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Risk-based cost-benefit analysis for evaluating microbial risk mitigation in a drinking water system

Viktor Bergion*, Andreas Lindhe, Ekaterina Sokolova, Lars Rosén

Chalmers University of Technology, Department of Architecture and Civil Engineering, SE-41296 Gothenburg, Sweden

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ABSTRACT

Waterborne outbreaks of gastrointestinal diseases can cause large costs to society. Risk management needs to be holistic and transparent in order to reduce these risks in an effective manner. Microbial risk mitigation measures in a drinking water system were investigated using a novel approach combining probabilistic risk assessment and cost-benefit analysis. Lake Vomb in Sweden was used to exemplify and illustrate the risk-based decision model. Four mitigation alternatives were compared, where the first three alternatives, A1-A3, represented connecting 25, 50 and 75%, respectively, of on-site wastewater treatment systems in the catchment to the municipal wastewater treatment plant. The fourth alternative, A4, represented installing a UV-disinfection unit in the drinking water treatment plant. Quantitative microbial risk assessment was used to estimate the positive health effects in terms of quality adjusted life years (QALYs), resulting from the four mitigation alternatives. The health benefits were monetised using a unit cost per QALY. For each mitigation alternative, the net present value of health and environmental benefits and investment, maintenance and running costs was calculated. The results showed that only A4 can reduce the risk (probability of infection) below the World Health Organization guidelines of 10^{-4} infections per person per year (looking at the 95th percentile). Furthermore, all alternatives resulted in a negative net present value. However, the net present value would be positive (looking at the 50th percentile using a 1% discount rate) if non-monetised benefits (e.g. increased property value divided evenly over the studied time horizon and reduced microbial risks posed to animals), estimated at 800−1200 SEK (€100−150) per connected on-site wastewater treatment system per year, were included. This risk-based decision model creates a robust and transparent decision support tool. It is flexible enough to be tailored and applied to local settings of drinking water systems. The model provides a clear and holistic structure for decisions related to microbial risk mitigation. To improve the decision model, we suggest to further develop the valuation and monetisation of health effects and to refine the propagation of uncertainties and variabilities between the included methods.

1. Introduction

Risk management of drinking water systems (DWSs) is an iterative process including risk assessment and risk mitigation (i.e. risk treatment) (ISO, 2009). To be effective in providing safe drinking water supply, the risk management must comprise the entire system, from catchment to consumer. If the risks are unacceptable, risk mitigation measures should be implemented, and alternatives for risk mitigation evaluated. Water Safety Plans procedures, developed by the World Health Organization (WHO), can serve as a risk management strategy for water providers (Bartram et al., 2009). However, in order to allocate societal resources for risk mitigation in an efficient manner, the economic dimension of risk levels and possible risk mitigation measures must be considered (WHO, 2011).

Risks related to DWSs have been extensively discussed in the literature (e.g. Beuken et al., 2008; Keller and Wilson, 1992; WHO, 2011). Health risks in DWSs can be related to chemical, microbial and radiological hazards (WHO, 2011). In this paper, the microbial risks are the main focus. Microbial risks in the form of pathogenic microorganisms can originate from faecal sources (Dufour et al., 2012; Ferguson et al., 2009) related to humans (municipal wastewater treatment plants (WWTPs) or on-site wastewater treatment systems (OWTSs) on private properties) or animals (wild animals, domestic grazing animals or use of manure on cropland). Pathogens

* Corresponding author.
E-mail address: viktor.bergion@chalmers.se (V. Bergion).

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in DWSs can cause endemic waterborne illness (Payment and Hunter, 2001) as well as waterborne outbreaks of gastrointestinal diseases, resulting in high costs for the society (Corso et al., 2003; Larsson et al., 2014). The WHO pointed out that the societal costs for endemic waterborne illness and related gastrointestinal disease are commonly underestimated (WHO, 2001).

Quantitative microbial risk assessment (QMRA) has been applied to DWSs in various settings (Haas et al., 2014; WHO, 2016) in order to assess the risk in relation to an acceptable or tolerable risk level. The result from a QMRA is typically reported as probability of infection, disability adjusted life years (DALYs) or quality adjusted life years (QALYs). Both DALYs and QALYs are health metrics that combine mortality and morbidity. Drinking water producers commonly look at the (WHO) for guidance and the suggested risk levels of an annual probability of infection of 10^{-4} per person per year, and DALYs of 10^{-6} per person per year (WHO, 2011).

To make informed decisions on which risk mitigation measure to implement in order to use societal resources effectively, the alternatives need to be compared. Comprehensive lists and procedures for identifying risk mitigation measures (e.g. Åström and Pettersson, 2010; NZMH, 2014; Rosén et al., 2010) are available. Decision support systems or decision models such as cost-effectiveness analysis (CEA) and multi-criteria decision analysis (MCDA) can aid decision makers in comparing the alternatives. If there are no regulations regarding acceptable risk levels, other evaluation methods might be needed in order to justify the implementation of risk mitigation measures. Cost-benefit analysis (CBA) provides a robust well-established decision support approach to investigate the measure that is the most profitable or least costly (if a certain risk level is required) for society (Boardman et al., 2011; Cameron et al., 2011).

Comparing mitigation measures directed at different parts of the supply system and identifying the options most profitable for society are key steps towards a holistic and sustainable risk management approach. Adopting holistic risk management also enables the multi-barrier approach emphasised by the WHO (2011). Using CBA as a basis for decision support helps to allocate monetary resources in an efficient manner providing possibilities to compare mitigation measures with interventions in other sectors (e.g. food, health care, traffic and environmental risk management). CBA facilitates optimisation of the societal resources by comparing economic metrics, such as net present value (*NPV*), and performing distributional analysis (Cameron et al., 2011). CBA also helps highlight the societal benefits of reducing microbial risks in DWSs and creates a systematic and transparent decision support tool.

Different frameworks for combining risk management, decision making process and CBA in the drinking water context have been investigated (e.g. Assmuth et al., 2016; Rizak et al., 2003). Despite the aforementioned implementations, there are few, if any, methods that use a probabilistic quantitative risk-based approach to create decision support in the form of a CBA for microbial risk management in DWSs. To include an economic dimension and to perform a CBA in this way is uncommon, even though the need is emphasised by the WHO (WHO, 2001).

1.1. Aim

In this study we develop a method for creating a systematic, holistic and transparent decision support for microbial risk management in DWSs. We present a novel CBA approach from catchment to consumer. More in detail, we perform a CBA using a combination of water quality modelling and QMRA to compare microbial risk mitigation alternatives in a DWS. The methodology is exemplified using Lake Vomb in the south of Sweden. Different alternatives of removing OWTSs are compared to installation of an additional treatment step in the drinking water treatment plant (DWTP). We also highlight the choices that needs to be made in the CBA-model, and what implications these might have on the outcome of the CBA.

2. Risk-based decision model

The suggested approach for combining the methods for QMRA and CBA is presented as a decision model in Fig. 1. The four major compartments are: (i) source characterisation, (ii) water quality modelling, (iii) dose-response, and (iv) CBA. The source characterisation provides input to the water quality modelling, and the water quality modelling provides input to the dose-response. The QMRA framework, including (i), (ii) and (iii), describes the entire risk chain in the DWS and provides input for the CBA. Epistemic uncertainties (associated with lack of knowledge) and aleatory uncertainties (associated with natural variations) in all compartments are incorporated into the model by means of Monte Carlo (MC) simulations. The combination of methods aims to enable an estimation of the microbial risk in the DWS as well as an estimation of the effect of risk reduction measures and their societal profitability. Hence, the decision model can serve as a tool within the water safety plan framework. When analysing different mitigation measures, each compartment of the decision model needs to be executed. Detailed method descriptions of each compartment are presented in sections 3.2–3.4. It should be noted that this decision model is generic, and the applied methods in each case study should be selected to fit the specific context of the analysed DWS.

3. Methods

3.1. Lake Vomb

Lake Vomb is a small lake in Scania, the southernmost part of Sweden, providing 330,000 consumers with drinking water. The average water depth is 6.6 m, and the maximum depth is 16 m. Three major tributaries discharge into Lake Vomb: Borstbäcken, Torpsbäcken and Björkaån draining 26, 42 and 340 km^2, respectively. There are approximately 2800 OWTSs in the catchment (Norwegian Water BA 2009) posing a risk to the drinking water source. Other sources of microbial risks are e.g. WWTP, fertilisation using manure, grazing animals, wild animals. Raw water is extracted from Lake Vomb and artificially infiltrated into a glaciofluvial aquifer and then treated using conventional treatment consisting of rapid sand filtration and chlorination (Norwegian Water BA 2009). Fig. 2 illustrates the case study area.

Microbial risk mitigation alternatives in different parts of the DWS were chosen to illustrate how the risk-based decision model can be used. The mitigation alternatives also reflect the contemporary trends in Sweden regarding OWTSs management and an increase in installation of UV-disinfection in DWTPs. Three of the analysed alternatives represent connection of different proportions (25, 50 and 75%, respectively) of the OWTSs in the catchment to the municipal WWTP. The costs for the alternatives were based on connection of clusters of closely located OWTSs. However, the pathogen load from these OWTSs was assumed to be removed evenly across the different types of OWTSs and geographically across the catchment area. This assumption was made because of the short transport time in the catchment (Sundahl et al., 2008). The fourth alternative was to install UV-disinfection at the DWTP at Lake Vomb. The four decision alternatives and one reference alternative were analysed: