration probability distributions in Figure 4, they seem to be fairly consistent with the results of the Monte-Carlo simulations. This indicates that the chosen dilution factors are in the right order of magnitude, though may be slightly conservative.
The results of the Monte Carlo simulations for infection risk posed by *Campylobacter*, *Cryptosporidium* and *Giardia* are shown in figure 5.

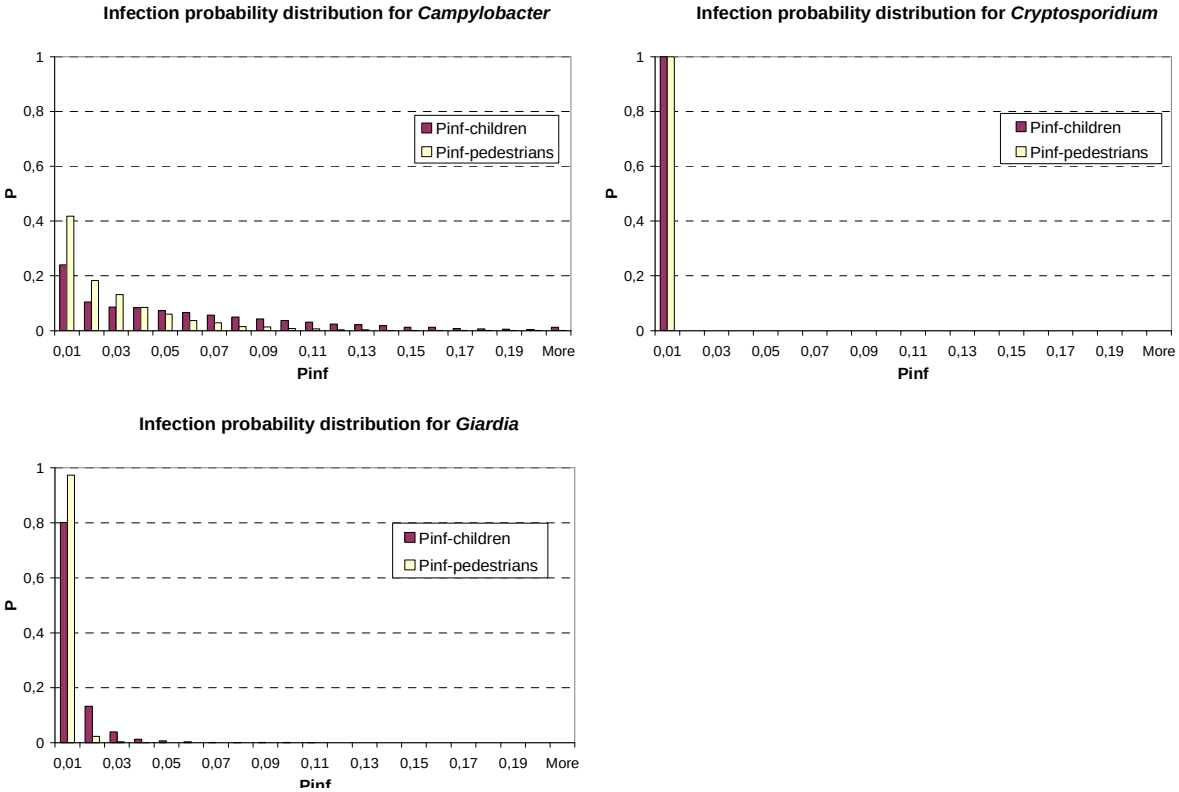

Figure 5 *Infection probability distributions for Campylobacter, Cryptosporidium and Giardia for exposure of children and pedestrians*

Table 11 gives the mean *E.coli* and *Enterococci* concentrations based on the results of the measurement experiments along with the values prescribed in the EU Bathing water directive.

Table 11 *Concentrations and doses of Enterococci and E.coli in bathing water of good quality and in urban flood water. For swimmers the mean ingestion volume is 50 ml, for pedestrians the mean volumes as given in Table 5 are used.*

	Good bathing water quality– Bathing water directive (CFU/100mL)	Mean estimated dose for swimmers (CFU)	Mean water quality in urban flooding (CFU/100ml)	Mean estimated dose for pedestrians/ children (CFU)
Enterococci	200	100	30,000	3,000 / 9,000
E.coli	500	250	48,600	4,860 / 14,580

Based on the assumptions made here, the health risk posed by pathogens in urban flood water appears to be significantly higher than the health risk of swimming in water of good quality as described by the EU Bathing water directive (2006). According to the epidemiological studies that the WHO Guideline for safe recreational water environments (2003) is based on, the health risk of obtaining gastrointestinal illness in urban flood situations is higher than 10%, and the risk of obtaining respiratory illness is higher than 3.9%.

CONCLUSIONS

Quantitative Microbial Risk Assessment has been applied as a method to quantify health risks posed by urban pluvial flooding, focusing on the health risk caused by *Campylobacter, Cryptosporidium* and *Giardia*, common pathogens in wastewater.

Due to variations in the composition of wastewater in time and space, the health risk of being exposed to urban flooding differs from situation to situation. For the duration of the flooding event the concentrations of pathogens in the flood water are expected to remain at the same level. More research is needed to prove this statement, especially for *Campylobacter.*

The doses of pathogens for two different exposure types are calculated using measurements on pathogen concentrations in wastewater from the sewer system of Utrecht. Dose-response relations are used to quantify infection probabilities caused by urban flooding. Mean infection probabilities in urban flooding situations are given in the following table.

	Pedestrian	Playing child
Campylobacter	28.0×10^{-3}	$>57.0 \times 10^{-3}$
Cryptosporidium	10.4×10^{-6}	$>13.6 \times 10^{-6}$
Giardia	5.8×10^{-3}	$>9.6 \times 10^{-3}$

Vulnerable groups like children and elderly people face higher infection probabilities when ingesting a dose of pathogens; no dose-response relations are available for these groups.

To give a framework for the magnitude of the risk, flood water is compared to bathing water, since for bathing water 'acceptable risk' is defined by the WHO, based on *E.coli* and *Enterococci.* The doses of *E.coli* and *Enterococci* in urban flooding are 20-30 times higher for pedestrians and 60-90 times higher for children than what is considered acceptable for swimmers according WHO guidelines. This results in a gastrointestinal illness risk of 10% and a respiratory illness risk of 3.9%. The magnitude of the public health risk posed by urban flooding is significant.

When comparing the results of the Monte-Carlo simulations for *E.coli* and *Enterococci* concentrations in flood water to samples from a real urban flood the results of the simulations appear to be conservative. More data from real urban flooding situations is needed to be able to verify the method.

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