Changing climate and socio-economic conditions as part of quantitative microbial risk assessment of surface drinking water sources: a review

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Changing climate and socio-economic conditions as part of quantitative microbial risk assessment of surface drinking water sources: a review

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ABSTRACT

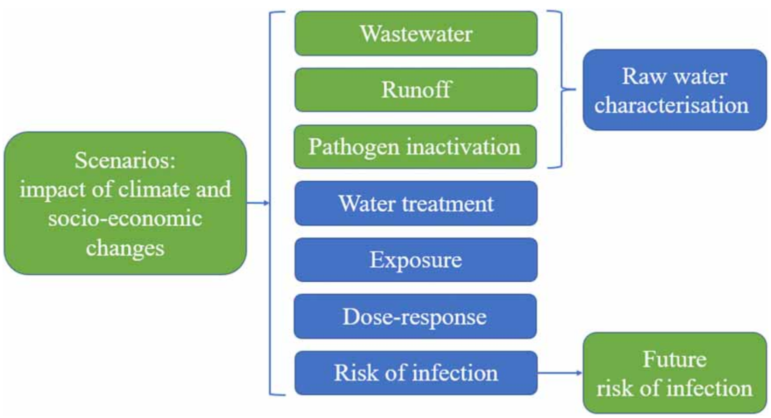
Climate and socio-economic changes are expected to significantly impact waterborne pathogens and associated health risks, yet the full extent of these effects remains unclear. Accurate quantification of these risks is crucial for informing effective interventions and policy decisions. Quantitative microbial risk assessment (QMRA) serves as a valuable tool for estimating the risk of infection caused by microorganisms in drinking water. This study reviews existing QMRA studies and tools in the context of surface water and drinking water provision. Most studies have implemented various steps of the QMRA framework but often without the application of specific QMRA tools. Although several QMRA tools address climatic factors, there are currently no tools that integrate socio-economic factors into their risk assessments. This study proposes an approach for incorporating both climatic and socio-economic factors into QMRA tools. Specifically, we suggest enhancements to the Swedish QMRA tool – an open-source tool that currently does not incorporate climate and socio-economic changes. Our proposed advancements aim to systematically account for future climatic and socio-economic impacts on health risks, providing a more comprehensive microbial risk assessment tool. These recommendations are also applicable to other QMRA tools, offering a pathway for their development and improving the overall assessment of microbial health risks.

Key words: climate change, QMRA, quantitative microbial risk assessment, risk of infection, socio-economic factors

HIGHLIGHTS

- Climate and socio-economic changes may significantly impact waterborne pathogens, but the full effects are unclear.
- Some quantitative microbial risk assessment (QMRA) tools address climate factors, but none include socio-economic factors.
- This study proposes enhancements to the Swedish QMRA tool to incorporate climate and socio-economic changes.
- Our proposed advancements provide a more comprehensive QMRA tool.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Microbial risks pose a major global concern for ensuring a safe water supply. Consumption of water polluted with pathogenic microbes can lead to severe waterborne diseases. The impact of waterborne pathogens on public health may be exacerbated by climate change and the associated increase in extreme events (Sterk *et al.* 2016). Moreover, socio-economic and land-use changes can also affect water quality and exacerbate the risk of illness (Islam *et al.* 2018; Iqbal *et al.* 2019). It is therefore important to evaluate water safety in the context of change in climate and socio-economic conditions for guiding adaptation measures. The probability of acquiring a gastrointestinal illness through consumption of polluted water can be calculated by means of quantitative microbial risk assessment (QMRA). QMRA is an effective tool to estimate the risk of infection or illness caused by microorganisms and to formulate water safety management strategies to mitigate that risk (Van Abel & Taylor 2018). The World Health Organization (WHO) advises conducting a QMRA for pathogenic microorganisms when using surface waters for the production of drinking water (WHO 2011; Islam 2024). QMRA examines the whole drinking water production process to assess its potential impact on human health. Understanding the microbial quality of source water and the removal or inactivation of pathogens during the water treatment process is therefore crucial (Petterson & Ashbolt 2016; Islam 2024). The key steps in the QMRA framework are hazard identification, exposure and dose-response assessment, risk characterization, and risk management (Haas *et al.* 1999).

Climate change-induced extreme weather events, such as rising temperatures, droughts, sea level rise, cyclonic storm surges, floods, and changes in precipitation patterns, are expected to increase waterborne pathogen loads in surface water sources and affect pathogen growth and survival. These shifts could elevate health risks (Funari *et al.* 2012; Islam 2024). While climate change may exacerbate microbial pollution and influence the prevalence, growth, and survival of waterborne pathogens, the overall impact on public health remains uncertain (Hofstra 2011). Socio-economic and land-use changes can also affect water quality and consequently health risks (Islam *et al.* 2018; Iqbal *et al.* 2019). Changes in socio-economic factors, e.g., population growth and urbanization, may increase wastewater generation and subsequently increase the spread of pathogens in water environments. With the increase in livestock numbers, manure deposition to grazing land and to agricultural land as organic fertilizer is increasing, leading to increased pathogen load with agricultural runoff (Islam *et al.* 2021). It is therefore important to evaluate water safety in the context of change in climate and socio-economic conditions for guiding adaptation measures.

Since the exposure pathways of waterborne pathogens are affected by climatic and socio-economic conditions, future human exposures are likely to differ from current patterns (Schijven *et al.* 2013). Therefore, for strategic decision-making, a risk assessment tool that describes the behavior of pathogens under both current and projected future conditions is needed. The development of decision support tools for assessing health risks from climate change is one of the priority research areas of WHO (2011). In recent years, several specialized QMRA tools have been developed to streamline and standardize these steps. These tools often integrate various mathematical models and data sources to support risk assessments more effectively. However, such tools remain scarce globally, and as a result, many studies focus on following the QMRA steps individually without using a dedicated tool or model (Islam 2024). Of the identified existing tools, Health Canada QMRA (Smith *et al.* 2015) and CC-QMRA of the Netherlands (Schijven *et al.* 2013) account for several climatic factors. However, to the best of our knowledge, currently, there are no QMRA tools that incorporate socio-economic factors to quantify health risks from future socio-economic development. In 2009, Sweden developed a QMRA tool specifically to illustrate how the risk of microbial infection is impacted by the various stages of drinking water production (Petterson & Ashbolt 2016; Islam 2024). However, this tool currently does not account for future changes in climate factors and socio-economic conditions (Islam 2024).

The aim of this study was to propose further development of the QMRA approach to make it possible to systematically account for the future climate and socio-economic effects on health risks. To achieve this aim, we reviewed scientific literature reporting QMRA application in the context of surface water sources and drinking water provision and proposed further development of the Swedish QMRA tool as a representative open-source tool that does not currently account for climatic and socio-economic change factors. Our proposed interventions are also applicable to other QMRA tools, facilitating their further development.

2. SEARCH STRATEGY

This study reviews original QMRA studies based on surface waters used for drinking water production or recreation. Only articles published in English and those published since 2005 (to focus on relatively recent articles) were included in the review. The online databases of Google Scholar, PubMed, ScienceDirect, Scopus, and SpringerLink were searched to identify relevant articles. The following keyword combinations were used: QMRA and surface water, QMRA tools and water safety, QMRA tools, and climate change, health risks and waterborne pathogens, microbial risk assessment of source water, extreme events and health risks, climate change scenarios and health risks, socio-economic factors and pathogens, and efficiency of water treatment. For climate change and socio-economic factors, additional specific keywords such as urbanization, land-use changes, temperature and precipitation effects, seasonality, sanitation coverage, wastewater treatment, and economic growth were also used to refine the search. Relevant articles from the reference lists of identified articles were also included. The AND operator was used to ensure both keywords appeared in the same paper, narrowing the search to studies addressing both topics.

A total of 126 articles were initially identified across all databases. After screening titles and abstracts for relevance, 58 articles were ultimately selected, as reflected in Tables 2 and 3, the discussion, and other sections. QMRA studies that focused on drinking water distribution networks (i.e., risks originating from the pipe network) did not apply the QMRA framework or QMRA tools or did not address at least one waterborne pathogen or fecal indicator bacteria (FIB) and were excluded from this review.

3. EFFECTS OF CLIMATE AND SOCIO-ECONOMIC CHANGES ON MICROBIAL HEALTH RISKS

Alterations in climate patterns are likely to exacerbate microbial pollution in water sources, impacting the behavior and distribution of pathogens that pose public health risks. Previous studies have found significant correlations between FIB and climatic factors such as precipitation and water temperature. For example, Islam *et al.* (2017) observed a positive correlation between *Escherichia coli* and precipitation ($R = 0.57$–0.62), as well as a correlation between precipitation and enterococci ($R = 0.50$–0.71) in rivers in Bangladesh. Islam & Islam (2022) identified a moderate positive correlation ($R = 0.42$) between *E. coli* and precipitation, along with a negative correlation with water temperature ($R = -0.33$). Iqbal *et al.* (2017) found positive correlations between *E. coli* concentrations and both temperature ($R = 0.32$–0.67) and precipitation ($R = 0.22$–0.47) in the Kabul River basin in Pakistan. Vermeulen & Hofstra (2014) used a regression model and determined that climatic variables accounted for nearly half ($R^2 = 0.49$) of the observed variation in *E. coli* concentrations in surface water from the Rhine, Meuse, and Drentse Aa rivers in Europe. Several studies have linked climatic factors to outbreaks of diseases caused by pathogens such as *Campylobacter*, *Cryptosporidium*, *Salmonella*, and noncholera *Vibrio* (Smith *et al.* 2015). Rising temperatures have been associated with increased rates of salmonellosis in Europe (Semenza & Menne 2009) and Australia (Schijven *et al.* 2013). These trends suggest a potential rise in health risks, though the exact magnitude remains uncertain.

Although these observed correlations suggest a potential increase in disease incidence, establishing a clear causal relationship is challenging. The dynamics of pathogens are influenced by a combination of environmental factors, pathogen characteristics, and human behavior, complicating efforts to directly link climate change with disease incidence. To address this uncertainty, the QMRA framework offers a valuable tool to quantify the health risks associated with climate change. By incorporating various climate scenarios, QMRA can predict the effects of changes in temperature and precipitation patterns on pathogen dynamics, providing a more precise estimate of future health outcomes related to microbial water pollution.

Mean seasonal and annual surface air temperatures are projected to rise at an increasing rate in the 21st century (IPCC 2021). At increased air and water temperatures, some pathogens show faster inactivation, while some pathogens may proliferate (Schijven *et al.* 2013). In many areas, total annual precipitation is also expected to increase, and a large part of that is expected to fall during heavy events (IPCC 2021). Precipitation patterns differ largely by region, with already arid regions expected to become drier, while wet regions are expected to become wetter, and extreme precipitation events are expected to occur more frequently worldwide (IPCC 2021). The changes in precipitation patterns can result in increased flooding and runoff transporting pathogens from agricultural lands and urban areas (Smith *et al.* 2015). Increased stormwater runoff can result in more frequent sewer overflows, leading to elevated peak concentrations of waterborne pathogens in aquatic environments. Peak concentrations significantly influence the infection risk associated with the consumption of drinking water (Schijven *et al.* 2015). High water flows may also cause resuspension of fecal pollutants from sediments (Coffey *et al.* 2014). At the same time, low water flows during dry periods may result in less dilution of wastewater effluents, leading to higher concentrations in the water sources (Hughes *et al.* 2021).

The aforementioned effects of climate change on the microbial water quality may be exacerbated by socio-economic and land-use changes, as these changes affect the hydrological regime and the pollutant load into the water sources, and ultimately the health risks. With rapid human population growth and urbanization, wastewater generation increases, and surface water sources receive an increased load of fecal pollution, leading to the deterioration of microbial water quality (Islam *et al.* 2018), if wastewater treatment is not enhanced accordingly. At the same time, urbanization is causing an increase in runoff due to the alteration of evapotranspiration and infiltration by the expansion of impermeable surfaces (Guo *et al.* 2020). The growth of livestock populations has led to an increased deposition of manure on grazing lands and a rise in the application of manure as organic fertilizer on croplands. Consequently, without adequate treatment of manure, agricultural runoff may contribute to elevated pathogen loads in surface waters (Islam *et al.* 2021). In areas with rapidly declining human and animal populations, decreased wastewater and manure generation may lead to lower pathogen concentrations in the environment (Table 1). These dynamics warrant further exploration to understand the long-term consequences of both growing and declining populations, alongside other socio-economic factors.

Socio-economic factors such as population growth, urbanization, and wastewater treatment levels significantly impact microbial concentrations in surface water, often more so than climate change alone (Islam *et al.* 2018; Iqbal *et al.* 2019). Higher population densities lead to increased wastewater generation, and inadequate treatment raises pathogen concentrations, increasing infection risks. Economic constraints may limit resources for infrastructure improvements, exacerbating the issue, particularly for vulnerable, low-income populations who have limited access to clean water and sanitation, making them more susceptible to waterborne diseases. Existing QMRA models, however, often rely on generic assumptions and fail to account for regional differences in infrastructure, sewer systems, and socio-economic conditions that influence pathogen dynamics. To better assess waterborne disease risk in a changing climate, future studies should integrate socio-economic and infrastructure factors into QMRA models while refining dose-response models to account for extreme weather events and altered environmental conditions. Addressing these gaps will be crucial for developing more effective tools to mitigate waterborne disease risks.

The IPCC proposed shared socio-economic pathways (SSPs) that provide narratives and quantifications of future possible developments of socio-economic conditions such as population growth, urbanization, economic and technological

Table 1 | Effects of climate and socio-economic changes on the presence and fate of pathogens in surface waters

Climate and socio-economic changes	Environmental effect	Pathogens in surface water
Water temperature increase	• Water temperature increase • Seasonal shift in water temperature and water flow • Change in evaporation due to the temperature change	• Growth of bacteria • Increased inactivation/die-off of enteric waterborne pathogens • Seasonal shift in concentrations of waterborne pathogens in surface water
Increased frequency and intensity of precipitation. Increased cyclones and storm surges	• Flooding • Runoff • Resuspension of river sediments • Sewer overflows • Elevated turbidity due to increased substances in storm runoff	• Increase in the intensity and frequency of peak concentrations of waterborne pathogens in surface waters • Excessive rainfall may dilute pathogen concentrations.
Water availability and drought	• Change of water source • Atmospheric water vapour content • Snow cover and ice melting	• Change in source water pathogen concentrations
Sea level rise	• Salinity intrusion	• Change in source water pathogen concentrations
Solar exposure	• Exposure of pathogens to UV	• Deactivation of pathogens with increased UV
Human and animal population growth	• Increased wastewater and manure production • Potential elevated pathogen loads in surface water	• Increased pathogen concentrations in surface water sources
Urbanization	• Increased wastewater generation	• Increased pathogen concentrations in surface water
Improved sanitation and wastewater treatment	• Reduced pathogen load to surface water	• Reduced pathogen concentrations in surface water

development, sanitation coverage, and change in land use (Kriegler *et al.* 2017). Identifying trends and future scenarios for microbial water quality caused by socio-economic and climate changes is required to assess health risks and effectively manage surface water sources. One way to assess these risks is to combine QMRA and scenario analysis, investigating the effects of climate and socio-economic changes on pathogen load, presence, and fate in surface waters.

Recent studies have started integrating climate change projections into QMRA frameworks, focusing on extreme weather events such as heavy rainfall, which can increase pathogen concentrations in water sources. This integration typically adjusts pathogen load models based on climate-induced changes in precipitation and runoff patterns (Schijven *et al.* 2013; Sterk *et al.* 2016; Islam *et al.* 2018; Iqbal *et al.* 2019). However, high uncertainty in climate projections, particularly concerning the frequency, intensity, and spatial distribution of extreme weather events, complicates risk predictions The non-linear relationship between precipitation, runoff, and pathogen concentration further complicates predictions (Schijven *et al.* 2013). Additionally, the lack of standardized methods for integrating climate change into QMRA models limits the comparability of results across studies (Demeter *et al.* 2021). Existing studies often rely on short-term or generalized climate projections, which fail to capture the full complexity of climate change impacts on microbial risks. To improve risk assessments, future QMRA models should incorporate long-term, site-specific data on pathogen dynamics and consider the combined effects of climate change and socio-economic factors, ensuring a more comprehensive understanding of microbial risks under varying environmental conditions.

4. EXISTING QMRA STUDIES

QMRA is a useful approach for estimating the risk of infection or illness caused by microorganisms. Table 2 summarizes existing QMRA studies, providing an overview of the models/tools, major findings, and the geographic distribution of the studies. While numerous QMRA studies have been conducted in developed countries (Eregno *et al.* 2016; Timm *et al.* 2016; Amoueyan *et al.* 2020), such research remains limited in developing areas (Table 2).

In developing nations, where data on pathogens are often inadequate, some studies have relied on FIB for QMRA (e.g., Howard *et al.* 2006; Wang *et al.* 2022; Yan *et al.* 2024). However, the use of FIB requires assumptions about the relationship between pathogens and indicators, which introduces uncertainty (Islam *et al.* 2021). Another limitation of QMRA is the availability of exposure and dose-response data. Most studies obtain dose-response data from previous studies that use clinical trial data, typically based on young and healthy adults (Chigor *et al.* 2014). This introduces uncertainty, as susceptibility can vary depending on factors such as age and immune status (Van Abel & Taylor 2018; Islam *et al.* 2021).

Although many studies have applied the steps of QMRA, fewer have used specific QMRA tools or models. In cases where site-specific microbial data were unavailable, process-based models were used to simulate microbial concentrations in source water. These simulated concentrations were then incorporated into the QMRA framework (e.g., Ito *et al.* 2017; Limaheluw *et al.* 2019) or used in a QMRA tool (e.g., Ngubane *et al.* 2022) to assess health risks. The use of such models and analytical tools can be particularly valuable in regions with limited water quality monitoring data and laboratory facilities for microbial analysis.

Some studies have analyzed the influence of climatic and environmental factors, as well as water treatment processes, on microbial health risks (Table 2). However, we did not identify any studies that incorporated socio-economic factors into the QMRA. Given the variability in infrastructure, socio-economic conditions, and climate across regions, it is important to select different QMRA approaches tailored to specific countries or regions. In developed countries, where water treatment technologies are more advanced, QMRA models may focus on other risk factors than in developing countries, where challenges such as limited access to sanitation or inadequate wastewater treatment may play a more significant role in microbial pollution. The application of standardized models across all contexts may not be effective, as factors like local water management practices, pathogen types, and population health vary significantly. Therefore, future scenario analyses should adopt a more flexible QMRA approach that takes into account the unique climatic, environmental, and socio-economic factors of each region to better capture the complexity of microbial risks. Such an approach would better inform interventions and policy decisions to manage health risks effectively. However, to date and to the best of our knowledge, examples of such integrated approaches are lacking in the scientific literature.

5. EXISTING QMRA TOOLS

Several QMRA tools exist that can be applied to assess health risks associated with the use of surface waters for recreation or drinking water production. The QMRA tools currently available worldwide are summarised in Table 3. There is a legal

Table 2 | Summary of the published studies (in chronological order) that conducted microbial health risk assessment

Pathogens/fecal indicators	QMRA tools/ framework	Climatic/socio-economic factors/ water treatment	Study location	Main findings	Reference
Giardia, *Cryptosporidium*	QMRA framework	Water treatment	USA	The infection risks using chlorination and UV disinfection would meet the annual acceptable risk of 10^{-4}	Ryu *et al.* (2007)
Cryptosporidium, *Giardia*, norovirus, enterovirus, *Campylobacter*, *E. coli* O157:H7	QMRA framework	Water treatment	Sweden	Annual risk with a wastewater discharge was acceptable for *Giardia*, borderline for *Cryptosporidium*, and high for norovirus and enterovirus	Åström *et al.* (2007)
Campylobacter, *E.coli*, *Cryptosporidium*	QMRA framework	Water treatment	Uganda	The level of detail required largely depends on the risk management question	Medema & Smeets (2009)
Campylobacter, *Giardia*, enterococci, *Salmonella*, *Cryptosporidium*, norovirus	QMRA framework	–	USA	The predicted median probability of illness was less than the illness benchmark of 0.01	Schoen & Ashbolt (2010)
Enterovirus, *Campylobacter*, *Cryptosporidium*, *Giardia*	QMRAspot	Water treatment	Netherlands	Effective tool to conduct QMRA for drinking water produced from surface water	Schijven *et al.* (2011)
Cryptosporidium, *Giardia*	QMRA framework	–	England and France	The annual risks of infection in the small water supplies were high, 25–28% for *Cryptosporidium* and 0.4–0.7% for *Giardia*	Hunter *et al.* (2011)
Norovirus, *Campylobacter*, *Cryptosporidium*, non-cholera *Vibrio* species	CC-QMRA tool	Temperature, precipitation, heavy rainfall, drought, water treatment	Netherlands	Increasing temperature and precipitation lead to increasing risks of *Campylobacter* and *Vibrio* exposure.	Schijven *et al.* (2013)
E. coli O157:H7, *Cryptosporidium*, *Campylobacter*, rotavirus, *Ascaris*	QMRA framework	–	Ghana	The sum of the disease burden of the pathogens was 0.5 DALYs per person per year, which is much higher than the WHO reference level	Machdar *et al.* (2013)
Campylobacter, *Giardia*, *Cryptosporidium*, norovirus, enterovirus	QMRA framework	Flooding, heavy rainfall, runoff, CSO	Netherlands	The results revealed that floodwater contains enteric pathogens and may therefore pose a high health risk	De Man *et al.* (2014)
Human adenovirus, enterovirus	QMRA framework	–	South Africa	The yearly risks of infection in individuals exposed to the river/dam water were	Chigor *et al.* (2014)

(*Continued*.)

Table 2 | Continued

Pathogens/fecal indicators	QMRA tools/ framework	Climatic/socio-economic factors/ water treatment	Study location	Main findings	Reference
				very high, exceeding the acceptable risk of 0.01%	
Cryptosporidium, Giardia, rotavirus, *Campylobacter*, *E. coli* O157:H7	HC- QMRA tool	Water treatment plants	Canada	Chemical disinfection is effective and most of the water treatment plants comply with the DALY requirements	Tfaily *et al.* (2015)
Cryptosporidium, Giardia	HC- QMRA tool	Temperature, heavy rainfall, runoff, water treatment	Canada	Increased treatment compliance and boiled water can mitigate increased risks from climate change	Smith *et al.* (2015)
Norovirus	Hydrodynamic model and QMRA framework	Water treatment	Sweden	The water treatment performance was estimated to be adequate but was heavily dependent on chlorine disinfection	Sokolova *et al.* (2015)
E. coli, enterovirus, norovirus, *Campylobacter, Cryptosporidium*	QMRAcatch model	Water treatment	Austria	The tool can assess microbial infection risks and determine the required pathogen removal by wastewater treatment plants to meet river water quality targets	Schijven *et al.* (2015)
Fecal coliforms, rotavirus, enterovirus	QMRA framework	–	Argentina	A high risk of rotavirus infection was found. The viral occurrence was not explained by the levels of bacteria indicators, thus monitoring of viruses is needed	Prez *et al.* (2015)
Giardia, Cryptosporidium, Campylobacter, E. coli O157:H7, norovirus	QMRA framework	Water treatment plants	Canada	Small surface water systems can cause more risk compared to larger systems	Murphy *et al.* (2016)
E. coli, Salmonella spp., Ascaris species, norovirus, rotavirus, *Campylobacter, Cryptosporidium*	QMRA framework	–	Uganda	A total of 59,493 disease episodes per year across all 18,204 exposed people and an annual disease burden of 304.3 DALYs	Fuhrimann *et al.* (2016)
Fecal coliform, *E. coli*, enterococci, coliphages, adenovirus, enterovirus, *Giardia, Cryptosporidium*	QMRA framework	–	California, USA	The mean risks of infection per recreational exposure event during the wet season were more than an order of magnitude below the USEPA's illness level	Seto *et al.* (2016)
Giardia, Cryptosporidium, norovirus, rotavirus	QMRA frameworkand DALY	–	Germany	The calculated DALYs were 1.19 DALY/1000	Timm *et al.* (2016)

(*Continued.*)

Table 2 | Continued

Pathogens/fecal indicators	QMRA tools/ framework	Climatic/socio-economic factors/ water treatment	Study location	Main findings	Reference
Norovirus, *Campylobacter, Salmonella, Giardia, E. coli, Cryptosporidium*	Process-based model, QMRA framework	Heavy rainfall event	Norway	The risk after the rainfall event was acceptable for the bacterial and parasitic pathogens, but high for the viral pathogen	Eregno *et al.* (2016)
Norovirus	Process-based model, QMRA framework	Water treatment	Japan	The Log_{10} reduction target values for norovirus corresponding to the annual disease burden of 10^{-6} DALY per person per year was 5.7 Log_{10} at 99.9% reliability	Ito *et al.* (2017)
Norovirus	QMRA framework	Water treatment	South Africa	The risk of norovirus infection or illness from polluted surface water is extremely high, especially for individuals in the lower socio-economic class	Van Abel *et al.* (2017)
Campylobacter, Cryptosporidium, norovirus	Hydrologic model, hydrodynamic model, QMRA framework	Water treatment	Sweden	To connect 25% of on-site wastewater treatment systems to the wastewater treatment plant was found as the most societally beneficial	Bergion *et al.* (2018)
E. coli O157:H7, *Salmonella*, norovirus, *Cryptosporidium*	QMRA framework	–	India	Annual mean diarrhea risk from fresh produce ranged from 18 to 59% for *E. coli* O157, and was <0.0001% for *Cryptosporidium* and 11% fornorovirus	Kundu *et al.* (2018)
Norovirus, *Cryptosporidium*	Process-based model and QMRA framework	Extreme precipitation events, water treatment	Norway	Risks of infection are high and extreme precipitation events may pose treatment challenges in the future	Mohammed & Seidu (2019)
Cryptosporidium	GloWPa-Crypto model and QMRA framework		Sub-Saharan Africa	An estimated 43.1 million cases of *Cryptosporidium* infection annually representing 1.6 million DALYs	Limaheluw *et al.* (2019)
Campylobacter, Cryptosporidium, norovirus	Hydrologic model, hydrodynamic model, QMRA framework	Water treatment	Sweden	It was found important to include unexpected risk events in the decision model for evaluating microbial risk reduction	Bergion *et al.* (2020)
Adenovirus, Salmonella, Vibrio, norovirus	QMRA framework	Water treatment	Italy	The cumulative illness risk was found a median of around 1 case/10,000 exposures during river bathing	Federigi *et al.* (2020)

(*Continued.*)

Table 2 | Continued

Pathogens/fecal indicators	QMRA tools/ framework	Climatic/socio-economic factors/ water treatment	Study location	Main findings	Reference
E. coli O157:H7, Cryptosporidium, norovirus, rotavirus	QMRA framework	–	Bangladesh	The overall risk of illness due to river bathing was 7–19%	Islam & Islam (2020)
Campylobacter, Salmonella spp., *Shigella* spp., *V. cholera, E. coli*, rotavirus	QMRA framework	–	Pakistan	The risk of illness due to bacterial infection was higher (19–70%) than due to rotavirus (3–22%)	Ahmed *et al.* (2020)
Cryptosporidium, Campylobacter, adenovirus	QMRA framework	Rainfall, Sewer overflows	Australia	Sewer overflows are not the primary driver of public health risks during and immediately following high rainfall events.	Kozak *et al.* (2020)
Enterococci, fecal coliforms, somatic coliphages, Bacteroides, adenovirus, *Salmonella* and *Cryptosporidium*	QMRA framework	Water treatment	United Kingdom	Mean adenovirus and *Cryptosporidium* infection risk were 0.95–1.00 and 0.01–0.06, respectively, for all recreational activities	Purnell *et al.* (2020)
Campylobacter, Cryptosporidium enterovirus, norovirus	Hydrological and QMRAcatch model	Precipitation, air temperature, demographic changes	Austria	If the pathogen load from wastewater is reduced through improved treatment, the climate change-induced increases in combined sewer overflows could still have a major impact	Demeter *et al.* (2021)
Fecal coliforms	SaniPath exposure assessment tool and QMRA framework	–	Bangladesh, Cambodia, Ghana, India, Mozambique, Senegal, Uganda, USA, Zambia	Food pathways were the most prevalent route of exposure to fecal pollutants in cities across low- and lower-middle-income countries	Wang *et al.* (2022)
E. coli, Cryptosporidium	Hydrologic model coupled with Swedish QMRA tool	–	South Africa	The likelihood of infection from *E. coli* and *Cryptosporidium* for most users exceeds the acceptable levels for both recreational activities and drinking water	Ngubane *et al.* (2022)
Cryptosporidium, Enterococci, *Giardia*	Hydrologic model and QMRA framework	Hydrology, rainfall	Austria	Infection risks for *Cryptosporidium* and *Giardia* vary from 0.08% in winter to 8% per person per exposure event in summer	Derx *et al.* (2023)
Fecal coliforms, *E. coli*	QMRA framework	–	China	Self-supplied water sources often exhibited higher risks compared to community-supplied sources	Yan *et al.* (2024)

Abbreviations: DALY, disability-adjusted life years; WHO, World Health Organisation; USEPA, United States Environmental Protection Agency; CSO, Combined Sewer Overflow.

Table 3 | Existing QMRA tools to predict health risks from consumption or exposure to polluted surface water

QMRA tool	Brief description	Applications	Climatic factors	Access
CC-QMRA Netherlands (Schijven *et al.* 2013)	A computational decision support tool that uses location-specific climate data to predict microbial risks from norovirus, *Campylobacter*, *Cryptosporidium*, and noncholera *Vibrio* species	Drinking water, recreational water, food safety	Temperature, rainfall, flow, agricultural land-use	Available upon request
Health Canada QMRA (Smith *et al.* 2015)	An Excel-based QMRA tool that estimates health risks from five reference pathogens, using hydrodynamic modeling to assess the impact of fecal loads on drinking water intakes	Drinking water	Temperature, rainfall, and runoff	Not open
Swedish QMRA tool (Petterson & Ashbolt 2016)	The tool has both online and offline versions and is designed to demonstrate how microbial risks are influenced by different steps of the drinking water production process	Drinking water	–	Open
QMRAspot (Schijven *et al.* 2011)	A computational tool that conducts QMRA for the drinking water production process where surface water is the source	Drinking water	–	Open
QMRAcatch (Schijven *et al.* 2015)	An interactive computational tool that simulates concentrations of microorganisms in surface water with treated wastewater and tributary river inputs, and assesses infection risks related to swimming or using the water as a drinking water source. Diffuse and point sources of fecal pollution are modeled considering dilution and temperature-dependent degradation. The tool predicts the required pathogen reduction goals for treatment systems to meet health-based goals	Drinking water, recreational water	–	Open
QMRA Treatment Calculator Tool (https://www.watershare.eu/tools/)	A web-based tool that provides users with access to a summary of data from the literature regarding the pathogen removal efficiency in various treatment processes	Drinking water	–	Membership required
Vesiopas (http://fi.opasnet.org/fi/Vesiopas)	A web-based tool that addresses the potential microbial health risks of drinking water. The risks are due to the pollution of raw water with microbes that cause potential health hazards to people using tap water. It determines the potential health risk of certain microbes in raw water based on the mathematical Water Guide model	Drinking water	–	Open
AquaNES QMRA tool (https://mp.watereurope.eu/d/Product/26)	A web-based interactive tool for microbial risk and chemical water quality assessment. The QMRA tool enables users to estimate the risk of a wide array of wastewater treatment steps and combinations of these steps in treatment trains in regard to different purposes of water use. A calculation is performed according to the QMRA approach that	Drinking water	–	Open

(*Continued.*)

Table 3 | Continued

QMRA tool	Brief description	Applications	Climatic factors	Access
	involves the estimation of infection risk for pathogens			
T15: QMRA tool (https://inowas.com/tools/t15-quantitative-microbial-risk-assessment/)	The tool facilitates QMRA implementation through a user-friendly web-based application. It enables the quantification of pathogens in source water and pathogen removal through treatment steps, employing a QMRA approach	Drinking water	–	Open
DPRisk (https://cawaterdatadive.shinyapps.io/DPRisk/)	The tool was developed in the R statistical language that facilitates QMRA and probabilistic assessment of treatment train performance for various direct potable reuse scenarios	Drinking water	–	Open

All the tools account for drinking water treatment, and none of the tools account for the socio-economic factors.

requirement for Dutch drinking water producers that use surface water as a water source to carry out a QMRA every 3 years. In order to facilitate this process, the State Institute for Health and the Environment of the Netherlands (RIVM) developed the tool QMRAspot (https://www.rivm.nl/en/who-collaborating-risk-assessment-of-pathogens-in-food-and-water/tools/qmra-spot), as the drinking water producers shall carry out the QMRA analysis with this tool (Schijven *et al.* 2011). In this tool, the user needs to enter the data on the treatment processes and pathogen levels in source water, whereupon the tool analyses these data by fitting a probability distribution and calculating the associated risk.

Later on, Schijven *et al.* (2013) developed the CC-QMRA tool by incorporating climate change scenarios. The tool is programed in Mathematica 8 and is freely available. The tool includes 16 separate modules to perform QMRA for various site-specific climate conditions and variables, including climate factors, microbial data, wastewater treatment, and river dimensions. If users lack the complete range of input data, the tool offers default values derived from existing literature. All calculations are conducted for a whole year, and Monte Carlo samples from distributions are generated for each day of the year. Climate conditions that the tool considers include air and water temperatures, annual precipitation, and frequency of heavy rainfall. Users can set the dates for the coldest and warmest days of the year, along with the minimum and maximum mean daily air and water temperature values. Temperature change between current and future conditions can be set from –6 °C to +6 °C, surpassing IPCC scenarios to enable more extreme location-specific changes. Users can also specify annual precipitation and the number of heavy precipitation days per annum for present and future climate conditions. The researchers report that the tool provides information that can help inform climate change adaptation (Schijven *et al.* 2013). For instance, if the results indicate an increased risk of infection from drinking water under future climate conditions, recommendations could include enhancing wastewater treatment and implementing measures to prevent sewer overflows.

QMRAcatch (https://www.rivm.nl/en/who-collaborating-risk-assessment-of-pathogens-in-food-and-water/tools/qmra-catch) is another Dutch tool for pollution transport in water sources. In this tool, the health risks within a catchment area are assessed using indicator bacteria, microbial source tracking markers, and pathogens. The risk of infection is calculated for exposure while swimming in the water source or through consumption of produced drinking water (Schijven *et al.* 2015).

The Guidelines for Canadian Drinking Water Quality encourage the adoption of a multi-barrier source-to-tap approach to produce clean, safe, and reliable drinking water (Smith *et al.* 2015). Health Canada developed a QMRA tool (HC-QMRA) to support the establishment of drinking water guideline values for enteric viruses and protozoa, as well as to promote site-specific risk assessments at drinking water treatment facilities. This tool was created using Analytica software, which facilitates mathematical computations to assess the impact of weather and climate variables on food and water safety risks. It is anticipated that drinking water quality will be primarily affected by increased frequency, intensity, and duration of rainfall, resulting in higher runoff and elevated levels of *Cryptosporidium* and *Giardia* in source water (Smith *et al.* 2015). Additionally, rising air temperatures may lead to snowmelt and subsequent parasite-laden runoff into source water, along with changes in wildlife host species as temperatures increase. Drinking water treatment and management practices were also taken into consideration in the HC-QMRA tool (Smith *et al.* 2015). The HC-QMRA tool accounts for climate change and water treatment but does not include the influence of socio-economic factors (Table 3).

The Swedish Water and Wastewater Association developed a QMRA tool in 2009 (further developed in 2012, 2016, 2020, and 2021) for drinking water production from surface water specifically to support the application of QMRA for understanding the system (Petterson & Ashbolt 2016). The latest version of the tool (called in Swedish 'QMRA-verktyg ytvattenverk') is freely available online (https://www.chalmers.se/institutioner/ace/centrum-och-infrastrukturer/dricks/qmra-verktyget/). The tool is constructed in the Analytica software platform and is designed to be flexible and to allow a diverse range of treatment trains to be modeled. The tool includes eight reference pathogens (*Salmonella*, *Campylobacter*, *E. coli* O157:H7, *Cryptosporidium*, *Giardia*, rotavirus, norovirus, and adenovirus). In the Swedish QMRA tool, each treatment step allows for different failure scenarios to be selected and investigated against normal conditions, but it does not account for interdependencies between the treatment steps. The tool could be improved by linking the performance of the treatment barriers to account for the fact that failure of one barrier can trigger failure of the following barrier(s). The Swedish QMRA tool does not account for the impacts of climate (e.g., temperature and rainfall) and socio-economic factors on source water quality. Currently, the tool does not consider the impact of temperature on inactivation/die-off and growth of pathogens, and it does not explicitly account for runoff from agricultural lands and accidental discharges of untreated or partially treated wastewater in urban areas.

While some of these tools, such as QMRAspot and the Swedish QMRA tool, quantify microbial risks from drinking water, other tools, such as CC-QMRA and QMRAcatch, allow users to quantify health risks from multiple pathways, such as drinking water, recreational water, and food safety. While most of the tools allow users to use their source-specific measured microbial water quality data, few other tools, e.g., CC-QMRA, can generate microbial concentrations using such inputs as sewer discharge, removal capacity of drinking water treatment plants, rainfall, and runoff. Most of the existing tools have been based on the pathogen removal efficiency in different water treatment processes. Although some QMRA tools, such as CC-QMRA and Health Canada QMRA, account for climatic factors, currently, to the best of our knowledge, no QMRA tool exists that incorporate socio-economic factors to quantify health risks from exposure to waterborne pathogens. Some of the QMRA tools are web-based, some are open-access, and some have both online and offline versions (Table 3). Since new risk assessment tools will continue to be developed, it is essential to maintain risk assessment knowledge repositories that may include tools and models in machine-readable formats for more effective reuse and dissemination of existing knowledge (Rose *et al.* 2023). Developing online analytical tools that allow users to run the models without the need for advanced computer programming skills or specific software is a good way to make models and tools more accessible to water managers and decision-makers.

6. STUDIES THAT COMBINE QMRA WITH OTHER TOOLS

QMRA has traditionally been focused on evaluating pathogen risks and health impacts based on microbial exposure. However, combining QMRA with other tools, such as life-cycle assessment (LCA), socio-economic assessments, and environmental impact models, provides a more comprehensive framework for understanding pathogen-related risks and their broader socio-economic implications. This integrated approach enables a better assessment of health impacts, environmental tradeoffs, and socio-economic implications, leading to more informed decision-making and effective risk management strategies. Duch (2008) emphasizes the value of integrating health, ecological, socio-economic, and cultural assessments into QMRA. This combined approach allows for a more holistic evaluation of pathogen risks by considering not only the direct health impacts but also the ecological and socio-economic contexts. Such integration helps in understanding the broader implications of pathogen exposure on different socio-economic groups and adapting risk management strategies accordingly. Haldar *et al.* (2022) demonstrate the application of QMRA to assess microbial contamination risks in surface water, specifically focusing on peri-urban farmers. This study illustrates how QMRA can be combined with local socio-economic data to evaluate risks pertinent to specific communities, emphasizing the need to tailor risk assessments to the particular contexts and activities of affected populations.

Harder *et al.* (2017) and Kobayashi *et al.* (2015, 2017, 2020) explore the combined use of LCA and QMRA. LCA provides a framework to evaluate the environmental impacts of various interventions or scenarios, including pathogen control measures. By integrating LCA with QMRA, researchers can address tradeoffs between different risk management strategies, assessing both the health burden and environmental impacts to identify the most sustainable and effective solutions. Hofstra *et al.* (2019) discuss using QMRA to simulate risks while also assessing socio-economic development and climate change impacts. This combined approach allows for the evaluation of how socio-economic factors and climate variations influence pathogen risks, offering insights into how future scenarios might affect health outcomes and guiding policy development in a dynamic context. Li & Kohn (2024) focus on how lake warming and changes in circulation patterns affect the inactivation of enteric viruses. Their approach highlights the importance of considering environmental changes in pathogen risk assessments, showing how QMRA can adapt to evolving conditions. The justification of QMRA risk estimates can be evaluated by comparing model predictions with empirical data, assessing assumptions, and addressing uncertainties. Timm *et al.* (2016) explore the application of QMRA and DALYs to evaluate health risks while considering socio-economic dependencies. This approach allows for a nuanced assessment of health impacts, taking into account how socio-economic factors influence both the probability of exposure and the resulting health outcomes.

7. PROPOSED INTERVENTIONS EXEMPLIFIED IN THE SWEDISH QMRA TOOL

Although the Swedish QMRA tool currently provides robust risk assessments, it has key limitations in addressing the impact of climate change, socio-economic development, and land-use changes on pathogen concentrations in source water. These factors are critical for future risk assessments, particularly in light of increasing extreme weather events, urbanization, and evolving agricultural practices. The existing tool does not integrate these future scenarios, which are essential for long-term, accurate risk evaluations. To address these gaps, we propose expanding the tool by incorporating new modules (Figure 1) that account for pathogen loads from wastewater discharges, agricultural runoff, and changes in pathogen inactivation due to climate-induced temperature shifts. These enhancements will enable users to evaluate future health risks under varying climatic and socio-economic conditions. The tool will also incorporate scenario analysis, utilizing projected climate, socio-economic, and land-use changes to simulate future pathogen concentrations, thus providing a more comprehensive risk assessment.

One way to incorporate the effects of climate, socio-economic, and land-use changes into the Swedish QMRA tool is by simulating future pathogen concentrations using process-based water quality modeling. The resulting projections for source water concentrations can then be used as input into the QMRA tool (e.g., Ito *et al.* 2017; Islam *et al.* 2018). This method explicitly accounts for complex changes in climate, land use, and other factors. However, while such models are useful for academic research, they may be less practical for water managers and other users due to their complexity and the expertise required.

The Swedish QMRA tool can be enhanced to estimate the risks associated with climate, socio-economic, and land-use changes by modifying the general QMRA framework (i.e., hazard identification, exposure assessment, dose-response assessment, and risk characterization). This would involve adapting the tool's existing modules to model both the current state (baseline) and the impacts of future projected changes on health risks. Currently, the tool consists of six modules: (1) characterization of raw water, (2) separating barriers, (3) additional barriers, (4) inactivation barriers (disinfection), (5) exposure, and (6) risk characterization. To incorporate future changes, we propose a two-step development approach: Step 1 involves

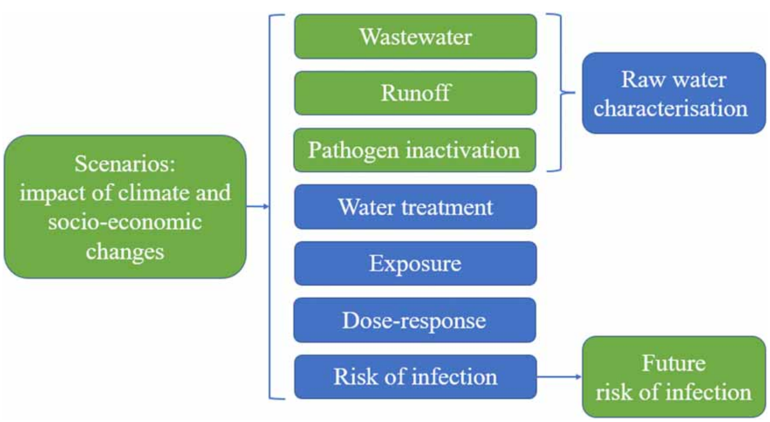


Figure 1 | Overview of the existing (blue) and proposed new (green) modules in the Swedish QMRA tool to enable assessment of future infection risks, including the integration of climate change, socio-economic development, and land-use changes.

replacing the 'Characterization of raw water' module with three new modules to enable scenario analysis: a wastewater module (for urban areas), an agricultural runoff module, and a pathogen inactivation module. Step 2 entails defining future scenarios and their effects on the interactions between these modules, enabling the simulation of how climate change, extreme events, socio-economic shifts, and land-use changes impact health risks for specific locations or regions. Parameters can be input as pre-set values from literature or location-specific values, and where local data variations exist, they can be represented as probability distributions in the model. Monte Carlo simulations will then be used to illustrate how these variations affect the overall risk calculation.

Additionally, the existing water treatment-related modules – separating barriers, additional barriers, and inactivation barriers (disinfection) – can be consolidated into a single 'Water treatment' module, improving integration and coherence within the tool.

Identifying and evaluating risk events is advocated in the WHO's guidelines for drinking water and its Water Safety Plans (WHO 2011). It is also recommended that various extreme events, such as heavy rainfall, floods, and sewer overflows, should be evaluated by implementing QMRA. In QMRA calculations, it is therefore important to not only focus on the risk of infection that the tool calculates for normal conditions but also use the tool to identify risk events. It is important to model various risk events, as modeling only the normal conditions, when all treatment steps function normally and nothing undesirable occurs in the water source, is not sufficient. Figure 2 illustrates the gap between the current QMRA tool and the proposed improvements. In the following, we describe in detail the new modules that are proposed to be incorporated into the Swedish QMRA tool to address these gaps.

7.1. Wastewater discharges

In a wastewater treatment plant with secondary treatment, the concentrations of pathogens can be reduced generally by 1–2 $\log_{10}$ units (Wang *et al.* 2022). The treated wastewater is discharged into surface water, resulting in the dilution of pathogens depending on the size of the surface water source. In a combined sewer system, the household wastewater is mixed with stormwater before reaching the wastewater treatment plant. In case of a heavy rainfall event, the capacity of the sewer

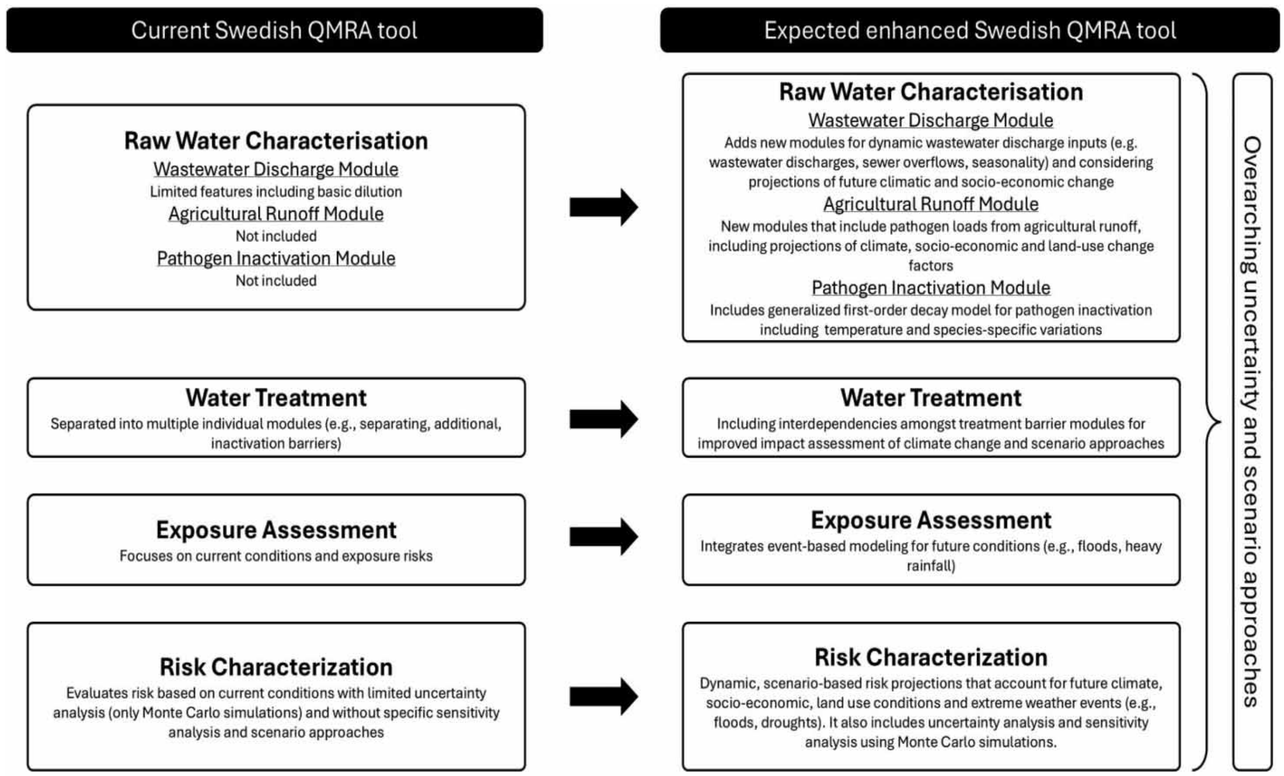


Figure 2 | Comparison of current and proposed enhanced features in the Swedish QMRA tool.

network and/or of the plant may be exceeded and cause overflows. Overflows/emergency discharges can also occur in a separated sewer system due to malfunctions in the sewer network or overload of the plant due to infiltration and inflow in the sewer pipes. During an overflow event, untreated wastewater is discharged into surface water sources, resulting in a peak concentration in source water for drinking water production.

It can be assumed that sewer overflow occurs at each heavy rainfall event, when the amount of rainfall exceeds a certain threshold, e.g.,13 mm/day (as reported by Demeter *et al.* 2021). Under climate change conditions with an increase in the number of heavy rainfall events, it can be assumed that there is an equal increase in the number of overflows. Thus, under current and future climate conditions, there are days without and with overflow. To assess the effects of wastewater discharges on a surface water source with and without sewer overflow event, different factors and processes need to be accounted for, including pathogen concentration in untreated wastewater; pathogen $\log_{10}$ removal by the wastewater treatment; amount of heavy precipitation and low precipitation; volume of the wastewater discharge; dilution factor (0.1–0.9 times) to account for mixing of wastewater and stormwater in the sewer after a heavy rainfall event; flow rate in the watercourse (river/stream); reduction of pathogen concentrations due to transport within the water body between the discharge point and the water intake (e.g., 0–5 $\log_{10}$ units, as in Bergion *et al.* 2018). Previous studies (Bouwknegt *et al.* 2009; Schijven *et al.* 2013) described in detail how to estimate the pathogen concentration in the surface water resulting from wastewater discharges.

7.2. Agricultural runoff

Heavy rainfall can pose a risk to water sources due to runoff transporting pathogens from surrounding land. Runoff from agricultural land can transport pathogens from grazing cattle and manure used as fertilizer. Zoonotic pathogens such as *Campylobacter* and *Cryptosporidium* can be released from manure due to heavy rainfall (Bouwknegt *et al.* 2009) and enter the surrounding water sources with runoff (Islam *et al.* 2018). The extent of runoff depends on several factors, including the specific soil types, land use characteristics, and the hydrologic conditions. To predict the approximate amount of direct runoff from a rainfall event, the runoff curve number (CN) method can be used (USDA 1986). The CN method considers the potential maximum amount of water retained by the soil and the amount of rainfall. Because of its simplicity, versatility, and availability of necessary data, this method is popular within the United States and other countries (Hawkins *et al.* 2008; Sartori *et al.* 2011). Several hydrologic and water quality models use the CN method, e.g., the Soil and Water Assessment Tool (Gassman *et al.* 2007), the sediment transport model based on CN (Mishra *et al.* 2006), and the coupled CN method and the Revised Universal Soil Loss Equation model (Gao *et al.* 2015). The concentration of pathogens in the surface water resulting from runoff can be estimated for days with average and heavy rainfall (Bouwknegt *et al.* 2009). The different factors and processes involved in the estimation are the area of agricultural land use; runoff volume during average rainfall and heavy rainfall; pathogen concentration in runoff; and reduction of pathogen concentrations due to transport within the water body between the discharge point and the water intake. The agricultural runoff concentrations of *Campylobacter* and *Cryptosporidium* are site-specific; the concentrations found in the literature are, e.g., 10^4 #/L (Sterk *et al.* 2016) and 5.5×10^2 #/L (Miller *et al.* 2008), respectively.

7.3. Inactivation/growth of pathogens

Inactivation or growth of a pathogen in water is influenced by a number of factors (e.g., water temperature, salinity, and light intensity). Most pathogens decay/inactivate faster with an increase in temperature, while some enteric bacteria can grow or replicate in surface water (Vital *et al.* 2010; WHO 2011). Distance and travel time can also affect surface water pathogen concentrations (Schijven *et al.* 2013). In this module, pathogens were assumed to undergo inactivation following first-order decay kinetics, as described by Bertrand *et al.* (2012). While decay rates vary among different pathogens, the use of a generalized first-order model simplifies the calculations. However, this approach does not account for species-specific variations in decay rates, which could influence accuracy in some cases. The distance and associated travel time between the pollution source and the water intake for drinking water production are critical factors in determining the pathogen concentration. This relationship is accounted for by calculating the change in pathogen concentration over time, as outlined in previous studies (Bouwknegt *et al.* 2009; Schijven *et al.* 2013), which consider both inactivation and transport processes. If pathogen growth is to be included, the overall pathogen concentration could be calculated as the net result of both growth and inactivation, as described by Cho *et al.* (2016). This would require additional parameters describing the environmental conditions that support pathogen growth. The required input parameters include the pathogen concentration entering the water body, the species of pathogen, current and projected water temperatures (considering climate change), the species-specific die-off rate, and transport time. These parameters are critical for accurately assessing pathogen inactivation and transport. The output of the module will be the projected increase or decrease in pathogen concentrations per volume of water, resulting from climate change-induced changes in water temperature.

7.4. Modification of the water treatment module

Climate change-induced extreme weather events can cause malfunction of drinking water treatment plants, causing failure to comply with drinking water quality standards. The required efficiency of pathogen reduction by microbial barriers (often expressed as $\log_{10}$ reduction targets) needs to be determined for the safe use of the water source and is site-specific. The systematic approach of the QMRA framework aids in establishing current and future $\log_{10}$ reduction targets and evaluating whether these targets are met with the existing treatment train (Petterson & Ashbolt 2016).

Most drinking water treatment employs a multi-barrier approach to achieve safe drinking water. In practice, each treatment barrier comprises multiple parallel process units, such as filters or sedimentation tanks. By combining different types of processes in series, the failure of one barrier can be partially compensated by others. The performance of the entire drinking water treatment train under normal and strained conditions can be assessed by testing scenarios in which the performance of individual barriers is adjusted, and this functionality is available in the current version of the Swedish QMRA tool. However, chain reactions, when a subsequent treatment step does not work optimally if a previous treatment step has failed, are not implemented in the Swedish tool. To describe the interdependencies between the microbial barriers, the existing modules related to treatment steps (separating barriers, additional barriers, inactivating barriers/disinfection) can be grouped and termed the 'water treatment' module. Then, the chain reactions could be accounted for by presenting the user with possible predetermined what-if scenarios that describe plausible consequences of different treatment failures. For example, a failure in the conventional treatment step (flocculation and sedimentation) can be linked to a subsequent failure in the filtration step and/or disinfection step. Formulation of such scenarios can be based on the failure events reported in the literature, providing default settings in the tool. In addition, the user may consult the known failures at the specific treatment facility and input site-specific assumptions, if available.

7.5. Inclusion of climatic and socio-economic scenarios

Pathogen concentrations in surface water under future conditions can be quantified using the proposed new modules in the Swedish QMRA tool (Figure 1). The wastewater module allows for accounting changes in pathogen loads from wastewater discharges and sewer overflows, while the runoff module considers changes in pathogen loads from grazing and manure used as fertilizer on agricultural land. These loads are influenced by climatic factors, primarily precipitation, as well as socio-economic development, such as population growth, urbanization, and related wastewater management and agricultural practices. For example, increased rainfall due to climate change can lead to higher pathogen loads entering water bodies, as heavy precipitation can wash pollutants, including pathogens, into surface water. Additionally, rising air temperatures may increase water temperatures, which could accelerate bacterial decay rates (Vermeulen & Hofstra 2014), potentially affecting pathogen survival and removal. Urbanization can also exacerbate these effects, as increased impervious surfaces and sewer overflows may contribute to higher pathogen concentrations in urban runoff. The effectiveness of wastewater treatment in removing pathogens also varies depending on factors such as the type of pathogen and changes in water quality, including suspended solids that may affect pathogen removal efficiency. Technological improvements in water treatment, trends in drinking water consumption, and possible shifts in pathogen infectivity can be incorporated into future scenario testing, providing a more comprehensive assessment of how these factors influence pathogen concentrations and health risks.

The time horizon of the scenarios can be defined by the user, for example, it can be the middle or the end of the current century (i.e., by the 2050s and 2100s). The scenario values should encompass IPCC scenarios and should be site/location specific. The scenarios can be developed using the most recent representative concentration pathways (RCPs) and SSPs. IPCC identifies four RCPs (RCP2.6, 4.5, 6.0, and 8.5) based on varying levels of radiative forcing ranging from 2.6 to 8.5 W/m² by 2100 (IPCC 2021). Two climate change scenarios: a relatively low emission pathway (RCP4.5) and a high emission pathway (RCP8.5) can be used. To encompass the best and worst potential future conditions of the study area, two extreme scenarios, SSP1 and SSP3, from the five SSP scenarios (SSP1–SSP5) can be chosen as contrasting but plausible futures. These scenarios illustrate divergent trends in populations, sanitation, agricultural development, and advancement of technology (O'Neill *et al.* 2017).

Data on climate and socio-economic scenarios can be entered into the tool separately or combined. By integrating climate scenarios driven by RCP4.5 with the socio-economic scenario SSP1 and RCP8.5 with SSP3, a scenario matrix can be established, as suggested by previous studies (Van Vuuren *et al.* 2011; Islam *et al.* 2018). The scenario matrix and the corresponding assumptions for the scenarios are summarized as an example in Table 4.

To assess future health risks under changing climate conditions, a scenario-based approach can be used to incorporate climate-driven changes in pathogen concentrations resulting from extreme weather events, particularly heavy rainfall. 'Normal days' are defined as days without runoff or sewer overflows, while 'event days' refer to those with heavy rainfall, which increase pathogen loads from urban and agricultural runoff. Pathogen concentrations on event days can be adjusted based on runoff increases, as described in previous studies (Islam *et al.* 2018; Iqbal *et al.* 2019). For future projections, an increase in the frequency of heavy rainfall days can be assumed based on climate change predictions, which can help estimate future pathogen concentrations. The daily pathogen concentration is calculated by combining pathogen levels from both normal and event days. This value is then used in the QMRA tool to calculate daily infection risks using dose-response models. The tool estimates average annual risks by compounding daily risks, accounting for both typical and extreme climate-induced conditions.

Despite this approach, the QMRA method involves assumptions and simplifications that introduce uncertainties. For example, while increased precipitation is assumed to directly result in higher volumes of sewer overflows and runoff, studies have shown that this relationship is not linear. Additionally, the impact of sewer overflows, runoff, and socio-economic factors on pathogen concentrations varies by location and sewer system characteristics (Schijven *et al.* 2013; Demeter *et al.* 2021). These uncertainties are further compounded when climate parameters, which are inherently uncertain and subject to significant error, are used as inputs in the model. These errors can accumulate, potentially leading to reduced model reliability. To address these challenges, scenario-based modeling can be integrated, allowing for the consideration of multiple climate scenarios to reflect a range of possible future conditions. This would help capture the uncertainty in climate projections and provide a more comprehensive assessment of potential risks. Additionally, sensitivity analysis can be incorporated to evaluate how input uncertainties, especially those related to climate conditions, influence risk predictions. This would help identify which parameters have the most significant impact on predictions and guide where improved data or model refinement is needed. Furthermore, implementing uncertainty quantification methods, such as probabilistic risk assessment, could provide a range of potential outcomes, presenting the predictions as probability distributions and acknowledging the uncertainty in future conditions.

Table 4 | The scenario matrix and associated assumptions for the future scenarios

Climate change and socio-economic factor	SSP1 + RCP4.5 ('sustainable scenario')	SSP3 + RCP8.5 ('uncontrolled scenario')	Impact on microbial risks in drinking water
Population growth	Low	High	Wastewater discharges
Urbanization	Rapid/planned	Slow/unplanned	Wastewater discharges
Intensification of agricultural production	Rapid	Slow	Agricultural runoff
Land-use	Forest cover increases and less agricultural land due to effective crop yield	Forest cover declined and increased use of agricultural land	Agricultural runoff
Sanitation	Improved	Current trend	Wastewater discharges
Wastewater treatment	Improved	Little improved	Reduction of pathogens
Manure treatment	Improved	Unimproved	Reduction of pathogens
Dependency on fossil fuels and CO_2 emissions	Reduced and declining	Uncontrolled	–
Environmental technology advancement	Rapid	Slow	Reduction of pathogens, Wastewater discharges
Economic development	Rapid	Slow	Dietary preferences and thus agricultural runoff

The review examines the potential for the QMRA framework to adapt to evolving challenges from climate change and socio-economic factors. It highlights the benefits of integrating these factors into microbial risk assessments and the challenges, such as complexity and uncertainties in climate projections. The proposed interventions aim to enhance the tool's applicability for water quality management and public health, but long-term, site-specific data remains essential for validating the tool's accuracy and practical use in managing waterborne pathogen risks.

8. CONCLUSIONS

Climate change and socio-economic development affect the microbial water quality in surface water sources, necessitating the assessment of the related effects on the health risks of drinking water consumers. The QMRA framework is widely used to assess current health risks and is thus the preferred approach to also assess health risks under future conditions.

There is a large body of literature reporting implementations of QMRA, albeit most examples are from high-income countries. While most of the studies apply the steps of the QMRA framework, there are several QMRA tools available, which were developed to simplify and harmonize the implementation of the QMRA framework. Several of the reviewed studies investigated the effect of climate conditions, and two of the nine identified QMRA tools had functionality to support testing climate change scenarios. The QMRA tools that were identified currently do not support systematic testing of future socio-economic conditions.

Based on the reviewed studies and the existing QMRA tools, we propose developments to one of the freely available tools – the Swedish QMRA tool – to enable systematic scenario testing to assess future health risks under conditions of climate and socio-economic changes. These proposed developments include the incorporation of three new modules to make it possible to describe source water quality under future conditions. These modules describe wastewater discharges, agricultural runoff, and microbial inactivation/growth. We also propose considering chain reactions and interdependencies between the microbial barriers in the water treatment module. Finally, we proposed how the scenarios describing future climate and socio-economic development can be formulated in the context of RCP and SSP projections. This review outlines the direction for the future development of the Swedish QMRA tool as well as the other QMRA tools currently available.

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ETHICAL APPROVAL

This research does not involve any human data requiring ethical approval.

AUTHOR CONTRIBUTIONS

M. M. M. I. conceptualized and investigation the whole process, developed the methodology, visualized the study and wrote the original draft. M. B. conceptualized and investigation the whole process, rendered support in project administration and resources, supervised the work, wrote the review and edited the article. V. B. conceptualized and investigation the whole process, visualized the study, wrote the review and edited the article. E. S. conceptualized and investigation the whole process, rendered support in project administration and resources, supervised the work, wrote the review and edited the article.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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