Application of a QMRA model for surface water treatment to investigate a waterborne outbreak of calicivirus

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Abstract
The QMRA modelling tool developed by the Swedish Water & Wastewater Association was applied to investigate a probably waterborne outbreak of calicivirus that occurred in the municipality of Lilla Edet, Sweden, after a period with heavy rain. Of the inhabitants that receive water from the municipal water works, 32% reported gastroenteritis in the period investigated. For the QMRA study, the pathogen load in the raw water source was estimated by describing specific discharge events of wastewater upstream the intake of the municipal water works, including dilution and transport time in the river. Estimates of the concentration of norovirus in wastewater, the efficiency of treatment processes in the waterworks, exposure volumes and dose-response relationships were based on literature data that are included in the modelling tool. In a scenario analysis, the probability of infection related to the three discharge events was quantified. The QMRA model estimated probabilities of infection comparable to the proportion of people reported estimated to have fallen ill in the epidemiological study. Sources of uncertainty and potential for improvement were identified for the in-data and for the modelling tool.

Introduction
A community outbreak of gastrointestinal infection occurred in the municipality of Lilla Edet, Sweden in September 2008. The primary agent was identified to be calicivirus, based on analyses for gastrointestinal pathogens in stool samples.

A questionnaire was sent out on to 2,000 randomly selected persons in the age 19-75 years. Of the persons that responded to the questionnaire, 379 persons reported gastroenteritis in the period 4-24 September. This number corresponds to about 2,400 persons likely to have been ill in Lilla Edet, or 32% of the inhabitants that receive water from the municipal water works. A strong positive correlation was observed between gastroenterical cases and living in households with water supply from the water works in the central parts of the town, in contrast to living in household with their own wells or with water supply from another water works. In addition, a correlation was found between the volume of consumed tap water and the risk for being infected (Larsson & Ekvall 2009). The distribution of cases by day of reported onset is given in Figure 1, with a peak of onsets on the 9 September and with high numbers until the 12 September.

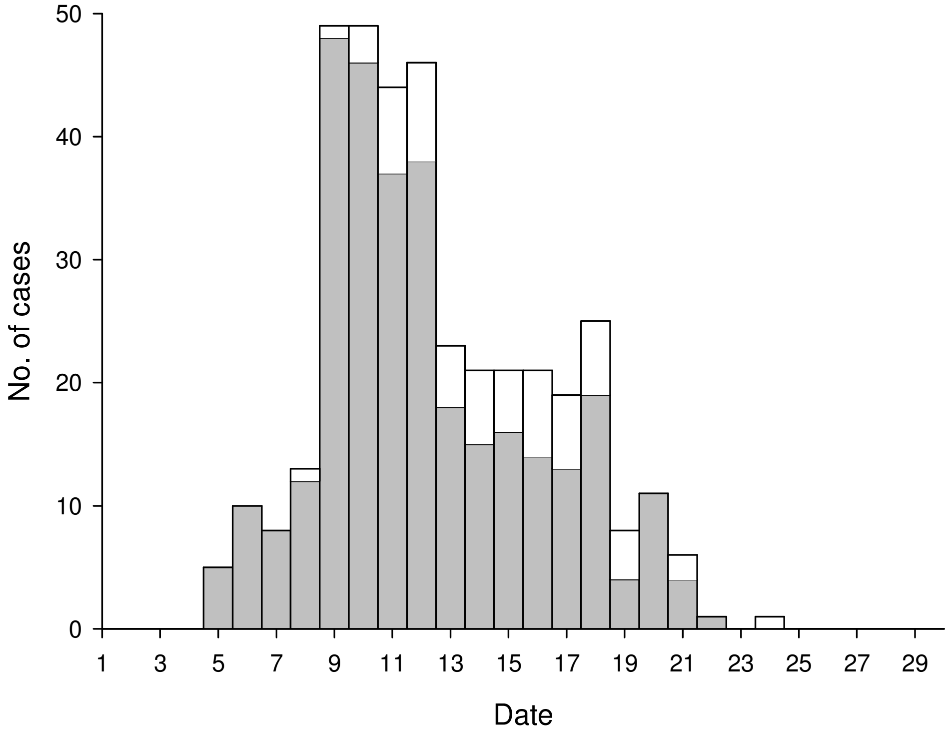

Figure 1. Cases (n=379) who experienced gastrointestinal infection, by the date on onset of first symptoms during September 2008. Grey bars represent persons from households supplied from Lilla Edet water works and white bars persons supplied from another water source. Modified from Larsson & Ekvall (2009).

In this work, the QMRA modelling tool developed by the Swedish Water & Wastewater Association (Abrahamsson *et al.*, 2009) was used to predict the infection risk during the period of the waterborne outbreak. Results from the QMRA were compared to the outcome of the epidemiological study.

Methods

The municipality of Lilla Edet is located in the Southwest of Sweden. The water works supplies 7,500 of the 13,000 inhabitants with water drawn from the river Göta älv. The microbial barriers in the treatment process are pre-chlorination, coagulation/direct filtration with poly aluminium-chloride, and post-chlorination with sodium hypochlorite.

Point sources of microbial contamination upstream of the intake include several wastewater treatment plants with secondary treatment, and several combined sewer overflows (CSOs). Diffuse sources include leakage from on-site household sewers and stormwater runoff from urban and rural areas, impacted by domestic and wild animals. The discharges to the river from the sewer networks are known to vary considerably, depending on weather conditions (Åström *et al.* 2009).

<u>Water quality monitoring</u>

Rainfall was registered in the area before the outbreak, notably about 30 mm on September 6th. Consequently, CSOs were activated in Trollhättan, 20 km upstream, with a total discharge volume of 29,800 m^3 from eight CSOs. In Lilla Edet, six CSOs were activated upstream of the water intake. In addition, an emergency discharge was reported on September 2, when 390 m^3 of untreated wastewater was released over three hours into one of the tributaries 14.2km upstream of the intake.

A turbidity peak was registered on September 6th at monitoring stations some km downstream of the raw water intake, suggesting heavy contamination of the river water. Downstream the raw water intake, levels of *E. coli* increased from 170 (2008-09-05) to 1,100 CFU/100 ml (2008-09-08). At the water works, the disinfection dose was increased for some days after a decrease in redox potential had been detected. When the outbreak was confirmed, samples from the distribution network and the raw water were all positive for somatic coliphages during one round of sampling. All water samples were negative for calicivirus.

<u>QMRA modelling</u>
The Swedish Water & Wastewater Association's QMRA modelling tool for drinking water production from surface waters was used to estimate the probabilities for infection. The tool consists of QMRA methodology programmed using the modelling software Analytica®, using Monte Carlo simulations to take into account variation and uncertainty. The latest version of the modelling tool can be obtained for free from the Swedish Water & Wastewater Association, see Abrahamsson *et al*. (2009). For this study, the version dated August 10th, 2009 was used. Eight waterborne reference pathogens can be explored using default performance data for common treatment processes such as conventional treatment, slow sand filtration, UV disinfection and several types of chlorination. The user can also define additional microbial barriers, or change the default values. The QMRA model contains a module for predicting pathogen concentration in sewage based on epidemiologic inputs including the magnitude and duration of virus shedding from infected individuals. All default input assumptions including exposure volumes and dose-response relationships are documented in the model, with references to the literature.

The probability of infection with norovirus (per day) was estimated for the three discharge events described above. The procedure was as follows:

Theoretical pathogen levels in the discharged wastewater were calculated by the number of persons connected, the volume and proportion of wastewater discharged untreated, and the incidence of infection in the population.

To estimate the pathogen concentration in the raw water, dilution factors and transport times in the water source were calculated (Hartlid, 2009). Parameter estimates for calculating the transport of each separate discharge event are given in Table 1. The discharge events were here described as continuous inputs with finite durations. The dilution and transport time from the upstream discharge points were estimated with advection-diffusion equations (Fisher *et al.* 1979). Following those equations, the transport pattern was described as lateral diffusion for the initial distance followed by longitudinal dispersion with a plug-flow further downstream. For the CSOs in Lilla Edet, lateral diffusion was the only transport mechanism.

Table 1. Parameter estimates for assessing the transport in river Göta älv of three wastewater discharge events preceding the outbreak in Lilla Edet.

	Microbial discharge event			
	CSOs Trollhättan	CSOs Lilla Edet	Emergency discharge	
Parameter estimates				
Type of channel	River	River	Tributary	River
Width (m)	150	150	10	150
Depth (m)	16.5	16.5	3.7	16.5
Flow (m^3/s)	550	606	1	570
Discharge volume (m^3)	29,800	218	393	-
Duration of discharge (h)	18	0.8	3	3.9
No. of people[a]	19200	24	313	
Resulting transport				
Transport time to raw water intake[b]	1.2	0	-	2.9
Passage time at raw water intake[c]	2008-09-07	2008-09-06	-	2008-09-05, 11 AM
Dilution factor[d]	1,200	1,900	-	39,000

[a]Calculated no. of people from whom, in the calculation, all sewage during 24h was discharged untreated. [b]Average transport time of the discharge plume. [c]Day for the contamination plume to pass the raw water intake in Lilla Edet. [d]A 10-fold dilution of the sewage was assumed for CSOs, due to mixing with stormwater.

For the pre-chlorination, the concentration of free chlorine after dosage was estimated to be 0.3 mg/l during the time when the raw water quality was affected by rainfall in the catchment. A default chlorine decay curve and pathogen lethality for low pH (pH 7) were chosen.

In the literature, coagulation with direct filtration is regarded as less effective for removing pathogens than conventional treatment (Smeets *et al.*, 2006). The effectiveness of Lilla Edets water works to remove microalgae, a naturally occurring surrogate, was investigated by flow cytometry as described by Bergstedt & Rydberg (2002). The process in Lilla Edet was found to be equally effective as a conventional treatment plant operated with water from the same raw water source. Therefore the coagulation/direct filtration step was modelled with the default virus reduction efficiency of a conventional treatment plant, i.e. a triangular distribution with min 1.2-$\log_{10}$, mode 3.0-$\log_{10}$ and max 5.3-$\log_{10}$ reduction.

For the post-chlorination, the concentration of free chlorine after dosage was estimated to be 0.19 mg/l. A default chlorine decay curve and pathogen lethality after pH adjustment (pH 8.5) were chosen.

Results

In the QMRA model, the average virus reduction efficiency in the treatment chain was estimated to be 4.2-log, *i.e.* in pre-chlorination 0.58-log (point estimate), in coagulation/direct filtration 3.2-log (triangular distribution, see above) and in post-chlorination 0.37-log (point estimate).

With the default water consumption and dose-response relationships, daily probabilities for infection with norovirus were calculated for selected concentrations in the raw water (Table 2). A concentration of approximately 25,000 organisms/l would result in 32% of the population becoming infected with norovirus, *i.e.* the proportion of inhabitants that reported gastrointestinal illness in the epidemiological investigation.

Table 2. Daily probability of infection (here expressed in %) vs. concentration of norovirus in the raw water, calculated with default conditions for norovirus incidence, treatment efficiency and water consumption.

Conc. (org/l)	5%-perc.	median	mean	95%-perc.
1000	0.1	3.4	7.9	32
10000	1.1	20	24	60
25000	2.1	32	33	66

Among the three discharge events, CSOs in Trollhättan resulted in the highest probability of infection with default conditions (Table 3). The calculated probabilities of infection are in the same order of magnitude as the proportion of inhabitants that reported gastrointestinal illness in the epidemiological investigation.

Table 3. Daily probability of infection with norovirus (here expressed in %) for the three discharge events. Calculated with default conditions for norovirus incidence, treatment efficiency and water consumption.

Discharge event	5%-perc.	median	mean	95%-perc.
CSOs in Trollhättan	0.3	17	24	69
CSOs in Lilla Edet	0.03	3.1	15	48
Emergency discharge	0.01	0.9	5.6	31

A scenario analysis was done to investigate the probability of infection depending on the incidence of norovirus infection in the population connected to the overflowing sewer systems (Table 4). According to the calculation, the CSOs in Trollhättan could have caused the outbreak with norovirus incidence around the model's default (0.9%, estimated from SMI, 2008), whereas for the other discharge events, a large proportion of the population needed to be infected to have caused the outbreak.

Table 4. Daily probability of infection with norovirus (here expressed in %) due to the three upstream discharge events, depending on norovirus incidence.

			Probability of infection for norovirus, $P_{inf/day}$ (%)		
Discharge event upstream	Infected persons connected to sewer system (%)	5%-perc.	mean	average	95%-perc.
CSOs in Trollhättan	3	0.9	32	34	77
CSOs in Lilla Edet	20	0.7	29	32	76
Emergency discharge	60	0.7	30	33	76

Discussion
The epidemiological investigation indicated that, with a high probability, the origin of the outbreak was drinking water contaminated with wastewater. In 23 of the 41 stool samples analysed, several different genotypes of calicivirus were detected (Larsson & Ekvall 2009). The multitude of genotypes suggests that different areas of sewer systems upstream of the raw water intake may potentially have been involved.

Epidemiological evidence is affected by uncertainties, although often assumed to give the "true" number of people who became ill. For example, that symptomatic illness must occur and that symptoms must be reported in similar ways in the questionnaires are both factors that produce uncertainty. Also, a feeling of disgust may affect the answers to a questionnaire. In this paper, results about gastrointestinal illness given from epidemiology were compared to the probabilities of infection given by QMRA modelling for different scenarios.

The QMRA model estimated probabilities of infection comparable to the proportion of people reported estimated to have fallen ill in the epidemiological study. However, the model results were affected by significant uncertainties and unknowns. Some examples:

Microbiological data: The available information on the magnitude of virus shedding by infected individuals was not norovirus-specific. In earlier testing of the QMRA model, the shedding data results in very high norovirus concentrations.

Time and dynamics of the discharge: The exact points of time for the CSOs in Trollhättan and Lilla Edet are missing. Also, the dynamics over time were here replaced by an assumption about constant flows. The in-data to the QMRA model can be improved by linking urban runoff modelling for the CSOs with a hydrodynamic model of the river.

An accumulation of sediments and contaminants during low-flow periods have been observed in the sewer system of Trollhättan, a phenomenon that may result in an accumulation of microorganisms. A release of accumulated sediments due to high stormwater flows and the CSO discharges on the 6^{th} September may therefore have further increased the loads of virus particles into the river, increasing the calculated infection risk related to this discharge event. Also, a sudden increase of organic matter from sewer systems may substantially lower the effect of pre-chlorination, by larger initial chlorine decay. The investigations could not answer why the norovirus outbreak occurred specifically in September 2008. Although the weather conditions were adverse, the raw water quality did not appear to be extreme. The river water is continuously affected by the discharge of microorganisms from treated wastewater, as quantified by (Åström *et al.* 2009).

The effect of chlorination: The calculation of virus reduction efficiency in the water works heavily depends on the effect of chlorination, in this case in 2 steps. The dynamics of free chlorine concentration for most water works can only be guessed, resulting in a large uncertainly in the CT-value. The chlorination module should be refined, for example with data from Ødegaard et al. (in press). However, if the outbreak was caused by contaminated raw water, the pre-chlorination, done at favorable pH, must have had a low efficiency against virus during the time preceding the outbreak. For bacterial pathogens, the model indicates that the reduction efficiency was still sufficient to avoid any infections.

Conclusions

The QMRA modelling tool developed by the Swedish Water & Wastewater Association, fed with data of upstream discharge events of wastewater, estimated probabilities of infection comparable to the proportion of people reported to have fallen ill in the epidemiological study. The application of the modelling tool was affected by uncertainties, but was valuable especially for scenario analysis.

From the study, potential points for improvement were identified:

Microbiological in-data such as virus shedding of infected persons and disease incidence in the population may be improved in the future.

Within the authors' sphere of influence, the description of the magnitude and dynamics of wastewater discharge events could be improved, together with the description of transport of pathogens in the raw water source. In the further development of the QMRA modeling tool for surface water applications, a refined chlorination module should be prioritized.

Acknowledgement

The development of the QMRA model was financed by the R&D fund of the Swedish Water & Wastewater Association, a project lead by the Stockholm Water Co., namely Mrs. Josefin Abrahamsson and Ms. Johanna Ansker. Mr. Göran Åberg at the Municipality of Lilla Edet commented on the manuscript.

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