QMRA (quantitative microbial risk assessment) and HACCP (hazard analysis and critical control points) for management of pathogens in wastewater and sewage sludge treatment and reuse

T. Westrell***, C. Schönning*, T.A. Stenström* and N.J. Ashbolt***

* Department of Parasitology, Mycology and Environmental Microbiology, Swedish Institute for Infectious Disease Control, SE-171 82 Solna, Sweden (E-mail: therese.westrell@smi.ki.se; caroline.schonning@smi.ki.se; thor-axel.stenstrom@smi.ki.se)

** Department of Water and Environmental Studies, University of Linköping, SE-581 83 Linköping, Sweden

*** Centre for Water and Waste Technology, School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW 2052, Australia (E-mail: n.ashbolt@unsw.edu.au)

Abstract Hazard Analysis and Critical Control Points (HACCP) was applied for identifying and controlling exposure to pathogenic microorganisms encountered during normal sludge and wastewater handling at a 12,500 m³/d treatment plant utilising tertiary wastewater treatment and mesophilic sludge digestion. The hazardous scenarios considered were human exposure during treatment, handling, soil application and crop consumption, and exposure via water at the wetland-area and recreational swimming. A quantitative microbial risk assessment (QMRA), including rotavirus, adenovirus, haemorrhagic E. coli, Salmonella, Giardia and Cryptosporidium, was performed in order to prioritise pathogen hazards for control purposes. Human exposures were treated as individual risks but also related to the endemic situation in the general population. The highest individual health risk from a single exposure was via aerosols for workers at the belt press for sludge dewatering (virus infection risk = 1). The largest impact on the community would arise if children ingested sludge at the unprotected storage site, although in the worst-case situation the largest number of infections would arise through vegetables fertilised with sludge and eaten raw (not allowed in Sweden). Acceptable risk for various hazardous scenarios, treatment and/or reuse strategies could be tested in the model.

Keywords HACCP; pathogens; quantitative microbial risk assessment; reuse; sewage sludge; wastewater

Introduction

The environmental goals of the Swedish Environmental Protection Agency are based on the concept of sustainable development. Conservation of natural resources, as a part of this, includes the reuse of nutrients from wastewater and sewage sludge (biosolids) to agricultural land. At the same time the demands from society on due diligence increase and more and more stringent norms and regulations are placed on producers. Despite limited definitive evidence for the association between human disease and current practices of sewage sludge and wastewater re-use (NRC, 2002), transmission of diseases through reuse practices is possible and highly unwanted. Microbial risk assessment can function as a valuable tool to identify potential human health threats, yet to proceed from the theoretical assessment to practicalities it must be incorporated into a risk management framework. With the use of a risk management system possible health risks can be controlled and the public’s acceptability towards different recycling alternatives and products fertilised with human wastes could more easily be achieved.

Within food and drinking water production the management system Hazard Analysis and Critical Control Points (HACCP) has been applied (FAO, 1997; WHO, 2003). HACCP offers a preventative management and quality assurance approach rather than random...
monitoring of the end product. The system involves identification of critical points to control hazards and maintain best management practices throughout production and distribution. Criteria are established for each control point, which are monitored, and corrective actions are established that should be carried out when critical limits are not met (FAO, 1997; WHO, 1999). Our aim was to apply this concept on treatment, handling and reuse of wastewater and sewage sludge. By this approach the “chain of production” of these fractions could be quality assured.

As a first step in applying HACCP to wastewater and sludge reuse we performed a quantitative microbial risk assessment on an existing site in Sweden in order to establish the most severe hazardous scenarios for pathogens in this system under “normal” operation. These were then ranked in order of severity both in relation to individual risks and to the community, accounting for the endemic background level of disease.

Methods
Adaptation of the hazard analysis and critical control points (HACCP) system
HACCP has been applied on drinking water and is incorporated as part of the Water safety plans in the WHO’s Guidelines for drinking water quality (WHO, 2003). It has been adopted in a wastewater reuse system, including groundwater recharge and production of drinking water (Dewettinck et al., 2001). A major difference in producing safe wastewater or biosolids compared to safe food is that the wastewater already contains the hazards while in the latter the goal is to prevent contamination. The focus must therefore be placed on controlling the exposure to wastewater or sludge and eliminate or reduce the hazards through effective treatment. The applied procedure used in our HACCP/QMRA approach is listed in Table 1.

Site description
The wastewater treatment plant in the city of Hässleholm received sewage from the town and surrounding areas, with 28,600 persons connected. The plant received a daily mean of 12,500 m$^3$ of sewage with a maximum of 32,300 m$^3$ per day. The primary treatment included pre-aeration and pre-sedimentation aided with sludge re-circulated from the chemical precipitation later in the treatment. The secondary and tertiary treatment consisted of activated sludge, chemical precipitation with iron chloride and a three-media (1.8 m deep) filter. The water was then “polished” in a constructed wetland before it was discharged into the recipient.

Primary and biological sludge was dewatered and then anaerobically digested at 34°C for 23 days in two consecutive digesters. After additional dewatering in a thickener and a belt press (with the addition of polymers), the sludge was stored outdoors on a concrete slab for one month up to a year. An entrepreneur transported part of the sludge from the plant and applied it to agricultural land. The remaining sludge was used for landfill covering or landfill.

Table 1 Procedure used in HACCP/QMRA case study

<table>
<thead>
<tr>
<th></th>
<th>Draw out systems structures and define system boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Compile literature data on pathogens and treatment processes</td>
</tr>
<tr>
<td>3</td>
<td>Site visits with specific questions</td>
</tr>
<tr>
<td>4</td>
<td>Construct model with data from literature and site specific data</td>
</tr>
<tr>
<td>5</td>
<td>Examine exposure pathways through QMRA and site discussions with personnel</td>
</tr>
<tr>
<td>6</td>
<td>Rank exposures after highest risk</td>
</tr>
<tr>
<td>7</td>
<td>Choose control point(s) for each type of hazardous exposure</td>
</tr>
<tr>
<td>8</td>
<td>Describe parameters governing the performance of a certain control point</td>
</tr>
</tbody>
</table>
Quantitative microbial risk assessment (QMRA)

The procedure for quantitative risk assessment was used in accordance to Haas et al. (1999).

Hazard identification

All pathogens that are excreted in faeces could potentially be found in wastewater. A selection of pathogens was made for the risk assessment, representing bacteria, viruses and protozoa. It included pathogens that mainly cause gastroenteritis (Salmonella, Giardia, Cryptosporidium, rotavirus), or milder respiratory infections (adenovirus) and pathogens that can cause more severe disease, such as haemolytic uremic syndrome (enterohaemorrhagic E. coli O157:H7, EHEC). All of these have been causes of waterborne disease, are known to occur in Sweden and have all been detected in sewage. Salmonella and reovirus (same family as rotavirus) have been found in aerosols at wastewater treatment plants (Carducci et al., 2000) and E. coli and Salmonella are able to grow in stored sewage sludge (Gibbs et al., 1997; Gantzer et al., 2001).

Exposure assessment

The hazardous exposures were identified by a systematic on-site survey of the treatment plant and its surroundings. At the treatment plant exposure of the workers to aerosols at the aeration basins and sludge dewatering were recognised as the major hazardous events, also reported from other studies (Khuder et al., 1998). The wetland for “polishing” of the wastewater effluent is used as a recreational area for school classes, bird-watchers and people living nearby. Accidental or intended immersions were considered as one exposure point and children playing by the water transferring water from hand to mouth as another. After the wetland the water is discharged into a lake that is used for recreation, with several hundred bathers on a sunny day. The storage of sludge takes place outside the wastewater treatment plant and is accessible, for example, to children. An entrepreneur collects the sludge and spreads it on agricultural land, which involves direct contact with the sludge and exposure to aerosols during application. We also tested the hypothesis that vegetables eaten raw were cultivated in the sludge-mixed soil directly after application.

The frequency of exposure, the number of persons exposed at each point and the amounts likely to be ingested per exposure were determined (summarised in Table 2). In exposure 6, the sludge ingestion was based on the upper range of estimated daily soil ingestion for children (LaGoy, 1987; Stanek and Calabrese, 1995) justified as a rare event. The numbers and calculations can be varied according to the prevailing conditions at other sites.

The doses of pathogens for each exposure were estimated from the concentrations in raw sewage based on literature data and the removal, inactivation or growth at different stages. The reduction in the wastewater treatment was based on previous studies at the plant.

<table>
<thead>
<tr>
<th>Type of exposure</th>
<th>Volume ingested (mL or g)</th>
<th>Frequency (times per year)</th>
<th>Number of persons affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. WWTP worker at pre-aeration</td>
<td>1</td>
<td>52</td>
<td>2</td>
</tr>
<tr>
<td>2. WWTP worker at belt press</td>
<td>5</td>
<td>208</td>
<td>1</td>
</tr>
<tr>
<td>3. (Un)intentional immersion at wetland inlet</td>
<td>30</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>4. Child playing at wetland inlet</td>
<td>1</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>5. Recreational swimming</td>
<td>50</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td>6. Child playing at sludge storage</td>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>7. Entrepreneur spreading sludge</td>
<td>2</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>8. Consumption of raw vegetables</td>
<td>1</td>
<td>2</td>
<td>500</td>
</tr>
</tbody>
</table>
(Stenström et al., 1985) and in Swedish wetlands (Stenström and Carlander, 2001) with faecal coliforms, sulphite-reducing clostridia spores and somatic coliphages representing bacterial, protozoan and viral pathogens, respectively. The numbers of EHEC in sewage were estimated from epidemiological prevalence data and by the expected excretion during a year diluted in the volume of water produced during a year. The recreational water was assumed to be fully mixed and under steady-state conditions and first-order pathogen inactivation equations were used.

The concentration of the pathogens in the raw sludge was based on measured concentrations in sewage and calculated ratios between various microbes in raw sewage and sludge (Chauret et al., 1999). The inactivation of pathogens during the anaerobic digestion was assessed from literature data (e.g. Chauret et al., 1999; Gantzer et al., 2001). In the dewatering processes fifty percent of the pathogens were assumed to attach to sludge particles. No inactivation was assumed for protozoa and viruses before exposure to the sludge. The die-off of EHEC and Salmonella can be rapid in sludge but large regrowth may also occur (Gibbs et al., 1997; Gantzer et al., 2001). We therefore assumed that the concentration was back to initial levels at the time of sludge collection.

On agricultural land the sewage sludge was assumed to be homogenously mixed into the top 25 cm of soil according to current practices and harvest of crop taking place one month after application. As an example of crop likely to be eaten raw we used strawberries where sludge-soil mixture could contaminate the berries especially during episodes of heavy rains. Probability distributions were used to describe the majority of the pathogen exposure parameters.

**Dose–response assessment**

The dose–response relationships used can be found in Haas et al. (1999). For EHEC the dose–response relationship developed for Shigella was used as proposed by Strachan et al., 2001.

**Risk characterisation**

The entire model was simulated with Monte Carlo techniques (10,000 iterations), using @Risk software (V4.5, Palisade Corporation, Newfield, NY). Results were expressed as the risk per person and exposure and as the annual number of infections resulting from each exposure. The latter was compared to the background endemic level of infection in the community, which was estimated from epidemiological statistics on reported cases of disease, adjusted for underreporting and morbidity rates (e.g. Haas et al., 1999; Wheeler et al., 1999). Secondary transmission was excluded. A ranking was then performed according to suggested definitions of severity of consequences listed in Table 3. Since EHEC can result

<table>
<thead>
<tr>
<th>Item</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic</td>
<td>Major increase in diarrhoeal disease &gt;25% or &gt;5% increase in more severe disease or large community outbreak (100 cases) or death</td>
</tr>
<tr>
<td>Major</td>
<td>Increase in more severe diseases* (0.1–5%) or large increase in diarrhoeal disease (5–&lt;25%)</td>
</tr>
<tr>
<td>Moderate</td>
<td>Increase in diarrhoeal disease (1–&lt;5%)</td>
</tr>
<tr>
<td>Minor</td>
<td>Slight increase in diarrhoeal diseases (0.1–&lt;1%)</td>
</tr>
<tr>
<td>Insignificant</td>
<td>No increase in disease incidence (&lt;0.1%)</td>
</tr>
</tbody>
</table>

* In this paper represented by EHEC

---

**Table 3** Suggested definitions of severity of consequences of hazards based on increase of endemic disease in the community
in the very severe disease haemolytic uremic syndrome with a significant mortality, a
higher ranking was proposed for this organism.

Results and discussion
The highest individual health risk per single exposure was achieved through exposure to
droplets and aerosols for workers at the treatment plant (exposures 1 and 2), particularly at
the belt press for sludge dewatering, and through contact with digested sludge (exposures 6
and 7) with a risk of viral infection nearly or equal to 1 (Table 4). The lowest risk was from
swimming in the lake (exposure 5). The wastewater treatment, the wetland and the dilution
in the receiving water reduce the pathogen numbers to a great extent. If currents transport
undiluted wetland discharge to the bathing area the risk could increase a thousand times.

The viruses gave the highest risk for a single exposure due to high influent concentra-
tions, low infectious doses and lesser removal than bacteria and protozoa. *Giardia* is more
infectious than *Cryptosporidium*, which was reflected in the risk calculations. The higher
risk for EHEC than for *Salmonella* was mainly due to the difference in dose-response equa-
tions and the median infectious doses. Haas *et al.* (2000) have however reported a median
infectious dose for EHEC 500 times higher than the one used here.

The yearly number of infections estimated to occur per hazardous exposure was
generally very low for non-viral pathogens (<<1, Table 5). The number of cases should,
however, be compared to the number of exposed individuals listed in Table 2. The major
risk was due to viruses, with maximum number of infections reached for both adenovirus

### Table 4  Median risk of infection per single exposure listed in Table 2

<table>
<thead>
<tr>
<th>Exposure</th>
<th>EHEC</th>
<th>Salmonella</th>
<th>Giardia</th>
<th>Cryptosporidium</th>
<th>Rotavirus</th>
<th>Adenovirus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6×10⁻⁴</td>
<td>3×10⁻⁵</td>
<td>1×10⁻³</td>
<td>2×10⁻⁴</td>
<td>9×10⁻²</td>
<td>2×10⁻¹</td>
</tr>
<tr>
<td>2</td>
<td>2×10⁻³</td>
<td>1×10⁻⁴</td>
<td>4×10⁻³</td>
<td>9×10⁻⁴</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>3×10⁻⁵</td>
<td>2×10⁻⁵</td>
<td>3×10⁻⁵</td>
<td>3×10⁻⁵</td>
<td>5×10⁻²</td>
<td>1×10⁻¹</td>
</tr>
<tr>
<td>4</td>
<td>1×10⁻⁶</td>
<td>6×10⁻⁸</td>
<td>1×10⁻⁶</td>
<td>1×10⁻⁶</td>
<td>2×10⁻³</td>
<td>4×10⁻³</td>
</tr>
<tr>
<td>5</td>
<td>9×10⁻¹⁰</td>
<td>5×10⁻¹¹</td>
<td>2×10⁻⁶</td>
<td>5×10⁻⁸</td>
<td>1×10⁻⁵</td>
<td>6×10⁻⁵</td>
</tr>
<tr>
<td>6</td>
<td>1×10⁻¹²</td>
<td>6×10⁻⁴</td>
<td>2×10⁻²</td>
<td>6×10⁻³</td>
<td>4×10⁻¹</td>
<td>9×10⁻¹</td>
</tr>
<tr>
<td>7</td>
<td>5×10⁻³</td>
<td>3×10⁻⁴</td>
<td>1×10⁻²</td>
<td>2×10⁻³</td>
<td>3×10⁻¹</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>2×10⁻⁵</td>
<td>9×10⁻⁸</td>
<td>2×10⁻⁶</td>
<td>9×10⁻⁶</td>
<td>2×10⁻⁴</td>
<td>4×10⁻⁴</td>
</tr>
</tbody>
</table>

### Table 5  Median number of yearly infections resulting from the frequency of exposures and number of affect-
ed persons as listed in Table 2. Numbers within brackets represent 95% confidence interval

<table>
<thead>
<tr>
<th>Exposure</th>
<th>EHEC</th>
<th>Salmonella</th>
<th>Giardia</th>
<th>Cryptosporidium</th>
<th>Rotavirus</th>
<th>Adenovirus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.06</td>
<td>0.004</td>
<td>0.14</td>
<td>0.02</td>
<td>1.98</td>
<td>1.99</td>
</tr>
<tr>
<td></td>
<td>(0.03–0.83)</td>
<td>(0.0002–0.05)</td>
<td>(0.04–0.38)</td>
<td>(0.002–0.12)</td>
<td>(1.69–2.00)</td>
<td>(1.30–2.00)</td>
</tr>
<tr>
<td>2</td>
<td>0.33</td>
<td>0.02</td>
<td>0.57</td>
<td>0.16</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>(0.05–0.80)</td>
<td>(0.0007–0.43)</td>
<td>(0.05–0.99)</td>
<td>(0.01–0.71)</td>
<td>(0.99–1.00)</td>
<td>(0.97–1.00)</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0.0006</td>
<td>0</td>
<td>0.11</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>(0–0.0003)</td>
<td>(0)</td>
<td>(0–0.004)</td>
<td>(0–0.0008)</td>
<td>(0.03–0.34)</td>
<td>(0.02–1.87)</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0.0006</td>
<td>0</td>
<td>0.13</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>(0–0.0003)</td>
<td>(0)</td>
<td>(0–0.004)</td>
<td>(0–0.0009)</td>
<td>(0.03–0.53)</td>
<td>(0.02–5.21)</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0.0005</td>
<td>0.0001</td>
<td>0.04</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>(0–0.0003)</td>
<td>(0)</td>
<td>(0–0.004)</td>
<td>(0–0.0018)</td>
<td>(0.008–0.20)</td>
<td>(0.01–4.26)</td>
</tr>
<tr>
<td>6</td>
<td>0.02</td>
<td>0.001</td>
<td>0.05</td>
<td>0.01</td>
<td>0.76</td>
<td>1.87</td>
</tr>
<tr>
<td></td>
<td>(0.003–0.08)</td>
<td>(0–0.03)</td>
<td>(0.003–0.32)</td>
<td>(0.0005–0.16)</td>
<td>(0.23–1.28)</td>
<td>(0.22–2.00)</td>
</tr>
<tr>
<td>7</td>
<td>0.26</td>
<td>0.02</td>
<td>0.52</td>
<td>0.13</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>(0.03–0.85)</td>
<td>(0.0005–0.36)</td>
<td>(0.04–1.75)</td>
<td>(0.006–1.25)</td>
<td>(1.64–2.00)</td>
<td>(1.49–2.00)</td>
</tr>
<tr>
<td>8</td>
<td>0.002</td>
<td>0</td>
<td>0.01</td>
<td>0.21</td>
<td>0.41</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>(0–0.01)</td>
<td>(0–0.003)</td>
<td>(0–0.025)</td>
<td>(0.0004–0.15)</td>
<td>(0.01–2.91)</td>
<td>(0.01–20.51)</td>
</tr>
</tbody>
</table>

0 is equivalent to <0.0001 infections
and rotavirus in exposure scenarios 2 and 7 and nearly in scenario 1. This means that the workers at the treatment plant and the entrepreneurs handling and spreading sludge were quite certain to become infected during one year of performance, unless already immune or protected. Antibodies against enteric viruses, e.g. adenovirus, have been reported among wastewater treatment plant workers with higher prevalence among those subjected to high aerosol exposure (Clark, 1987).

The consumption of vegetables grown in sludge-amended soil gave a lower risk and a lower number of yearly infections than expected. A significantly higher risk would, however, result if the organisms occurred in higher concentrations in lumps of sludge rather than being homogeneously distributed as assumed. In the current Swedish legislation ten months must pass between sludge fertilisation and harvest of crops that is to be eaten raw, but in this study a worst-case scenario assuming only one month was applied.

In order to rank the hazardous exposures according to severity of consequences a comparison was made to the endemic level of these diseases in the community. Although several of the exposures only resulted in fractions of infections (Table 5) they had a large impact on the community as a whole (Table 6). This was due to anticipated low prevailing numbers of infection.

From the society’s perspective it is most important to control exposures 1, 2, 6 and 7 at this sewage treatment plant. Wastewater treatment does normally not include any complete barriers and the treatment processes are not optimised for pathogen removal, although each process generally inactivates or removes a part of the pathogens. Control points for all of the hazardous exposures could be to make sure that the each treatment step maintains measurable process parameters within operational limits and does not exceed established critical limits. For exposure 1, 2 and 7 a measure that is easy to achieve and efficient is the use of personal protective equipment, especially crucial for exposure early in the treatment where few other control measures are possible. In fact, two persons at the studied plant had had to change their working environment because of continuous inflammatory symptoms as well as respiratory problems and nausea. Symptoms most frequently reported from investigations in WWTP workers include gastrointestinal symptoms, headache and fatigue, but also upper respiratory symptoms, eye and skin irritation (Thorn and Kerekes, 2001). Several of these symptoms have been related to specific workstations that generate aerosols.

Table 6 Comparison between estimated median number of infections (Table 5) and incidence of infection in the community. Values within brackets represent 95% confidence interval

<table>
<thead>
<tr>
<th>Exposure</th>
<th>EHEC</th>
<th>Salmonella</th>
<th>Giardia</th>
<th>Cryptosporidium</th>
<th>Rotavirus</th>
<th>Adenovirus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Major</td>
<td>–</td>
<td>–</td>
<td>Minor</td>
<td>Minor</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>(Catastrophic)</td>
<td>(–)</td>
<td>(Minor)</td>
<td>(Moderate)</td>
<td>(Minor)</td>
<td>(Moderate)</td>
</tr>
<tr>
<td>2</td>
<td>Major</td>
<td>–</td>
<td>Minor</td>
<td>Moderate</td>
<td>Minor</td>
<td>Minor</td>
</tr>
<tr>
<td></td>
<td>(Catastrophic)</td>
<td>(Minor)</td>
<td>(Minor)</td>
<td>(Major)</td>
<td>(Minor)</td>
<td>(Minor)</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>(Minor)</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>(Moderate)</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>(Minor)</td>
</tr>
<tr>
<td>6</td>
<td>Major</td>
<td>–</td>
<td>–</td>
<td>Minor</td>
<td>Minor</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>(Major)</td>
<td>(–)</td>
<td>(–)</td>
<td>(Moderate)</td>
<td>(Minor)</td>
<td>(Moderate)</td>
</tr>
<tr>
<td>7</td>
<td>Major</td>
<td>–</td>
<td>Minor</td>
<td>Moderate</td>
<td>Minor</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>(Catastrophic)</td>
<td>(Minor)</td>
<td>(Minor)</td>
<td>(Catastrophic)</td>
<td>(Minor)</td>
<td>(Moderate)</td>
</tr>
<tr>
<td>8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Minor</td>
<td>Min –</td>
<td>(Moderate)</td>
</tr>
<tr>
<td></td>
<td>(Major)</td>
<td>(–)</td>
<td>(–)</td>
<td>(Moderate)</td>
<td>(Minor)</td>
<td>(Moderate)</td>
</tr>
</tbody>
</table>
In order to avoid children from getting access to the sludge storage (exposure 6) an easy control measure would be to fence the area. Other improvements that would also increase the safety in the subsequent exposures of handling sludge or eating vegetables grown in sludge amended soil would be to change from mesophilic to thermophilic digestion or prolong the storage times.

The QMRA and HACCP procedure was in this case study applied to conditions of normal operation of the treatment plant. Worst-case scenarios or hazardous events need to be further evaluated in order to propose a final management system. Such events could be flooding, a major failure in the wastewater treatment or sudden peaks based on treatment variability. A further development of our HACCP/QMRA approach would include the remaining steps in HACCP: to establish critical limits, propose monitoring strategies and corrective actions, procedures for record keeping and to verify that the management system is working correctly and prevents transmission of infectious diseases. As a generic tool it could be applied to any plant and adjusted to site-specific demands.

Conclusions
The most hazardous exposures identified in this case study included some of the early processes in treatment and the sludge handling. These could be controlled by use of personal protection equipment and extended treatment of the sludge. Viruses generally yielded the highest risks and resulted in the largest number of potential cases, while EHEC and Cryptosporidium, with only a few cases constituting the endemic level, was identified as having the largest impact on the community (i.e. major to catastrophic), with above 5% and 25% increase in disease rate, respectively.

Acknowledgements
The authors acknowledge the good co-operation with Per-Åke Nilsson and the rest of the staff at Hässleholm wastewater treatment plant as well as the financial support from the Swedish research council FORMAS.

References


