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doi: 10.2166/wpt.2019.038

Quantitative microbial risk assessment (QMRA) to support decisions for water supply in affluent and developing countries

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Abstract

Providing microbially safe water is a main goal of water supply to prevent endemic waterborne disease and outbreaks. Since increasing the level of safety requires resources, it is important to identify most relevant risks and efficient ways to reach health-based targets. Over the past decades, quantitative microbial risk assessment (QMRA) developed into a systematic, science-based approach to assess microbial risks through drinking water supply. In this study we present the QMRA approach and how it can be used to support decisions in both affluent and developing countries. This includes examples from the statutory QMRA in the Netherlands that led to efficient and effective improvements in water supply, not only in treatment, but also in monitoring and operation. In developing countries people often need to use various sources of drinking water. We will demonstrate how QMRA can help to improve insight in the relative risks of these routes and the effect of interventions.

Key words: decision support, health, India, Netherlands, QMRA, quantitative microbial risk assessment, water safety planning, water supply, WSP

INTRODUCTION

The availability of sufficient, safe, acceptable and physically accessible and affordable water for personal and domestic uses was declared a human right in 2010 (United Nations General Assembly 2010). Although the Millennium Development Goal to halve the people without access to an improved water source was achieved in 2015, improved water sources are not always safe (Shaheed *et al.* 2014). Contamination with fecal pathogenic microorganisms (viruses, bacteria, protozoa and helminths) is the main waterborne water. This poses challenges not only in developing, but also in developed countries.

Due to the limited availability of water in many developing countries, people use various sources of water such as open wells, boreholes, surface water and harvested rainwater, even if some form of centralized water supply is provided. The safety of these sources is often compromised by contamination with human or animal feces. In addition this water is often carried by hand and stored in the home, resulting in additional risk of contamination (Mattioli *et al.* 2014). Although household water treatment such as boiling, disinfection or filtration is practiced by some, these interventions are not always effective (Hunter *et al.* 2009). Due to the complexity of this situation it is not always clear which route of exposure is most relevant and which intervention would therefore be most effective. In this study we present how quantitative microbial risk assessment (QMRA) can be used to identify the most relevant routes of exposure and effective interventions.

In developed countries water is often supplied through a centralized system to the point of use in the household. Contaminated surface water is treated with advanced technology and water is supplied through a constantly pressurized system, reducing the number of pathogens in the water and protecting

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it against recontamination. Still, outbreaks of waterborne disease occur through these systems (Hrudey & Hrudey 2004) and a proportion of endemic disease may be attributed to drinking water. QMRA has been used by various regulators to set health-based targets (VROM-Inspectorate 2005) and water suppliers need to assess if they comply with these standards at all times. As a response, water suppliers could keep adding treatment processes, since an extra barrier will always provide more safety. However, this may needlessly increase the costs of water supply. In this study we present how QMRA has been used to support decisions on treatment design, operation, monitoring and verification in affluent countries.

METHODS

QMRA approach

QMRA consists of four steps: hazard identification, exposure assessment, dose-response assessment and risk characterisation. Microbial hazards in drinking water are assessed for the index pathogens *Cryptosporidium*, *Giardia*, *Campylobacter* and enteroviruses that represent various challenges to water supply due to their occurrence in water sources, persistence in the environment and during treatment and respective health effects. Exposure is assessed by monitoring or estimating pathogen levels in source water, their removal by treatment, potential recontamination and the consumption of unboiled drinking water. The health impact is derived from the resulting pathogen dose through dose-response relationships. The risk characterisation is presented either as point estimate or a distribution of risk that represents the variation in risk over time and population or the uncertainty about the mean population risk, depending on the goal of the risk assessment. The models used allow for various interventions, scenarios and monitoring strategies to be tested.

Case studies

Case studies for affluent countries were selected from the statutory QMRA studies that have been performed in the Netherlands since 2005. These include significant water quality monitoring of pathogens in source water and removal of model organisms through treatment. The Watershare QMRA Treatment Calculator (Watershare 2016) is a web-based knowledge tool that provides an easy overview of the current state of knowledge on pathogen removal by drinking water treatment processes. The pathogen removal data in the tool is obtained through literature review. The tool provides an overview of all reported log removal values (LRV) in tables and graphs and provides guidance on how removal can be improved. For some treatment processes, log removal is calculated based on user input. For example, based on disinfectant concentration and temperature, inactivation of various pathogens can be calculated. The tool is used in the statutory QMRA to estimate treatment efficacy for situations where monitoring provides insufficient data. The case studies are focussed on the decisions that were made as a result of QMRA.

Case studies for developing countries were based on field assessment of water uses in rural India combined with regulatory indicator monitoring data and literature data on the occurrence of pathogens in various water sources and contaminations. From this typical, multi-routes of exposure scenarios were constructed. The case studies focus on identification of interventions that have the most significant health effect.

RESULTS AND DISCUSSION

Case 1: Statutory QMRA in the Netherlands

About 40% of the drinking water in the Netherlands is produced from surface water from the rivers Rhine and Meuse. Both rivers flow through densely populated areas in Europe and receive most of the

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wastewater from these areas. Since 2001, legislation in the Netherlands requires that the risk of infection is below one infection per 10,000 people per year, adopting the health target by the USEPA to develop the Surface Water Treatment Rule in the 1990s (Regli *et al.* 1991). Later the disability-adjusted life-year (DALY) was applied as a metric within the WHO guidelines in order to provide a different relative weight to pathogens based on severity of disease outcomes (Havelaar & Melse 2003). The DALY target of 10^{-6} first appeared in the 3rd edition of WHO guidelines for drinking water quality (GDWQ) in 2004. The risk of infection is actually an intermediate step in determining the DALY. Table 7.4 in the current GDWQ (WHO 2011) shows that the 10^{-6} DALY target allows a seven to 24 times higher risk of infection than the 10^{-4} infection risk target in the Netherlands. The 2001 Dutch legislation is currently still applicable, including the 10^{-4} infection target. The water companies use QMRA not only to show compliance to the legal health-based target (as explained under methods), but also to optimize treatment operation.

The QMRA studies in the Netherlands all use river water as drinking water source. These rivers are contaminated by sewage, resulting in relatively high levels of pathogens in the water. Figure 1 shows that at one site the required log removal of the index pathogens to reach the health-based target of one infection per 10,000 people ranges from 3.5 to 8.2 log. This removal can only be achieved by multiple barrier systems that combine various treatment processes. For the example in Figure 1, UV disinfection was added to the treatment to achieve sufficient inactivation of enteroviruses *Campylobacter* and *Giardia* based on the QMRA.

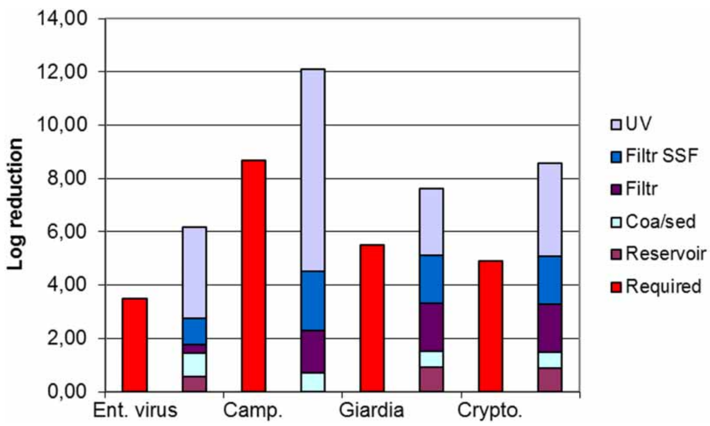

Figure 1 | Example of required log removal of various pathogens to reach the health-based target at a surface water treatment site in the Netherlands (Smeets *et al.* 2009).

The following example shows how the combination of scientific knowledge in the QMRA treatment calculator and water quality monitoring increased insight in the full scale situation and thus led to improvements (Figure 2). According to treatment models included in the Watershare treatment calculator, ozonation would be very effective against bacteria. However *E. coli* was detected at some occasions after ozonation. Further investigations led to hydraulic improvements of the ozonation

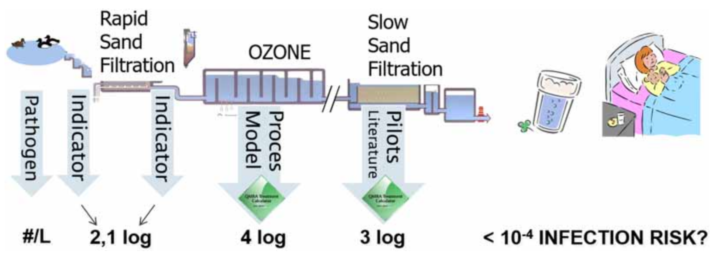

Figure 2 | Illustration of using the Watershare treatment calculator in QMRA.

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system, resulting in better mixing of the ozone with the water and improved contact time distribution. QMRA showed that the health target could be achieved with lower ozone dosage, reducing the risk of disinfectant byproduct formation (DBP) and reducing energy costs and environmental impact.

Case 2: Cleantech Playground: Evaluating decentralized treatment systems

The Cleantech Playground (CTP) is a testing ground for innovative clean technologies in Amsterdam city center, which aims to (biological) cycle closure. The concept was first realized at De Ceuvel, a breeding ground for creative entrepreneurs. Food production (partly under glass) is combined with decentralized power generation, water treatment and processing of organic waste using innovative technology. De Ceuvel started in the spring of 2013. This is a temporary industrial area where offices are composed of recycled houseboats that are placed on land for a period of 10 years. Currently, the area is still supplied by the conventional centralized water supply system. The QMRA Treatment calculator was used to evaluate the safety of three conceptual decentralised water supplies (Roest *et al.* 2016).

At De Ceuvel, canal water, rainwater and grey water are potential water sources for local drinking water supply. Canal water is approximately the same quality as Rhine water. The conceptual treatment system consists of many steps including reverse osmosis (RO) membrane filtration and UV light disinfection. This system can meet the health target if the processes are fully functional (seven infections per 10 million). This means that membranes and UV lamps are replaced regularly and their operation is monitored. Monitoring the full potential of these technologies is problematic however since even small leaks or failures can substantially compromise the performance. Detection of these small deviations requires advanced sensors or substantial water quality analysis in a laboratory. These extra costs and efforts for performance monitoring need to be taken into account when evaluating the system, which can then achieve about seven infections per 100,000.

Rainwater contains few pathogens, but rainwater harvesting on rooftops includes the feces of birds and other animals that have access to the roof. Their feces can contain zoonotic pathogens that infect humans. Transmission of waterborne viruses is unlikely but bacteria and protozoa can be abundant. Treatment with only membrane filtration, such as the village pump, results in a slight non-compliance of four infections per 10,000 people from *Campylobacter*. However, in the long term, due to limitations of integrity monitoring, the system could start leaking without detection, resulting in three infections per 10 people, which can be regarded as an outbreak of waterborne disease.

Grey water quality from kitchen sinks at De Ceuvel is hard to predict since it depends on the behavior of a small group of people on an individual house boat. A standard advanced home water treatment consisting of RO membrane filtration and UV disinfection could be installed per boat to recycle the water from the sink. Again, potentially this system produces water with a very low risk (four infections per 10 million). However, monitoring long term performance is also challenging. A long term risk estimate would be around five infections per 1,000, exceeding the target 50 times.

The QMRA treatment calculator was used in these assessments to estimate the potential treatment efficacy, but also provided guidance on how to address issues of maintenance and monitoring needed to verify this in practice.

Case 3: Evaluating water supply alternatives in rural India

Drinking water supply in rural India faces many challenges of quantity and quality. The government is investing in centralized surface water treatment systems, while the population still largely depends on local sources. A QMRA study was performed to assess the risks from the various water sources in rural India and how various interventions help reduce the risk (Smeets *et al.* 2015). We visited two regions in rural Karnataka, India: Gulbarga and Shimoga. There we spoke with the population, village

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leaders, local and regional authorities, water suppliers, NGOs and medical doctors and observed their behavior with respect to drinking water. From this we developed a multi-route QMRA model that allowed for variations in use of water sources and treatment over the year. Routes included centralized surface water supplies (treated), rainwater harvesting and private groundwater wells as sources, each being used partially through the year. Since no pathogen data is available for Indian water sources (raw water) and indicator data are unreliable, we estimated pathogen densities in various sources from literature and performed a sensitivity analysis for these assumptions. Contamination of treated water during transport through a piped distribution system (primary distribution) or when transporting water by hand in containers from a standpipe or well (secondary distribution) was also modeled. Inputs for contamination events were the level of pathogens in human and animal feces, the amount of feces entering the system during an event and the likelihood of an event. Reduction of pathogens by water treatment in the household (household water treatment, HHWT) was based on results from the WHO testing program (WHO 2016) and additional research. Subsequent recontamination during in-house storage and handling (recontaminated) was modeled similarly to the distribution contamination events. The QMRA model estimated the exposure to various pathogens and combined that with dose-response models to estimate the risk of infection through Monte Carlo simulation of the variable conditions, including the contamination events occurring according to their likelihood. The contribution of each route used in various periods to the total annual risk was thus evaluated.

Conclusion of the study was that current surface water treatment systems only provide partial protection against infection risks through drinking water. Figure 3 shows the assessed distribution of risk in time at different stages of centralised water supply. The legend refers to the terminology used in the model description. The bars indicate the likelihood of a certain risk level to occur, which can be regarded as the distribution of the risk over a population that would use these various water sources. Drinking raw surface water obviously leads to a high risk. Centralized water treatment somewhat reduces that risk, although the pathogen removal is limited due to the poor conditions at water treatment plants. Contamination during primary distribution is likely, since water is supplied intermittently, open defecation of humans and animals occurs near water pipes and therefore dirty water surrounding the distribution pipes will ingress during periods of no pressure. This risk further increases when water is transported by hand from a standpipe to the home. Effective household water treatment can then significantly reduce the risk. However, recontamination during inproper storage

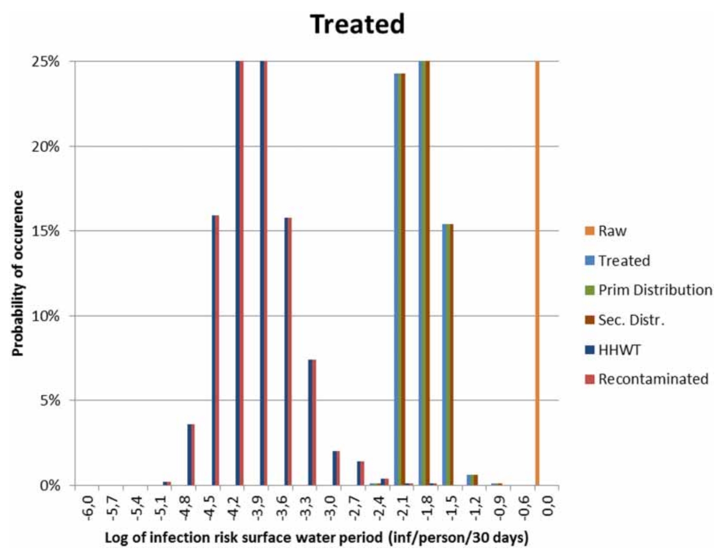

Figure 3 | Results of theoretical risk estimation at various steps of water supply from surface water supply through intermittent distribution to standpipe, manual transport and storage in the home in India.

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in the house leads to an increase of risk again. For the short term, interventions at the household level seem to be most effective in reducing health risk. Centralised supply needs to become reliable, continuously pressurized and delivered into the home to be a safe source of water. In particular, protozoa may still pose a risk.

Case 4: Reverse QMRA to design monitoring after contamination event

Bank filtration provides an excellent barrier against pathogens. However, in this case contamination of the bank filtration well field occurred due to construction failure of some wells. The water supply from this well field was stopped immediately and safe water was supplied from another plant. After repairing the site, the site needed to be remediated by 'flushing' out any contaminants. The question was when the water could be considered safe again, since monitoring indicators would provide insufficient basis for this. A reverse QMRA approach was developed to design a monitoring plan that would sufficiently verify compliance to a health based target of one infection per 10,000 persons per year (Figure 4). For the Netherlands, this corresponds to approximately one pathogen in one million litres of water. It is not feasible to monitor water quality for compliance to this target directly. The QMRA Treatment calculator was used to determine the effect of each treatment barrier on each pathogen. Thus a maximum allowable pathogen concentration in the raw water could be calculated, which can be monitored directly through large volume samples. Using this approach the water company could guarantee safe water for its clients and satisfy the health inspector (Smeets & Hornstra 2013).

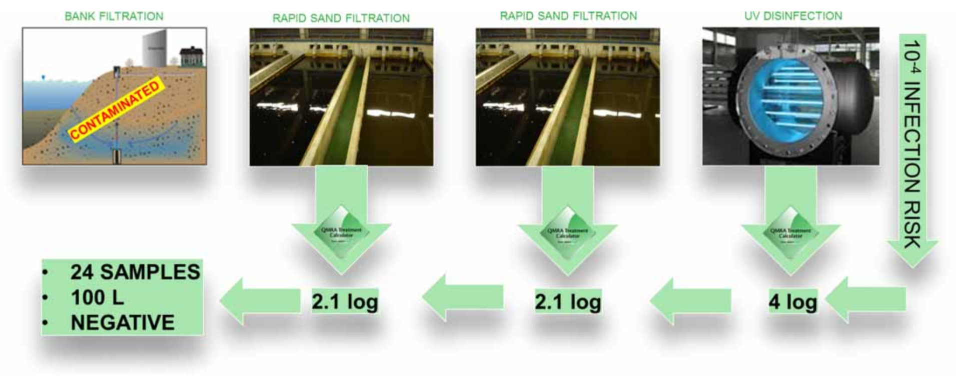

Figure 4 | Illustration of the reverse QMRA approach to develop a monitoring program.

DISCUSSION

These examples of how QMRA has been used in practice illustrate the versatile ways of how QMRA can support decisions. The contexts of the examples is very different. The legislative requirement in Case 1 has led to a more uniform QMRA execution, making results comparable between the various water systems. This has also led to funding of monitoring and research to fill the most important data gaps on occurrence of pathogens in source waters and their removal by treatment. The QMRA treatment calculator is an example of how the obtained knowledge is being made available for others. This provides a basis for QMRA in less affluent settings such as Case 3. Although adequate knowledge of the local pathogen abundance in source waters is missing, the QMRA approach still provided valuable insight in the relevance of various contamination routes and how effective measures may be. Still, it highlights the need for better local data on pathogen occurrence. The presented QMRA study can be used to mobilize funds for local monitoring and research in India. Similarly, for Case 2, QMRA allowed to compare various scenarios of water supply without actually

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realizing and monitoring them. In that case, QMRA led to the decision not to implement such experimental systems in practice since the risk to the population would be too high. The QMRA put the focus on the need for development of sensitive and affordable monitoring methods or technologies in order to make safe decentralized water supply feasible. The reverse QMRA in Case 4 also linked health targets to a required program for adequate monitoring. In Case 4, not providing water wasn't an option since the water supply was already operational. The QMRA provided a quantitative basis to justify the required costs of monitoring, by making sure that monitoring was proportional to the risk. Together the cases show how QMRA can both support decisions for current issues and guide further research to improve water safety in the future. This will become more important in a water scarce future where water reuse is an important strategy to mitigate water shortage, and microbial safety will be a relevant concern.

CONCLUSIONS

Providing safe water can require significant resources and effort. QMRA provides a systematic, science-based method to identify effective and efficient interventions or improvements to reach health-based targets. Thus, it is a very useful tool for decision support that can be used in the water safety plan process. The QMRA approach needs to be tailored to the context, e.g. affluent or developing country, and the goal of the risk assessment, e.g. treatment design, monitoring plans or household interventions.

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