Quantitative risk assessment in the Water Safety Plan: case studies from drinking water practice
Gertjan Medema and Patrick Smeets

ABSTRACT
System assessment is the part of the Water Safety Plan that evaluates whether a water supply system is capable of producing drinking water that meets the health-based targets. System assessment can be done at increasing level of detail, requiring more site specific information as the level of detail increases. Four case studies are presented with increasing level of detail, showing the type of information that is required for each of these levels and how each level informs risk management. The first case study shows how a system assessment can be performed without other site specific information than the type of source water and the type of treatment processes. The required data for the system assessment are collected from the large body of literature available. The second case study uses site specific microbial indicator data. The third study uses pathogen data and the fourth case study combines data on pathogens, microbial indicators and process parameters. The case studies show that the level of detail required largely depends on the risk management question.

Key words | drinking water, non-piped, pathogens, QMRA, risk assessment, Water Safety Plan

INTRODUCTION
The principle purpose of a Water Safety Plan is to ensure safe drinking water through good water supply practice. Within the WHO framework for safe drinking-water (Figure 1), health-based targets are used to set a benchmark for the water supplier to evaluate their water supply system and all the elements of the Water Safety Plan against.

Within the Water Safety Plan, system assessment is the process of characterizing a water supply and determining whether a water supply system, from source to tap, is able to deliver a water quality to the consumer that meets the health-based targets.

SYSTEM ASSESSMENT
System assessment in the Water Safety Plan (WSP) has a sequence of steps. The first four steps, (1) assemble a team, (2) describe the water supply system from catchment-to-tap, (3) analyze and prioritise hazard and hazardous events and (4) identify control measures, are steps in the preparation of the actual system assessment to determine if the water supply system as a whole is able to meet the health-based targets. A good description of these preparatory steps can be found in the Water Safety Plan background document (Davison et al. 2005) and the Water Safety Plan manual (Davison et al. 2007). Information about control measures, including examples, can be found in Davison et al. (2005), in Schmoll et al. (2006) for groundwater protection, Medema et al. (2004) for surface water catchments, LeChevallier & Au (2004) for water treatment, Ainsworth (2004) for piped supplies and in Howard et al. (2006) for small systems.

Once the priority hazards and the hazardous events are identified and the control measures are listed, the true system assessment can be conducted. The system
assessment evaluates whether the total suite of control measures are adequate to ensure delivery of drinking water that consistently meets the health-based targets for a specific system given the local priority hazards and hazardous events. System assessment requires input from data about the (priority) hazards, hazardous events and efficacy of control measures. Depending on the available site-specific input, system assessment can be done at different levels of detail. More detail is not always best, in many cases in practice, system assessment evolves as a tiered approach, starting with a generic, deterministic assessment and moving towards more site-specific and statistical assessment if the decisions on appropriate risk management measures require a more detailed assessment of the risk.

The case studies presented here are Quantitative Microbial Risk Assessment studies that evaluated the ability of water supply systems to meet the microbiological health-based targets. The logic applies similarly to chemical health-based targets.

TIER 1. USING DEFAULT VALUES

The most generic form of system assessment does not require site specific water quality testing, but used information from the available literature about pathogen occurrence, fate and transport and removal by treatment processes.

Example: default values for Cryptosporidium in surface water treatment

For surface water systems, data is available in the literature about pathogen occurrence and efficacy of water treatment processes. A water utility wanted to assess their systems against predefined health-targets for Cryptosporidium (see Medema et al. 2006). They used the translation of a health target ($10^{-4}$ probability of infection per person per year) to a water quality target for Cryptosporidium (0.003 per 100 litre) published by Haas et al. (1996). The utility did not have site-specific data on Cryptosporidium occurrence in source waters, nor data on pathogen removal by their water treatment systems. They made an inventory of the available data in literature on Cryptosporidium occurrence in source waters. They concluded that a conservative estimate of the concentration of Cryptosporidium in surface water is 100/100 litre. Therefore, the treatment performance target was 4.5 log removal (log 100/0.003). Generic log credits were assigned to the removal or inactivation of Cryptosporidium by water treatment processes. A treatment system with pre-ozonation (0.5 log credit), coagulation/floation (1 log credit), ozonation (1.5 log credit) and rapid sand filtration (2 log credit) was considered to remove/inactivate Cryptosporidium with 5 logs, more than enough to meet the health-based treatment performance target. Similar system assessments were conducted for the 1700 supplies they operate. The results of this system assessment were used to prioritise the utility’s investment program in treatment optimisation/upgrade.

TIER 2. USING INDICATORS

In many cases, there are (at least some) data available on micro-organisms that are indicative for the presence of pathogens. Mostly this is data on E. coli or thermotolerant (faecal) coliform data. In some cases, also data on bacteriophages and/or (an)aerobic spores are available. The concentration of these indicators can be used as a rough estimate of the pathogen concentration, although there is no strict quantitative relation between indicator and pathogen concentration (Rose et al. 1988).
Example: piped and non-piped water supply in Uganda (Howard et al. 2006)

In Kampala, 72% of the population uses piped water supply. 20% of the population uses piped water through household connections, the rest collects water at stand-pipes and stores it in-house. The piped water is produced from Lake Victoria water through (coagulation/settling) rapid sand filtration followed by chlorination. The rest of the population (28%) uses protected springs for their water supply.

Data on thermotolerant coliforms were available from Lake Victoria and from the protected springs and the household containers. Using an estimate of the percentage of E. coli within the thermotolerant coliforms and an estimate of the percentage of pathogenic E. coli within E. coli, the thermotolerant coliform concentration data were translated to pathogenic E. coli concentrations. For the removal of (pathogenic) E. coli by the water treatment processes, the authors used a 3 log credit for the physical removal processes and an additional 2 log credit for the chlorination. This was used to calculate the concentration of pathogenic E. coli in drinking water. With data or estimates on consumption of unheated drinking water, dose-response for infection, probability of illness when infected and disease burden (DALY), the concentration of pathogenic E. coli in drinking water was translated into the estimated disease burden by exposure (Table 1).

Similar assessments were made for Cryptosporidium and Rotavirus exposure for the population using piped water supply. For Cryptosporidium, they showed that treatment failure was the cause of a very significant increase of the disease burden (from $10^{-4}$ to 4 DALYs per person per year (pppy)). The authors have compared the calculated levels of disease burden to the WHO reference level of risk ($10^{-6}$ DALY). Upgrading the treatment would be necessary to achieve this health-target, but the authors argue that, given the low level of access to piped water in the home and the disease burden associated with the use of alternative (more contaminated) sources, this would not be cost-effective. Improving access to piped water supply in homes, sanitation and hygiene would be more effective in reducing the disease burden.

<table>
<thead>
<tr>
<th>Raw water quality thermotolerant coliforms/L</th>
<th>Raw water quality E. coli/L</th>
<th>Raw water pathogenic E. coli/L</th>
<th>Treatment water quality (L)</th>
<th>Drinking water quality (L)</th>
<th>Consumption of unheated drinking water (L)</th>
<th>Exposure (pathogens/day)</th>
<th>Risk of infection (day)</th>
<th>Risk of diarrhoeal disease given infection</th>
<th>Disease burden (DALYs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>143</td>
<td>15</td>
<td>1</td>
<td>11.5</td>
<td>1.15 x 10^-4</td>
<td>0.18</td>
<td>1.15 x 10^-4</td>
<td>0.001</td>
<td>104 x 10^-6</td>
</tr>
<tr>
<td>140</td>
<td>135</td>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>1.06 x 10^1</td>
<td>0.18</td>
<td>1.06 x 10^1</td>
<td>0.01</td>
<td>104 x 10^-6</td>
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</tr>
</tbody>
</table>

Table 1: Assessment of disease burden for pathogenic E. coli from different water sources (adapted from Howard et al. 2006)
This example illustrates that system assessment is feasible also in settings with limited data. The authors discuss limitations and assumptions used in their study, but illustrate the value of system assessment to inform risk management of the area where control measures will be most effective.

TIER 3. USING SOURCE WATER PATHOGEN DATA

For many water utilities in the industrialised countries, the use of a tier 1 or 2 system assessment is not specific enough for the evaluation of individual systems. The first step surface water utilities usually take to make the assessment more site specific is to conduct pathogen monitoring of source water.

Example: the US Long-term 2 enhanced surface water treatment rule

In the US, new drinking water regulation LT2 ESWTR (Federal Register 2006, 71(3):654–786)) has come into force that uses pathogen monitoring (specifically *Cryptosporidium*) in source water as the basis for the system assessment. The health-based target in this regulation is given as treatment performance objectives. The higher the *Cryptosporidium* concentration in source water, the more log-credits are needed to comply with the rule. The *Cryptosporidium* monitoring data are used in a bin-classification (Table 2). The rule assigns log-credits for *Cryptosporidium* removal or inactivation by water treatment processes, based on scientific evidence. The processes must meet process performance criteria, such as effluent turbidity levels for filter performance or dose validation of UV reactors. These criteria are specified in the rule.

Table 2 | Required *Cryptosporidium* removal for filtered surface water treatment plants based on the bin range of *Cryptosporidium* concentration in source water

<table>
<thead>
<tr>
<th><em>Cryptosporidium</em> concentration</th>
<th>Required removal (log)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.075/L</td>
<td>3</td>
</tr>
<tr>
<td>0.075 ≤ x &lt; 1/L</td>
<td>4</td>
</tr>
<tr>
<td>1 ≤ x &lt; 3/L</td>
<td>5</td>
</tr>
<tr>
<td>≥3/L</td>
<td>5.5</td>
</tr>
</tbody>
</table>

1 There is an exception; a (filtered) treatment system that receives more than 5.5 log credits is not required to perform *Cryptosporidium* monitoring.

A system assessment under this rule is:

- conducting a *Cryptosporidium* monitoring program to determine the bin for the required log-removal;
- an evaluation of the treatment processes at the site to determine whether they meet the process performance criteria and may receive the specified log-credits;
- a simple addition to see if the assigned log-credits are equal to or higher than the required log removal.

In this example, two types of water quality testing are needed to be able to perform a system assessment: *Cryptosporidium* monitoring in source water as the basis for the system assessment. For *Cryptosporidium* monitoring, several elements are important: sample size, frequency, location, method, processing method (recovery efficiency), detection/enumeration assay (viability/infectivity), QA/QC and data analysis. The LT2-ESWTR has defined each of these elements, acknowledging differences between large and smaller systems in resources. For treatment performance monitoring, for instance turbidity monitoring, measurement location (individual filters), measurement frequency, accuracy at low turbidity levels (0.15 NTU), calibration and maintenance of the monitors and data analysis are important elements. For both types of monitoring, the EPA refers to standard methods. The use of treatment performance monitoring is an essential element of the Water Safety Plan to ensure that the treatment system is operating at the required level at all times.

TIER 4. USING SITE-SPECIFIC DATA TO INCLUDE VARIABILITY

The examples in the tier 1, 2 and 3 produced a single estimate of the pathogen concentration in source water and assigned log-credits to water treatment processes. This assumes that the concentration of pathogens in source water is represented by this single concentration and treatment process removes at least the assigned log-credit 100% of the time. In drinking water practice, both pathogen concentration in source water and treatment
efficacy may vary substantially and peaks of pathogen occurrence and moments of suboptimal treatment performance occur in almost every treatment system. These may be triggered by rainfall or snowmelt events in the catchment, turbidity peaks in source water, maintenance activities, mechanical or electrical failures, operator errors etc. These moments may have a profound impact on the health risk, which is illustrated by the many treatment event-related waterborne outbreaks. In many practical cases, an appropriate system assessment therefore includes the occurrence of events in the source water quality and of failures in the treatment performance.

**Example: probabilistic system assessment**

A surface water supply takes water from a small lake and treats it with rapid sand filtration, ozonation, (biological) GAC filtration and slow sand filtration. The lake can be heavily occupied by waterfowl that give rise to high *Campylobacter* concentrations in the source water. The utility wanted to know whether the treatment system was able to reduce the *Campylobacter* to levels that would not produce more than 1 infection in 10,000 persons in a year.

34 Source water samples were analysed for *Campylobacter* over a one year period. The *Campylobacter* concentration obtained was combined with the variation in a 6-year *E. coli* data set (n = 1366) to determine the multiyear variability of the *Campylobacter* concentration in source water (Figure 2). For the removal of bacteria by the rapid sand filtration, *E. coli* data were available from filter in- and effluent for the same 6 years (n = 800). These were used to calculate the log-removal (average: 1.1 log/uncertainty factor 0.1 log) by the filtration.

For the inactivation of *Campylobacter* by ozone, a disinfection model was used (using a continuous stirred tank reactor approximation of the contact time (Smeets & Medema 2005)). Data from on-line measurement of flow and temperature and daily measurement of ozone-residual at several places in the ozone contact chambers were fed into the model, producing 380 data on ozone Ct values. The inactivation kinetics of environmental *E. coli* (Smeets & Medema 2005) were used to estimate the *Campylobacter* inactivation by the ozonation step. Figure 3 shows the predicted *E. coli* concentration in the ozone effluent (n = 380), based on the *E. coli* concentration in the influent and the log inactivation calculated by the disinfection model. The figure shows that the model rightly predicts the periods with relatively high *E. coli* concentrations in the effluent of the ozonation step.

For the slow sand filtration, no indicator or process data were available that allowed a reliable description of the removal of *Campylobacter*. A pilot study was conducted to determine the removal of *Campylobacter*, *E. coli*, bacteriophage MS2, *Cryptosporidium* and *Clostridium* spores (Hijnen et al. 2007). The removal of *Campylobacter lari* was shown to be 4.8 log at 10°C.

The data on *Campylobacter* in source water, removal by rapid sand filtration, inactivation by ozonation and removal by slow sand filtration were combined in a Monte Carlo analysis to calculate the concentration of *Campylobacter* in treated drinking water. Together with data on consumption of cold tap water and dose-response of *Campylobacter* infection (see Medema et al. 2006), the

![Figure 2](image2.png)  | *Campylobacter* and *E. coli* in source water.

![Figure 3](image3.png)  | Predicted and measured *E. coli* after ozonation.
probability of infection and the uncertainty thereof could be calculated (Table 3). This showed that the required probability of infection (\( \leq 10^{-4} \text{pppy} \)) could not be met with this water supply system. Since the data analysis also showed that the ozonation was not performing optimally, especially at higher temperatures, the water utility is now performing studies to optimise the ozonation process.

**DISCUSSION**

The above case studies are examples of a system assessment in the Water Safety Plan that show the type of information that is needed to assess whether the water supply system is capable of producing drinking water that meets health-based targets. Most of the examples are surface water supplies with a piped distribution system, but the example from Uganda shows how the system assessment can work in non-piped standpipe and spring water supplies. The examples show how system assessment can be done in a tiered approach, and how even the lowest tier (no other site specific data than the source water type and the description of the treatment processes) is effective in informing risk managers (in this example for prioritisation of investment in treatment upgrades). Higher tiers require more site specific information. This produces information on the efficacy of individual elements in the system and supports risk managers in selecting appropriate risk management actions (see for instance the Tier 4 example).

**ACKNOWLEDGEMENTS**

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**REFERENCES**


Howard, G., Pedley, S. & Tibatemwa, S. 2006 Quantitative microbial risk assessment to estimate health risks attributable to water supply: can the technique be applied in developing countries with limited data? *J. Water Health* 4(1), 49–66.


### Table 3 | Campylobacter system assessment including variation in information

<table>
<thead>
<tr>
<th>Source water (n/L)</th>
<th>Average Campylobacter concentration</th>
<th>MLE 97.5% Campylobacter concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>After filtration (n/L)</td>
<td>17</td>
<td>123</td>
</tr>
<tr>
<td>After ozonation (n/L)</td>
<td>0.47</td>
<td>4.5</td>
</tr>
<tr>
<td>After slow sand filtration (n/L)</td>
<td>( 7.5 \times 10^{-6} )</td>
<td>( 7.3 \times 10^{-5} )</td>
</tr>
<tr>
<td>Exposure (n/day)</td>
<td>( 1.3 \times 10^{-6} )</td>
<td>( 1.4 \times 10^{-5} )</td>
</tr>
<tr>
<td>Probability of infection (pppy)</td>
<td>( 3.8 \times 10^{-4} )</td>
<td>( 3.9 \times 10^{-3} )</td>
</tr>
</tbody>
</table>