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THE INTEGRATION OF CLIMATE CHANGE IN A PRIORITIZATION METHOD FOR EMERGING RISKS TO DRINKING WATER QUALITY

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Abstract

Increasing pressure from anthropogenic sources in combination with more sensitive measurement techniques has led to an increase in the number of emerging contaminants detected in surface or drinking water. Emerging contaminants are chemical substances or pathogenic microorganisms that pose a new threat to public health through the exposure to drinking water. Since it is practically impossible to monitor all emerging contaminants, prioritization methods help to make a well-founded choice which contaminants require the most attention.

This study examined the added value of integrating climate change criteria in a prioritization method for emerging risks to drinking water quality, since there is scientific consensus that climate change has a negative effect on the quality of surface water and therefore also on drinking water quality. To formulate the climate change criteria, the Multi-Criteria Decision Analysis (MCDA) technique provided an assessment framework to combine objective technical information with subjective interpretations of experts. The MCDA framework aims to minimize the chance of bias by following a transparent and systematic approach.

A literature review on worldwide scientific literature in combination with a Dutch climate scenario showed the most dominant effects of climate change on surface water quality in the Netherlands. Thereafter, a final set of seven criteria was drawn up in consultation with drinking water experts. These criteria are related to three climate variables, namely air temperature, precipitation and drought.

A selection of fifteen chemical and twelve microbial contaminants was ranked using the formulated criteria. Evaluation of this ranking suggested an increased exposure potential of certain contaminants due to climate change, and also that not all contaminants are affected to the same extent. Mainly pathogens that are able to grow in nutrient-poor conditions with high water temperatures and contaminants that are able to be transported to the river system by runoff, resuspension or combined sewer overflow become more important. The results implicated that the integration of climate change in a prioritization method for emerging risks to Dutch drinking water quality does have added value. The integration can support futureproof policy and promote proactive identification of emerging contaminants of potential high concern.

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Introduction

Intensifying human activities such as industrialization, land use change and urbanization put an increasing pressure on the quality of surface water bodies (Delpla et al., 2009; Vörösmarty et al., 2010). Consequently, an increasing variety and amount of chemical and microbial contaminants is found in freshwater systems all over the world (Baken et al., 2018; Bunke et al., 2019; Lapworth et al., 2018). Since surface water is an important resource for the production of drinking water, a reduced water quality could negatively impact the production of safe drinking water.

In the Netherlands, more than a third of the drinking water is produced from surface water (Vewin, 2018). Despite the relatively large amount of surface water used, Dutch drinking water is internationally known for its high quality, which can be distributed without any disinfectants to be added (Rosario-Ortiz et al., 2016). In order to ensure drinking water of high quality, the condition of drinking water sources is constantly monitored. The monitoring programs primarily focus on the microbiological and chemical parameters stated in the Dutch Drinking Water Decree (Wuijts et al., 2014).

In addition to the regulated contaminants, an increasing amount of public and scientific attention is given to the appearance of newly detected chemical and microbial contaminants in the environment (Houtman, 2010; Richardson & Ternes, 2018). Almost all of these contaminants are released by anthropogenic sources, for example by wastewater treatment plants or runoff from agricultural land (Gavrilescu et al., 2015). As a result of increasing anthropogenic pressure in combination with more sensitive measurement techniques, a rapidly growing number of emerging contaminants is discovered in surface or drinking water (Baken et al., 2018; Houtman, 2010; Pal et al., 2010; Schriks et al., 2010).

In this study, emerging contaminants are defined as newly discovered chemical substances or pathogenic microorganisms, which pose a new threat to public health through the exposure to drinking water (Hartmann et al., 2018). Examples of emerging contaminants are pharmaceuticals, per- and polyfluoroalkyl substances (PFASs), disinfection byproducts, antimicrobial resistant organisms and (re-)emerging waterborne zoonoses (Dulio et al., 2018; Richardson & Kimura, 2017).

As a consequence of the novelty of emerging contaminants (ECs), they are often unregulated and inconsistently monitored while the knowledge of the environmental fate and health impact of the contaminants is often insufficient (Hartmann et al., 2018; Lapworth et al., 2018; Richardson & Ternes, 2018). Wuijts et al. (2014) showed that ECs pose a risk to a large majority of the sites in the Netherlands where surface water is extracted for drinking water production. Even though the concentration of ECs in surface water is usually very low, it is necessary to ensure that exposure to high-risk contaminants via drinking water is controlled.

Due to methodological limitations and cost constraints, it is unfeasible to monitor or regulate all newly discovered ECs (Lapworth et al., 2018). Therefore, a well-founded choice must be made which contaminants require the most attention. A systematic and transparent prioritization method can be useful to substantiate this choice. Furthermore, a prioritization of ECs can help to proactively identify ECs, which allows faster employment of appropriate measures (Hartmann et al., 2018).

The increased scientific awareness for ECs in surface and drinking water has led to a large variety of prioritization methods including many different criteria (e.g.(Brunner et al., 2019; Guillén et al., 2012; Lapworth et al., 2018; Mian et al., 2018). Most of the developed prioritization methods are risk-based and thus include both exposure- and hazard-based criteria. Examples of exposure-based criteria are usage, occurrence in the environment or removal rate in treatment plants. Hazard-based criteria deal with the potential of a contaminant to cause harm to humans or ecosystems.

The occurrence of ECs in surface and drinking water is likely to be influenced by changing climate conditions (Bunke et al., 2019; Delpla et al., 2009; Noyes et al., 2009; Richardson & Kimura, 2017; Sjerps, Ter Laak, & Zwolsman, 2017; Sterk et al., 2013; Whitehead et al., 2009). According to the Intergovernmental Panel on Climate Change (IPCC), the main climate conditions that impact surface water and drinking water quality are temperature, rainfall and droughts (Jiménez Cisneros et al., 2014). A temperature rise affects almost all physicochemical equilibriums and biological reactions, and more frequent extreme hydrological events alter the concentration of chemical substances or pathogenic microorganisms in the aquatic environment (Delpla et al., 2009; Whitehead et al., 2009).

Problem definition

As several studies have shown the importance of climate change-induced effects on the load and fate of ECs in the aquatic environment, this study investigates the added value of integrating climate change criteria in a prioritization method for emerging risks to drinking water quality. Up to now, to the best of the author's knowledge, the effects of climate change have not been included in a prioritization method to rank the risks of various contaminants to drinking water quality. To include climate change criteria in a prioritization method, it is necessary to find out which changes in climate have an impact on the occurrence of ECs in surface and drinking water. The urgency of the problem is illustrated by Wuijts et al. (2012), who argue that the quality of Dutch surface water could be significantly decreased by 2050 due to climate change, possibly to a point where surface water becomes unsuitable for drinking water production.

Research objective

The aim of this study is to evaluate the added value of integrating climate change criteria in a prioritization method for emerging chemical and microbial risks to drinking water quality. The prioritization method aims to rank emerging contaminants on the basis of increased exposure potential due to climate change. The prioritization method proactively identifies ECs that become more eminent as a result of climate change with a systematic, transparent and future-proof approach.

Research questions

The following four research questions have been formulated to structure the research and to achieve the research objective:

1. What are the most dominant effects of climate change on surface water quality in the Netherlands?
2. Which criteria can be formulated, based on the most dominant climate change effects, to prioritize emerging chemical and microbial contaminants?
3. How can the climate change criteria be incorporated into a systematic and transparent prioritization method for emerging chemical and microbial risks to drinking water quality?
4. What are the implications of integrating climate change into the prioritization method on a possible ranking of emerging contaminants?

Theoretical Framework

The risks of most emerging contaminants (ECs) in the aquatic environment is uncertain (Houtman, 2010). The paragraphs below discuss what this relatively high level of uncertainty means for the prioritization and shows how other studies have dealt with uncertainty. The method of Multi-Criteria Decision Analysis is discussed as a possible technique to tackle this uncertainty. Furthermore, the uncertainty regarding the risk of ECs is likely to increase as a result of changing boundary conditions, such as demographic change, population growth and urbanization, chemical substitution and technological developments (Bunke et al., 2019). This study investigates the impact of a changing climate on the risk of ECs. It is explained how previous research has dealt with climate change and the effects on water quality and the occurrence of ECs in the aquatic environment.

Prioritization under uncertainty

Prioritization methods help to identify the most critical ECs that pose a threat to public health. In response to the recent rapid increase of ECs discovered in the aquatic environment, a variety of prioritization methods was published (Baken et al., 2018; Brunner et al., 2019; Dos Santos & Nardocci, 2019; Guillén et al., 2012; Mian et al., 2018; Olson et al., 2017; Sjerps et al., 2016; Spiesman & Speight, 2014). These prioritization methods mainly consist of criteria concerning toxicity, measured or modeled concentrations and environmental fate of contaminants.

Most published prioritization methods are tailored towards either chemical or microbial contaminants. Only a small number of studies has formulated criteria that are applicable to both chemical and microbial contaminants (Olson et al., 2017; Rosen & Roberson, 2007; Spiesman & Speight, 2014). However, an integrated method for the prioritization of chemical and microbial contaminants is useful as chemical and microbial contaminants often originate from the same type of pollution sources. Furthermore, the properties that are relevant for risk-based prioritization, such as toxicity, persistence and mobility, are often similar for chemical and microbial substances (La Rose et al., 2012; Reemtsma et al., 2016).

Because of the uncertainty regarding the exposure to and potential hazard of ECs, it is unachievable to design a fully objective prioritization method merely based on technical evidence. Consequently, risk-based prioritization schemes have to rely to a certain extent on expert knowledge (Lapworth et al., 2018; Olson et al., 2017; Rosen & Roberson, 2007; Spiesman & Speight, 2014), but including expert knowledge into the prioritization can lead to biases. Rosen and Roberson (2007) argue that experts do not always identify the appropriate contaminants, possibly because experts are biased or influenced by public opinion. Possible reasons for expert bias are overconfidence and personal experiences (O'Hagan, 2019).

Therefore, when expert consultation is used as input for a prioritization method, it should be clearly explained how the information has been collected and processed (Krueger et al., 2012; Scholten, 2013).

Moreover, it is important to request information from various experts, after which the expert judgments are combined with mathematical (mean value) or behavioral (consensus) aggregation (O’Hagan, 2019). Krueger et al. (2012) argue that group discussions can make biases more explicit and omit redundant information.

Multi-Criteria Decision Analysis

The assessment framework of the Multi-Criteria Decision Analysis (MCDA) provides a transparent and systematic technique to order decision-making processes and to reduce the chance of bias (Eisenführ, Weber, & Langer, 2010; Rosen & Roberson, 2007; Scholten et al., 2015). Eisenführ et al. (2010) state that the more complex a certain decision problem becomes, the more important it is to support the decision process with tools that can systematically filter and process the relevant information. Also, optimal transparency and traceability is required to avoid biases and to make it clear how the prioritization is developed (Eisenführ et al., 2010).

An MCDA allows to integrate different types of technical information, which can be complemented with subjective interpretations of experts or decision makers in a structured manner (Linkov & Moberg, 2011). MCDA frameworks are increasingly used in water management, due to increased complexity of the problems and the urge for transparency in the decision-making process (Huang, Keisler, & Linkov, 2011). The advantage of using the MCDA technique is that various types of criteria can be integrated in one prioritization method.

An MCDA provides a framework to systematically address decision-making problems. The first main component is to specify the policy problem and frame the objective of the decision analysis. The second step is to collect relevant technical information about the problem. Thereafter, technical information and expert knowledge is combined to formulate criteria, and the experts are questioned about the importance of the different criteria. The last step of an MCDA is to assess how a set of alternatives scores on the formulated criteria. Alternatives are the variety of options that forms the input of the analysis, in this study the ECs are the alternatives. Systematic assessment of these ECs could support decision making.

Impact of climate change

The load and fate of contaminants in the aquatic environment in the future is likely to be influenced by climate change (Noyes et al., 2009; Sterk et al., 2013). There are multiple scientific articles that show a relation between climate change and the occurrence of ECs. For example, already in the 1990s, Patz et al. (1996) recognized that climate change influences the emergence of infectious diseases, among others by an increased water temperature. More recently, climate change is also related to the emergence of chemical substances. For example, Richardson and Kimura (2017) argue that climate change can worsen the negative effects of ECs by concentrating them during droughts or enhancing resuspension during floods. Olson et al. (2017) mention climate change as a cause for the increase in algae and algal toxins in California. These studies show that the integration of climate change in a prioritization could be important for the relative risks of different contaminants.

There is only a small number of prioritization methods to date that integrates both climate change and the occurrence of ECs. Cox, Sanchez, and Revie (2013) published one of the few prioritization methods with incorporated climate change criteria, in which they designed a method to identify which infectious diseases are most likely to be influenced by changing in climate. Moreover, as far as known, there are no prioritization methods published that study the effect of climate change on the occurrence of ECs in surface or drinking water.

The effects of climate change on water quality likely vary per region. To design a prioritization method specifically to the Dutch drinking water production, the climate change effects in the Netherlands should be examined. However, limited research has focused on the impact of climate change on water quality in the Netherlands. Most studies have looked at the potential impact of droughts on water quality (Doomen et al., 2006; Van Vliet & Zwolsman, 2008; Zwolsman & Van Bokhoven, 2007). Empirical research on previous severe droughts in 1976, 1991 and 2003 showed a temporary deterioration of the water quality of the Rhine and the Meuse. The main effects included higher water temperature and an increased concentration of chloride and fluoride. On the other hand, the droughts had varying effects on the concentration of heavy metals, and nutrient levels were not significantly affected.

The negative impact of climate change on surface water quality is expected to lead to a degradation of the quality of drinking water produced from surface water (Delpla et al., 2009). Modeling studies suggest this applies to both chemical (Sjerps et al., 2017) and microbial contamination (Sterk et al., 2013). Therefore, this study examines the climate change effects that could be relevant to the occurrence of ECs in Dutch surface water and evaluates the added value of incorporating these effects into a futureproof prioritization method for emerging risks to drinking water quality.

Because the most noticeable impacts of climate change are related to surface water quality, this research focuses specifically on drinking water processed with surface water. However, approximately two thirds of Dutch drinking water is produced with groundwater. Previous research has shown that climate change also has a negative effect on groundwater quality, but until now there is only limited data available (Lapworth et al., 2018; Treidel, Martin-Bordes, & Gurdak, 2011).

Methodology

Research strategy

The goal of this study is to assess the added value of integrating climate change criteria in a systematic and transparent prioritization method for emerging risks to drinking water quality, and to evaluate the effects of these criteria on a ranking of emerging chemical and microbial contaminants. To achieve this goal and to answer the research questions as presented on page 7, three consecutive phases were formulated.

The first phase of the study consisted of desk research to identify the most dominant effects of climate change on surface water quality in the Netherlands (RQ.1). In the method development phase, the identified most dominant effects were used to formulate climate change criteria (RQ.2), which were then used to develop a prioritization method for emerging risks to drinking water quality (RQ.3). Finally, the implications of integrating climate change into the prioritization method on a possible ranking of emerging contaminants were assessed (RQ.4). Figure 1 provides a schematic overview of the three phases and presents the main components of each phase, which are further elaborated in the sections below.

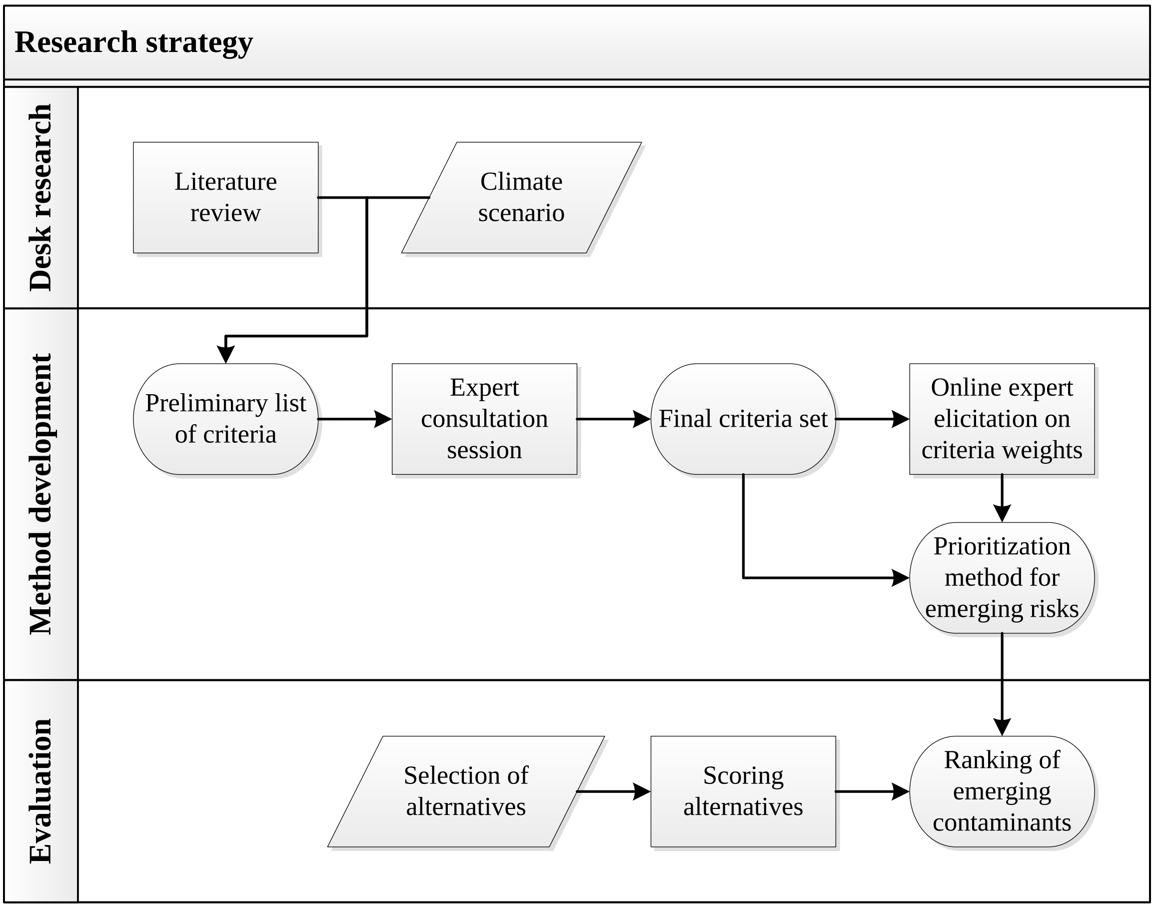

Figure 1. Synopsis of the research strategy divided over three main phases. The squared boxes represent processes, the parallelograms are information inputs and the rounded boxes are (preliminary) outcomes.

Phase 1. Desk research

Literature review

A literature review was used to identify worldwide observed or modeled effects of a changing climate on surface water quality. The scientific articles provided information on the impact of climate change on physico-chemical and biological parameters of the aquatic environment, such as changes in dissolved oxygen level, photo-activation and eutrophication (Wilby et al., 2006). These water quality parameters can in turn increase or decrease the concentration of ECs in the aquatic environment.

The search was conducted in the Scopus® database. Scopus was chosen as it is the world's largest database of peer reviewed literature (Falagas et al., 2008). Figure 2 shows the search query used. No requirement was added for the publishing year of the articles. With an eye on time efficiency, while still collecting as much relevant information as possible, it was decided to specify the search query to review articles. The search was not exclusively focused on the Netherlands to diminish the chance that important information was missed, because it might be possible that a specific effect has not yet been described for the Dutch situation.

A review article was included in the analysis in case it was written in English, and if it discussed an empirical, experimental or modeled impact of climate change on water quality. This could either be a physical, chemical or biological aspect of water quality. The relevance was assessed by reading through the abstract of the articles, and if necessary, scanning the main text. All the effects of climate change on water quality discussed in the relevant scientific literature were summarized in a mind map.

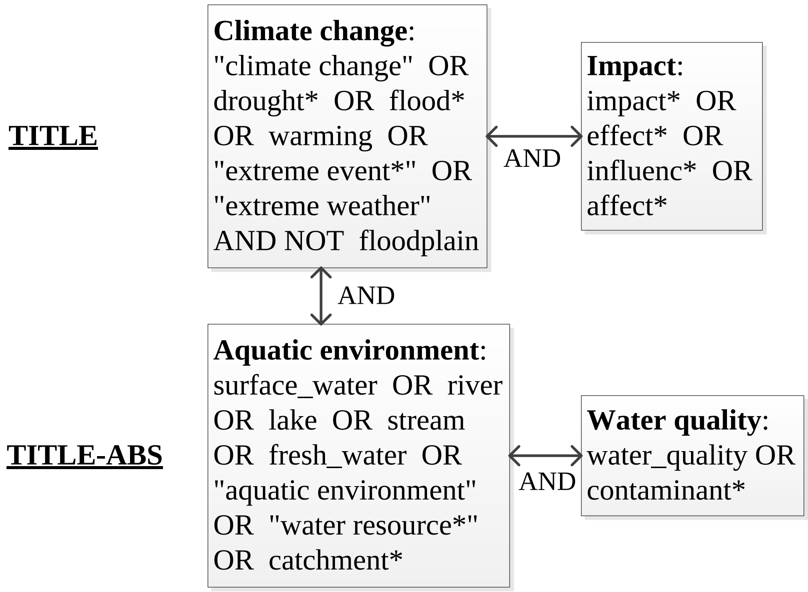

Figure 2. Keywords used for the Scopus® literature search on review articles about the effects of climate change on surface water quality (* are truncated words and words connected with a _ can either be spelled separately or as one word). The terms related to 'climate change' and 'impact' have to be in the title of the article, and terms related to 'aquatic environment' and 'water quality' had to be mentioned in the abstract.

Relevance to Dutch surface water quality

The worst-case Dutch climate scenario (W_H) of the Royal Netherlands Meteorological Institute (KNMI) was used to determine which of the global climate change effects on surface water quality found in the literature could be considered most dominant for the Netherlands. The W_H scenario consists of a relatively large global temperature rise of 3.5 °C in 2085 with respect to the climate in the reference period (1981-2010). Global climate change has major consequences for the weather conditions in the Netherlands. In general, precipitation will increase, the winters will become milder and the summers hotter (KNMI, 2014).

The UN Framework Convention on Climate Change (Art. 1) defines climate change as an addition to natural climate variability (IPCC, 2014). Therefore, if the scenario change is smaller than the natural variation, the effect was not considered dominant in the Netherlands. The main scenario changes of the W_H scenario and the corresponding natural variation are presented in Table 1. In addition, secondary literature was used to obtain a better understanding on the issues found in the literature review that were not discussed in depth in the climate scenario.

Table 1. A selection of modeled climatic changes of the W_H scenario for 2085 in comparison to the natural variation (KNMI, 2014). In case the scenario change for 2085 is smaller than the natural variation, it is not considered a dominant effect of climate change in the Netherlands.

1. Climate variable	**2. Indicator**		**3. Climate 1981-2010 (reference)**	**4. Scenario changes for 2085**	**5. Natural variation**	**6. Dominant effect?**
Temperature	Year	Mean	10.1 °C	**+3.7 °C**	± 0.16 °C	Yes
	Winter	Mean	3.4 °C	**+4.1 °C**	± 0.48 °C	
	Summer	Mean	17.0 °C	**+3.7 °C**	± 0.25 °C	
Precipitation	Year	Mean amount	851 mm	**+7 %**	± 4.2 %	Yes
	Winter	Mean amount	211 mm	**+30 %**	± 8.3 %	
	Summer	Mean amount	224 mm	**–23 %**	± 9.2 %	
		Number of wet days	43 days	**–16 %**	± 6.4 %	
		Max. hourly intensity	15.1 mm/hour	**+22 to +45 %**	± 14 %	
Sea level	Absolute level		3 cm above NAP	**+45 to +80 cm**	± 1.4 cm	Yes
Solar radiation	Radiative forcing		354 kJ/cm^2	**+1.4 %**	± 1.6 %	No

Phase 2. Method development

The desk research showed the expected impact of a changing climate on the water quality of Dutch surface water bodies. The most dominant effects of climate change helped to formulate climate change criteria to integrate in a prioritization method for emerging risks to drinking water quality. The development of the prioritization method for emerging risks to drinking water quality required information from scientific literature complemented with expert knowledge, since merely using the available technical information is not sufficient.

Preliminary list of criteria

The desk research provided insights into what effects climate change is expected to have on physico-chemical and biological water quality parameters of surface water. The prioritization criteria are based on the impact of these parameters on the exposure potential of ECs in the aquatic environment. The water quality parameters were translated into climate change criteria which were used to develop a prioritization method for ECs.

The prioritization method only incorporates distinctive criteria that do not affect all contaminants to the same extent. Effects that increase the risk of all contaminants were not included in the prioritization method as the goal of the prioritization was not to quantify the total risk of the emerging contaminants, but to provide insight to the relative importance of the different ECs (Spiesman & Speight, 2014). The final prioritization method therefore does not provide information about an increase in the absolute risk of ECs due to climate change.

Expert consultation session

The preliminary list of criteria was discussed in an expert consultation session. During this session, a group of (drinking) water experts was invited to think about possible climate change criteria that should be included in the prioritization method. The experts were invited because of their expertise in chemistry or microbiology, and their experience in the field of climate change.

The expert consultation session started with a short introduction on the program and goal of the session, a short explanation of what a Multi-Criteria Decision Analysis entails and what is meant with the term criteria. The introductory information was kept to a minimum, to prevent the experts from being forced into a certain line of thinking (Krueger et al., 2012). By asking open questions to the experts without giving much introductory information, experts could think of issues that did not come up in the literature review.

First, the experts were invited to individually brainstorm about which climate change issues influence the risk posed by a substance or microorganism to humans via exposure to drinking water. Thereafter, the experts discussed the criteria they had formulated in groups of six. The proposed criteria were grouped by theme on a poster to provide a clear overview. A plenary debate gave the experts the opportunity to discuss the most striking differences between the criteria formulated by the experts and the criteria of the literature review. Lastly, the consultation session was concluded by asking the experts to give individual (written) feedback on and suggestions for the preliminary list of criteria.

Final criteria selection

The final list of criteria was established by adjusting the preliminary list of criteria with the feedback of the experts. The criteria had to satisfy the following four requirements: I) the criterion should be related to a significant change in the climate scenario, II) the criterion can distinguish between different contaminants, III) the environmental change that underlies the criterion had to be of sufficient magnitude to be relevant to at least a number of contaminants, and IV) the criterion is a direct effect of a changing climate. Indirect effects of climate change, for example changes in species distribution or increased reuse of water, were avoided for clarity and accountability.

Online expert elicitation

Expert knowledge was used to determine the relative importance of the seven final prioritization criteria. The elicitation process was carried out with the Pairwise Comparison (PC) technique via the online software tool *1000Mind*. The PC elicitation technique is seen as reliable, since respondents only have to compare two options at a time and the individual consistency can be checked (Tayyar & Durmu, 2017). Furthermore, online individual elicitation makes it easier to ask standardized questions, and it gives the experts the opportunity to respond in their own time (Krueger et al., 2012).

The same experts that were invited to the consultation session were approached for the online survey. The experts were asked to make a number of tradeoffs based on their expert knowledge. The tradeoffs of the experts were analyzed with the PAPRIKA method of the *1000Minds* tool, which reduced the number of hypothetical tradeoffs that are asked to the experts due to implicit ranking by transitivity (Hansen & Ombler, 2008). In other words, if the experts gave consistent answers, the *1000Minds* tool had to ask fewer questions, making the survey less time-consuming for the experts.

The repetitive question of the survey was: Which of these two hypothetical contaminants could pose the highest risk to the production of drinking water in the Netherlands under the W_H climate scenario? The experts had to choose several times between two hypothetical contaminants with two intrinsic properties. These properties corresponded to the final criteria set. The number of criteria on the final list determined the number of tradeoffs that the experts had to make. From the tradeoffs made by the experts it was possible to deduce which criteria the experts considered important.

The analysis of the results of the survey was executed in Microsoft Excel. The individual expert values were combined into an arithmetic mean and normalized to criteria weights on a scale from zero to one.

In addition, the level of agreement among the experts was assessed with the Kendall's coefficient of concordance W (Kendall & Smith, 1939):

$$W = \frac{12S}{m^2(n^3-n)} \tag{1}$$

In Equation 1, *n* criteria are ranked by *m* respondents and *S* stands for the sum of squares of deviations. If *W* equals 1, there is absolute consensus across the respondents. An outcome of 0 indicates that the answers of the experts are completely unrelated.

Design of prioritization method

The prioritization method for emerging risks to drinking water quality consisted of the final climate change criteria with the associated weights. In addition, a sub-objective was formulated for each criterion in support of the main objective, which is to identify the contaminants with an increased exposure potential due to climate change. Eisenführ et al. (2010) argue that dividing an objective into sub-objectives ensures a more concrete formulation and an enhanced measurability. All criteria are coupled to a certain climate variable of the climate scenario (W_H) to indicate the expected magnitude of the change.

Finally, scoring levels were formulated per criterion to score the contaminant on the criteria. The scoring levels are dichotomous; a contaminant can score either 0 or 1. If the contaminant scores 1, the exposure potential of the contaminants is increased due to that criterion, and thus poses a higher risk to drinking water quality. The criterion scores of a contaminant are aggregated by an additive value function (Eisenführ et al., 2010):

$$v(x_1, x_2, \dots, x_i) = \sum_{i=1}^{n} w_i v_i(x_i) \tag{2}$$

The total score of the contaminant v is derived by adding the products of the weights w_i and scoring level v_i on each criterion x. The highest scoring contaminants are expected to have the highest increase in exposure potential due to climate change. Note that a contaminant with a total score of zero is not necessarily unaffected by climate change. It only indicates that the relative concentration of that contaminant does not increase with respect to the concentration of other contaminants due to climate change, since the prioritization method only refers to the relative risk of the contaminants.

Phase 3. Evaluation

The implications of integrating climate change criteria in a prioritization method for emerging risks to Dutch drinking water quality were assessed by prioritizing a selection of ECs. It was evaluated which groups of contaminants received the highest scoring and which criteria were the determining factor in the order of the contaminants ranking.

Selection of emerging contaminants

The prioritization method with the climate change criteria was tested on two already existing lists of emerging contaminants, namely the microbial contaminants from the Contaminant Candidate List of the US Environmental Protection Agency (Environmental Protection Agency, 2016), and a list of 42 emerging chemical substances of the Dutch National Institute for Public Health and the Environment (RIVM) (Van Leerdam et al., 2018). A selection of contaminants was ranked with the climate change criteria. The selection was based on data availability.

Emerging contaminants scoring

The *1000Minds* software tool was used to calculate the total scores of the selected contaminants using the additive value function (Eq. 2). The information sources for scoring the contaminants included research reports (Acha & Szyfres, 2001; Moermond et al., 2016; Van der Wielen & Van der Kooij, 2009; Van Leerdam et al., 2018), the SimpleTreat 4.0 simulation model, the REACH database, the Global Water Pathogen Project and scientific literature. Finally, the ranking is visualized with Microsoft Excel and the implications are summarized to evaluate the added value of integrating climate change criteria in a prioritization method for emerging risks to drinking water quality.

Results

Phase 1. Desk research

In the first research phase, scientific literature was reviewed to find out all potential effects of climate change on water quality. A Dutch climate scenario was then used to assess which global effects can also be relevant to surface water in the Netherlands.

General water quality impacts

The Scopus® search query resulted in 21 scientific review articles (run on June 18, 2019). In Appendix 1, the articles are briefly discussed in alphabetical order. Four articles were excluded from further analysis, namely Hamilton, Stamp, and Bierwagen (2010), Misra (2013), Teshager et al. (2016) and Xia, Wu, and Mou (2012). Hamilton et al. (2010) only studied the effects of climate change on the occurrence of macroinvertebrates; Misra (2013) did not specify any effects of climate change on water quality; Teshager et al. (2016) intertwined the effects of climate change with land use change; and the review paper of Xia et al. (2012) was written in Chinese.

The remaining seventeen relevant scientific review articles all addressed one or more effects of climate change on physico-chemical or biological water quality parameters. The articles mentioned a wide range of climate change effects, which are subdivided over six main climate variables, namely temperature (n=16 articles), precipitation (n=14), drought (n=12), solar radiation (n=6), freshwater acidification (n=3) and sea level rise (n=2).

The identified climate variables are the drivers of change in surface water quality. All the water quality impacts discussed in the literature are presented in Figure 3, where the numbers behind the effects refer to the articles as listed in Appendix 1. The following paragraphs discuss the effects of the six climate variables on surface water quality.

Increased temperature

All but one of the analyzed articles discussed the impact of a rising air temperature on the water quality. Several articles mentioned the increase in biogeochemical process rates (or similar terminology) and the related change in reaction kinetics due to a higher water temperature (Anawar, 2013; Carere, Miniero, & Cicero, 2011; Delpla et al., 2009; Mosley, 2015; Rehana & Mujumdar, 2013; Whitehead et al., 2009). Most important physicochemical changes are a decrease in DO level, slight increase in pH level and enhanced mineralization of organic matter (Anawar, 2013; Carere et al., 2011; Delpla et al., 2009; Johnson et al., 2009; Lake, 2003; Miller & Hutchins, 2017; Mosley, 2015; Park et al., 2010; Rehana & Mujumdar, 2013; Whitehead et al., 2009). Another frequently mentioned impact of higher water temperature was the boosted microbial and algae growth (Delpla et al., 2009; Johnson et al., 2009; Lipczynska-Kochany, 2018; Mosley, 2015; Park et al., 2010; Pinkney et al., 2015; Ritson et al., 2014; Wade, Rance, & Reynard, 2013; Whitehead et al., 2009). This could in turn cause a spread of water-borne diseases, but also increase the microbial degradation of chemical substances (Ahmed et al., 2016;

Anawar, 2013; Delpla et al., 2009; Wade et al., 2013). Finally, both Lipczynska-Kochany (2018) and Ritson et al. (2014) mentioned the increase in concentration of dissolved organic matter, which can stimulate again microbial growth and biodegradation.

Figure 3. The effects of climate change on physical, chemical or biological parameters of water quality, as discussed in the relevant scientific review articles. The numbers between brackets mentioned behind the effects refer to the number of the review articles as listed in Appendix 1.

Increased precipitation

Regarding the increase in precipitation and subsequent runoff, many scientific articles mentioned that more material is likely to be (re)mobilized from diffuse sources, like agricultural fields and roads

(Ahmed et al., 2016; Carere et al., 2011; Delpla et al., 2009; Lipczynska-Kochany, 2018; Miller & Hutchins, 2017; Mosley, 2015; Whitehead et al., 2009; Young, Smith, & Fazil, 2015). This remobilized material includes nutrients and organic matter, which could in turn lead to eutrophication, deoxygenation, changing of the water color and taste, and an increased risk of the formation of disinfection by-products (Delpla et al., 2009; Johnson et al., 2009; Mosley, 2015; Park et al., 2010; Pinkney et al., 2015; Ritson et al., 2014; Soh, Roddick, & Van Leeuwen, 2008; Whitehead et al., 2009). In addition, the increased amount of runoff could cause increased overflow of combined sewer systems (Wade et al., 2013; Whitehead et al., 2009; Young et al., 2015). In case of heavy rainfall, combined sewers directly discharge surface water runoff mixed with (untreated) sewage water into surface water. Lastly, Young et al. (2015) argued that an increase in the amount of water in the sewage can lead to a lower efficiency of sewage treatment plants.

Increased drought

With respect to the impact of drought and lower river discharges on water quality, the decreased dilution capacity of rivers and lakes leading to increased concentrations of substances and microorganisms was most often discussed in the literature (Anawar, 2013; Johnson et al., 2009; Lake, 2003; Miller & Hutchins, 2017; Mosley, 2015; Rehana & Mujumdar, 2013; Ritson et al., 2014; Whitehead et al., 2009; Young et al., 2015). On the contrary, multiple articles argued that a low river discharge and resulting reduced flow velocity enhances internal river processes like assimilation, adsorption, complexation and suspension, which could decrease the concentration of certain pollutants (Delpla et al., 2009; Mosley, 2015; Young et al., 2015). In addition, there are several water quality effects that were mentioned by just one or two articles, such as increased denitrification (Mosley, 2015; Whitehead et al., 2009), accumulation of dissolved organic matter (Lake, 2003; Ritson et al., 2014), cyanobacterial growth (Soh et al., 2008; Whitehead et al., 2009) and decreased dissolved oxygen (DO) level (Pinkney et al., 2015).

Increased solar radiation

The increase in penetration of solar radiation in the upper layer of freshwater bodies leads to enhanced degradation (photolysis) and transformation of chemical substances and organic matter (Delpla et al., 2009; Lipczynska-Kochany, 2018; Ritson et al., 2014; Soh et al., 2008). Furthermore, Anawar (2013) argued that the photo-enhanced toxicity of substances is altered by climate change, and Johnson et al. (2009) stated that UV radiation reduces enteric virus inactivation times.

Freshwater acidification

Two articles mentioned the impact of acidification on water quality parameters. Pinkney et al. (2015) showed that acidification might result in more algae blooms and lower DO level, and Mosley (2015) argued that acidification can lead to a decreased dissolved organic carbon level.

Sea level rise

Two articles discussed the effect of salt water intrusion and the subsequent salinization of freshwater surface bodies. Salinization might compromise the freshwater availability (Wade et al., 2013), since the maximum permitted chloride concentration in drinking water is 150 mg/L (Drinkwater Platform, 2019). Moreover, Ahmed et al. (2016) argued that the growth of pathogens is restrained in case of salt water intrusion.

Most dominant effects on Dutch surface water quality

The Dutch worst-case climate scenario determined which global climate change effects as discussed in the scientific literature are also applicable to the Netherlands. A change in climate conditions is only considered dominant when the scenario change exceeds the potential natural variation. The scenario changes and natural variation for each climate variable, and the resulting determination of dominance is presented in Table 1, column 6 (see page 13).

The W_H climate scenario includes a significant mean temperature rise of 3.7 °C in the Netherlands in 2085, which is clearly more than the natural variation of 0.16 °C (see Table 1 for all scenario changes) (KNMI, 2014). Therefore, the effects of temperature rise on water quality as discussed in the literature can be designated as relevant for the Netherlands.

Concerning the precipitation pattern, the climate scenario shows a seven percent overall increase in precipitation, due to an increase in (heavy) rainfall during winter. The amount of precipitation in summer will considerably decrease, while the maximum hourly intensity of summer rainfall events is expected to increase a lot (KNMI, 2014). The major scenario changes indicate that the effects of increased precipitation and drought found in the literature review also apply to the water quality in the Netherlands.

According to the W_H scenario, the increase in solar radiation in the Netherlands does not significantly differ with the natural variation in radiation (+ 1.4% respectively ± 1.6%). Therefore, the effects on water quality related to increased solar radiation are disregarded in this study, since the possible increase in incoming radiation cannot be considered a part of climate change in the Netherlands.

Acidification is not included in the climate scenarios of the KNMI, because the acidification of freshwater resources is a rather new field of research. Recent research showed that increased levels of CO_2 in the atmosphere can cause a decrease in pH level in freshwater lakes and reservoirs similar to oceans (Weiss et al., 2018). However, the W_H scenario does not provide information about this effect. Therefore, acidification is included on the preliminary list of criteria, so the relevance of acidification to water quality in the Netherlands can be discussed during the expert consultation session.

The W_H scenario includes a sea level rise up to 80 cm above NAP, while the natural variation is 1.4 cm (KNMI, 2014). The sea level rise is likely to result in a significant increase in salt water intrusion, which presents a threat to drinking water production in the western part of the Netherlands (Deltacommissaris, 2019). However, the result of salinization is not discussed in the climate scenario, so the relevance of this climate variable is also further discussed with the experts.

In conclusion, temperature, precipitation and drought are clearly dominant climate variables to consider in relation to water quality. These three issues are mentioned in almost all reviewed scientific articles and the W_H scenario confirms significant changes in the Netherlands. Due to the small scenario change, the climate variable of solar radiation is not considered a dominant effect of climate change on the surface water quality in the Netherlands and was excluded from further analysis. The impact of freshwater acidification and sea level rise is less frequently discussed in the literature and also the W_H scenario provides little information about these issues. The relevance of these two issues is discussed during the expert consultation session.

Phase 2. Method development

In the second research phase, a prioritization method was developed with climate change criteria to rank emerging risks to drinking water quality in the Netherlands. By combining information from scientific literature and expert knowledge, a set of climate change criteria, sub-objectives and scoring levels was formulated.

Preliminary list of criteria

The water quality effects related to the climate variables of temperature, precipitation, drought, acidification and sea level rise were translated into criteria. The criteria indicate the impact on the exposure potential of the ECs. Table 2 presents the list of eight preliminary criteria that were formulated.

Table 2. The preliminary list of criteria per climate variable. The effect climate change on the exposure potential of a contaminant is determined by these criteria. For example, the criterion 'higher water temperature' aims to identify contaminants that are likely to occur more due to an increased water temperature, such as microorganisms that prefer warmer environments.

Climate variable	Criterion
Increased temperature	Higher water temperature
	Decreased DO concentration
Increased precipitation	Increased runoff
	Increased nutrient loading
Increased drought	Reduced dilution capacity
	Decreased flow velocity
Freshwater acidification	Decreased pH level
Sea level rise	Increased salinity

Air temperature is the determining factor for water temperature. An increase in air temperature cannot be directly translated into a higher water temperature; normally water warms less than the air temperature rise (Badde et al., 2014; Van Vliet et al., 2013). A conservative estimate that the water temperature rises by two third of the increase in air temperature, results in a water temperature rise of approximately 2.5 to 2.7 °C after a temperature rise of 3.7 °C in summer and 4.1 °C in winter. Water temperature is a determining factor for the concentration and fate of both chemical and microbial contaminants. Relevant processes are, for example volatilization, degradation or microbial growth (Delpla et al., 2009; Noyes et al., 2009).

A secondary effect of an increased water temperature is a decrease of the saturation concentration of dissolved gases. The saturation concentration of dissolved oxygen (DO) decreases with approximately ten percent if the water temperature increases with 3 °C (Cox & Whitehead, 2009; Delpla et al., 2009). In this study, the reduction of DO concentration was estimated between five and ten percent. A lower oxygen availability has in particular effect on the microbiological contamination, because the survival of different pathogen groups strongly depends on the amount of dissolved oxygen in the water (Cabral, 2010).

The research institute Deltares calculated the consequences of the precipitation changes for the discharges of the Rhine and the Meuse, and they argued that the discharge regimes of both rivers is likely to become more extreme, with significant higher discharges in winter and (very) low discharges in summer (Klijn et al., 2015). A precipitation increase of seven percent would approximately lead to a similar increase in runoff, allowing more contaminants to end up in the aquatic environment. In addition, the runoff could increase the nutrient loading of the rivers, which could affect the growth of microorganisms and algae.

The increased chance of drought was translated in two criteria. On the one hand, drought leads to a reduced dilution capacity of the river, so the concentrations of all contaminants that are discharged from point sources into the river become higher. On the other hand, the flow velocity of the river decreases, which results in a longer period for contaminants to degrade, for example by assimilation of nutrients or adsorption of heavy metals on suspended matter (Delpla et al., 2009; Whitehead et al., 2009).

A recent study has shown that freshwater acidification has led to a decrease in pH level in four German lakes of 0.3 between 1981 till 2015 (Weiss et al., 2018). However, the rate of acidification on the long-term is still very uncertain, and it is further investigated whether this observed effect is a global phenomenon. The pH level is particularly relevant for the behavior of ionizable substances in water (Rendal, Kusk, & Trapp, 2011).

The rapid sea level rise is an important water safety issue for the Netherlands, and also the availability of freshwater for the production of drinking water and agriculture is under pressure due to the increasing saltwater intrusion (Van den Brink et al., 2019). The increase in salinity is closely related to subsidence and drought, which is expected to occur more according to the climate scenario (Wessels et al., 2019). An extreme drought could result in a salinity up to 190 mg/L in the surface waters closer to the coast (Drinkwater Platform, 2019). The chloride concentration can affect the solubility of non-polar compounds and the survival of microorganisms (Schwardzenbach, Gschwend, & Imboden, 2003; Virto et al., 2005).

Experts' adjustments

The expert consultation session consisted of a group of 22 experts with either a background in chemistry (15) or microbiology (7). They are employed in different parts of the drinking water sector, for example research institutes, drinking water companies, the RIVM and Rijkswaterstaat. A complete list of consulted experts is presented in Appendix 2. The experts were asked to provide feedback on the preliminary list of criteria as presented in Appendix 3, which is a more detailed version of Table 2.

The expert consultation session provided multiple important adjustments to the preliminary list of criteria. Firstly, there was a broad consensus about including three additional criteria into the prioritization method: I) combined sewer overflow, II) increased temperature in the drinking water distribution network, and III) climate change adaptation. The combined sewer overflow (CSO) criterion was suggested by the experts because combined sewer systems are likely to discharge more untreated sewage water into surface water, due to increased frequency of heavy rainfall events. The increased temperature in the distribution network was proposed because potential growth of pathogens in the distribution pipes increases the risks of those ECs to safe drinking water. Lastly, the experts advised to include a criterion related to adaptation in the prioritization method. The experts argued that adaptation to climate change could lead to increased use of certain products, such as pesticides or pharmaceuticals. Although this is a secondary effect of climate change, many experts were convinced it is an important issue to include in the prioritization method. After reviewing relevant scientific literature on these three topics, the three proposed criteria were indeed added to the prioritization method.

Some minor modifications were proposed by the experts about the formulation of certain criteria. In particular, many experts argued that the decreased dilution capacity was also important to contaminants from diffuse sources. Several experts also mentioned that increased precipitation does not only lead to more runoff from land, but also to increased resuspension of contaminants that are precipitated on sediment. After verification with scientific literature, these adjustments were all implemented in the prioritization method.

Furthermore, a large number of experts questioned the relevance of the criteria of DO concentration, nutrient loading, pH level and salinity. Indeed, follow-up research indicated that there is considerable uncertainty about the relation between temperature and nutrient availability (Xia et al., 2016). Cox and Whitehead (2009) showed that the decrease in DO concentration due to climate change is very small. The processes related to freshwater acidification require more research and the direction of change in pH in uncertain (Delpla et al., 2009). Moreover, although the chloride level could rise above the established drinking water standard (190 mg/L respectively 150 mg/L), it does not have a significant effect on the fate of contaminants (Schwardzenbach et al., 2003). In conclusion, the questions of the experts in combination with the uncertainty displayed in scientific literature led to the exclusion of the preliminary criteria concerning nutrient loading, DO concentration, pH level and salinity from the prioritization method.

The experts suggested also other criteria, such as ‘increased human susceptibility’, ‘change in species composition’, ‘increased reuse of water’ and ‘decreased efficiency of water treatment’. These suggestions were not accepted, because these criteria do not distinguish between contaminants or the direction and magnitude of change is uncertain. Also, proposed criteria that could not be linked to the climate scenario were excluded, for example a ‘change in ocean circulation pattern’ and an ‘increased influx of climate refugees’. If more information about these subjects would become available, it could be considered to include them in the prioritization method.

Final criteria set

The final list of criteria consisted of seven criteria, which were divided over three climate variables, namely temperature, precipitation and drought. All seven criteria were related to a significant scenario change as found in the W_H scenario. Figure 4 presents the conceptual model for the prioritization method with the scenario changes of the W_H scenario and the scenario-based criteria.

The ‘decreased flow velocity’ criterion of the preliminary list was ultimately not included in the final list, because the magnitude of the criterion could not be sufficiently quantified. Wuijts et al. (2013) mention a travel time in the order of 1 km per day for the Meuse during a drought, but it is unrealistic to give a generic travel time for all surface water bodies in the Netherlands. Therefore, it was difficult to quantify the effect of a longer travel time on the exposure potential of emerging contaminants in this study and the criterion was excluded from the prioritization method.

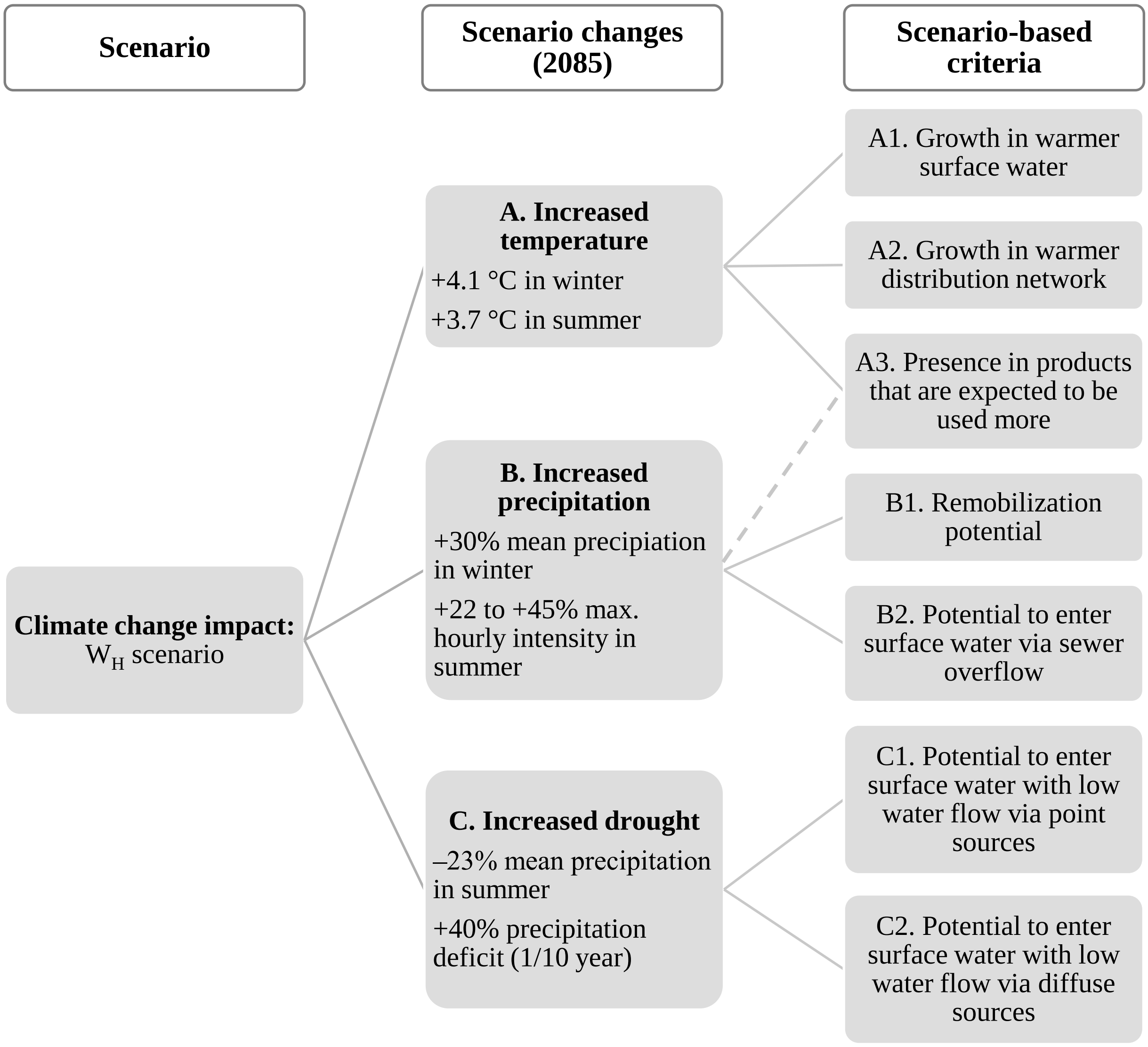

Figure 4. Conceptual model for the prioritization of emerging contaminants in drinking water. The scenario changes relate to the W_H scenario of the KNMI with values for the climate around 2085 (KNMI, 2014).

The main objective of the prioritization method is to identify the contaminants with an increased exposure potential due to climate change. The criteria have associated sub-objectives to specify the aim of the criteria and to support the main objective. All sub-objectives aim to identify contaminants that are likely to occur more in surface or drinking water. In the following paragraphs, the criteria that are included on the final list are discussed in detail and the sub-objective of each criterion is specified.

A1. Growth in warmer surface water

Criterion A1 aims to identify microbial contaminants that are likely to grow in surface water with an increased average temperature of 2.5 °C. Whether a microbial contaminant (mainly bacteria and protozoa) is able to grow depends on the growth temperature range and nutrient dependency of the pathogen, which can be examined with scientific literature.

Although the persistency of chemicals is also affected by temperature, the focus of the criterion is on microorganisms, since a water temperature rise of a couple degrees is not likely to have a notable impact on the solubility of chemical substances (Dickhut, Andren, & Armstrong, 1986; Shiu et al., 1997). A secondary effect of a higher water temperature could be increased biodegradation of certain chemicals (Noyes et al., 2009), but this effect is not taken into account in this study.

A2. Growth in warmer distribution network

Criterion A2 is similar to A1, but this criterion concerns the rise in water temperature in the drinking water distribution network. The distribution network refers to the entire system of pipes, pumps, valves and storage tanks that distribute the drinking water from the treatment plant to the houses of consumers. A temperature above 25 °C in the distribution network could enhance the growth of certain bacteria and protozoa. This could be hazardous to Dutch drinking water quality, since the water is distributed without additional disinfectants. According to a modeling study of the research institute KWR, there will be an additional seven days on which the temperature in the distribution network exceeds 25 °C in the W_H scenario (Agudelo-Vera et al., 2015).

A3. Presence in products that are expected to be used more

Although the focus of the prioritization method is on direct effects of climate change on the exposure potential of ECs, criterion A3 is a secondary effect as it concerns climate adaptation. Incorporation of the criterion was emphasized by the experts during the consultation session. Criterion A3 identifies contaminants that are expected to be used more due to human adaptation to climate change in agricultural practices and pharmaceutical use.

Two extensive review articles by Boxall et al. (2008) and Noyes et al. (2009) showed that temperature rise potentially leads to alterations in pathogen distributions and increased risk of pests. The authors argue that this is likely to result in an increased use of plant protection products, veterinary medicines and antihistamines. In addition, the incidence and pattern of human diseases is expected to change. Illnesses that are likely to occur more due to climate change are for example cardiovascular and respiratory diseases, but also the risk of mental problems increases. The change in disease pattern could increase the use of certain pharmaceuticals, which are mentioned in the study of Redshaw et al. (2013).

B1. Remobilization potential

The objective of criterion B1 is to identify contaminants that are likely to be remobilized and transported to the main river system after a rainfall event. This applies both to more runoff of contaminants that are present on paved or unpaved surfaces (for example roads and agricultural fields), and to the resuspension of contaminants from riverbed sediment. Even though rainfall simultaneously results in dilution of the contaminants in the system, some contaminants are more affected by the increased remobilization than others.

Chemical substances with a log K_{ow} between 1.0 and 4.5 are considered to be more likely to be remobilized after a rainfall event (Arp et al., 2017; Van Leerdam et al., 2018). Substances with a log K_{ow} lower than 1.0 are extremely hydrophilic, which suggests that these substances will never precipitate on land or sediment. Chemicals with a log K_{ow} above 4.5 are considered immobile and are not likely affected by the increased precipitation (Arp et al., 2017).

Microbial contaminants do not have a mobility scale, therefore only the potential presence of the pathogens in the environment is considered. If a pathogen is potentially present in soil, manure or other bio-solids, it is assumed that this pathogen is remobilized and transported to the main river system after a rainfall event (Venglovsky, Martinez, & Placha, 2006).

B2. Potential to enter surface water via combined sewer overflow

Criterion B2 concerns the increased occurrence of combined sewer overflows (CSO) due to climate change. In the Netherlands, approximately two thirds of all sewerage is still a combined system, which discharges untreated sewage water during heavy rainfall events. Therefore, a CSO can increase the entry of contaminants into surface water bodies (Sterk et al., 2016). Sterk et al. (2016) argue that the mean output flux of CSOs circa doubles in the W_H scenario around 2085.

The criterion aims to identify contaminants that are potentially present in sewage systems and are largely (>40%) removed in a simple wastewater treatment plant. A simple wastewater treatment plant consists of a primary settlement tank, an aeration tank with activated sludge and a third tank where the solids and liquids are separated. The removal of chemical substances can be calculated with the SimpleTreat 4.0 simulation model of the RIVM.

The removal rate of microorganisms during wastewater treatment is much more difficult to determine and for many contaminants there is limited data available. The removal of microorganisms is calculated in log reductions, but usually these are not known for individual pathogens (Leenen, 2015). The removal rate of *E. coli* and certain bacteriophages is often used as an indicator for the removal of bacteria and viruses respectively.

C1. Potential to enter surface water with low water flow mainly via point sources

The aim of criteria C1 and C2 is to differentiate between contaminants that are mainly discharged by point or diffuse sources into rivers with low flow conditions. Contaminants can have multiple and variable sources, but the criteria refer to the main source to prevent double counting. In case of a drought, contaminant influxes are diluted relatively little since the surface water bodies have low flow conditions. Point sources are defined by the European Environment Agency (EEA) as stationary emission locations with a fixed location, such as a municipal or industrial wastewater treatment plants (European Environment Agency, 2018).

C2. Potential to enter surface water with low water flow mainly via diffuse sources

The EEA describes contaminants from diffuse sources as contaminants with no specific point of discharge and no connection to treatment works. Examples of important diffuse sources are agriculture and urban surface runoff (European Environment Agency, 2018). When the most important source of a contaminant is the environment (soil or air) or animal manure, the source is defined as diffuse.

Prioritization method for emerging risks

To finalize the prioritization method for emerging risks to drinking water quality, the climate change criteria were linked to scoring levels. In addition, the relative importance of the criteria was translated into criteria weights with the aid of expert knowledge.

Scoring levels

Each criterion has two scoring levels (0 or 1) to indicate how a contaminant scores on the criterion. The levels are binary, which means that the exposure potential of the contaminant is either likely to increase (score 1) or unlikely to increase (score 0). A complete overview of the criteria with the associated sub-objectives and scoring levels can be found in Table 3.

Criteria weights

The online survey resulted in fourteen expert responses. This included nine experts with a chemical and five with a microbiological background. Among the fourteen experts, the coefficient of concordance was 0.238, which suggested that the level of agreement was relatively low (see Figure 5). Differences between the answers of chemical and microbiological experts were the most prominent in the criteria A2 (growth in warmer distribution network) and A3 (presence in products that are expected to be used more).

Figure 6 depicts the mean criteria weights according to the responses of the experts. In general, the fourteen experts indicated that the criterion concerning growth in a warmer distribution network received the highest weight, which could be because there is no more treatment after distribution. The criteria regarding contaminants from point sources and remobilization potential received relatively high weights from the experts. On the other hand, criteria about the combined sewer overflow and presence in products that are expected to be used more were weighted relatively low by the experts.

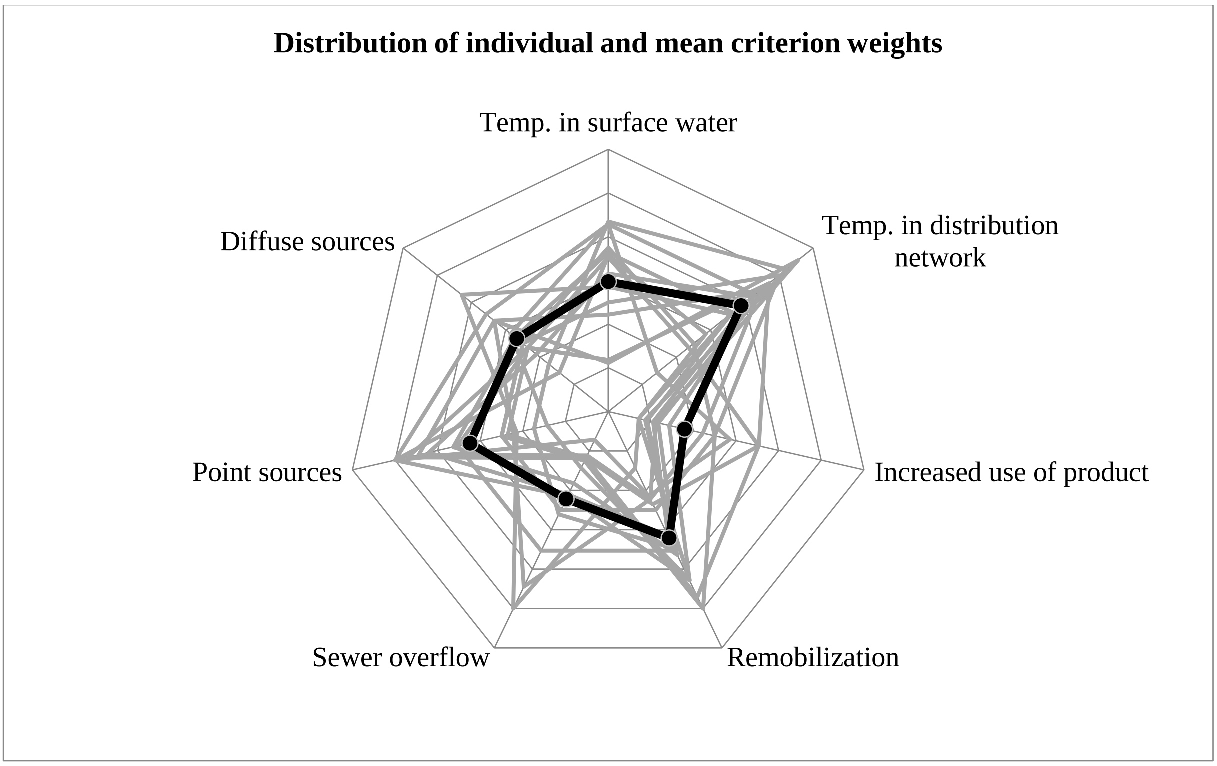

Figure 5. The distribution of the criteria weights of the individual experts (gray lines) and the arithmetic mean (thick black line). The spread of the gray lines indicates a relatively low level of agreement among the experts.

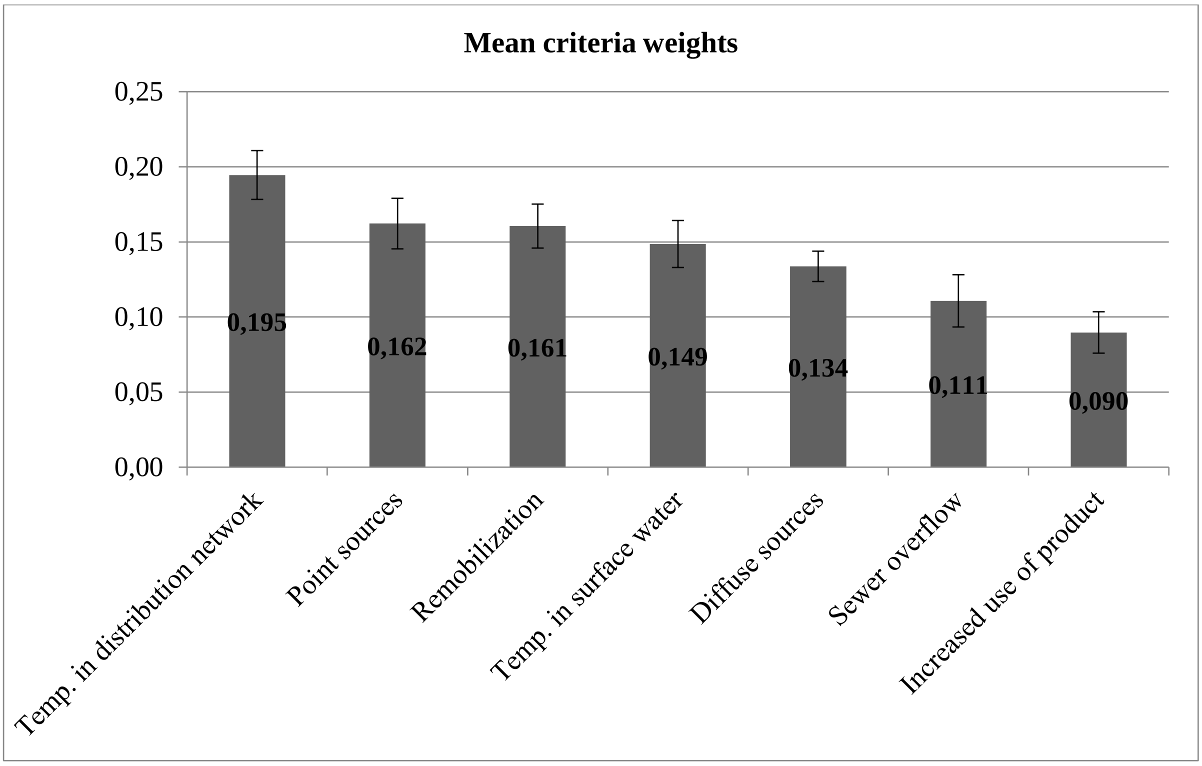

Figure 6. The arithmetic mean criteria weights as indicated by fourteen experts on a scale from zero to one. The higher the weight, the more important the criterion is according to the experts. The error bars display the standard error.

Table 3. Complete overview of the climate change criteria which can be integrated in a prioritization method for emerging chemical and microbial risks to drinking water quality. The abbreviation S.W. stands for surface water.

	Criterion	Sub-objective	Scoring levels	
			1	**0**
A1	**Growth in warmer surface water**	Identify contaminants that are likely to grow due to an increase in mean water temperature of 2.5 °C	Likely, growth of the microbial contaminant is reinforced in surface water with an increased temperature	Unlikely, contaminant is not affected by the temperature increase
A2	**Growth in warmer distribution network**	Identify contaminants that are likely to grow in the distribution network due to an additional 7 days of water temperatures between 25 and 28 °C	Likely, growth of the microbial contaminant is reinforced in a distribution network with an increased temperature	Unlikely, contaminant is not affected by the temperature increase
A3	**Presence in products that are expected to be used more**	Identify contaminants that are present in plant protection products, veterinary medicines or certain pharmaceuticals, which are likely to be used more	Yes, contaminant can be found in one or more of the products	No, contaminant cannot be found in any of the listed products
B1	**Remobilization potential**	Identify contaminants that are remobilized and transported to the main river system after a rainfall event	Likely, contaminant is able to be remobilized by runoff or resuspension after a rainfall event	Unlikely, contaminant is not affected by a rainfall event
B2	**Potential to enter surface water via combined sewer overflow**	Identify contaminants that are discharged on the surface water by combined sewer overflows, while under normal circumstances they are largely (>40%) removed in a simple WWTP	Yes, contaminant can be discharged by a CSO, while under normal circumstances it is largely (>40%) removed in a simple WWTP	No, contaminant cannot be discharged by a CSO, or is poorly (<40%) removed in a simple WWTP
C1	**Potential to enter S.W. with low water flow mainly via point sources**	Identify contaminants that are discharged by point sources during low water flow conditions	Yes, contaminant is mainly discharged by point sources (WWTP, industry)	No, contaminant is not mainly discharged by point sources
C2	**Potential to enter S.W. with low water flow mainly via diffuse sources**	Identify contaminants that are discharged by diffuse sources during low water flow conditions	Yes, contaminant is mainly discharged by diffuse sources (agricultural land, paved area)	No, contaminant is not mainly discharged by diffuse sources

Phase 3. Evaluation

In the third research phase, the prioritization method was used to rank a selection of chemical and microbial contaminants with the climate change criteria. The main implications of the criteria on the contaminant groups were evaluated. In particular, it was examined which groups of contaminants score high on the climate change criteria and which criteria were the determining factors in a possible ranking of emerging contaminants.

Ranking of emerging contaminants

To evaluate the impact of climate change criteria on a ranking of emerging contaminants, a selection of fifteen chemical and twelve microbial contaminants was ranked with the prioritization method. The chemical substances were taken from a RIVM report on 42 emerging substances that were detected with a concentration above 0.1 µg per liter in surface water (Van Leerdam et al., 2018). Fifteen chemicals were selected for the ranking based on data availability about mobility, removal rate and degradability. The microbial contaminants were taken from the US EPA Fourth Contaminant Candidate List, on which twelve pathogens are listed that are unregulated, "*but are known or anticipated to occur in public water systems*" (Environmental Protection Agency, 2016).

The ranking of the contaminants with the seven final criteria is presented in Figure 7, which shows that the climate change criteria are clearly distinctive between different contaminants. Furthermore, the twelve highest ranked contaminants consist of eight pathogens. In fact, the four highest ranked contaminants are pathogens: three bacteria and one protozoan.

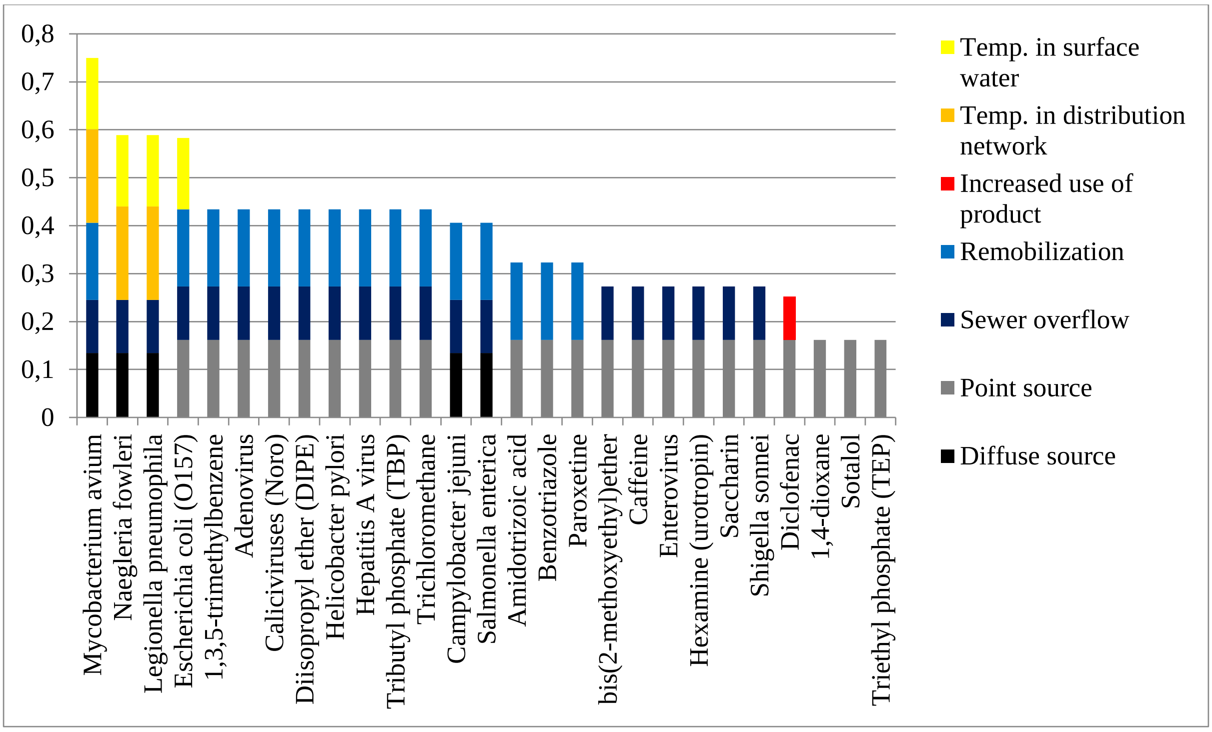

Figure 7. Ranking of chemical (n=15) and microbial (n=12) contaminants, by scoring the contaminants on the seven climate change criteria. The selection of contaminants was taken from a RIVM report and an EPA list (Environmental Protection Agency, 2016; Van Leerdam et al., 2018).

In order to score the selected chemical substances, multiple data sources were consulted. By design, the chemical substances did not score on the growth criteria. The main data source for the other criteria was the RIVM report on the 42 problematic substances (Van Leerdam et al., 2018). In addition, the SimpleTreat 4.0 model provided information about the removal rate in a simple wastewater treatment plant, supplemented with information about biodegradability from the REACH database. Information about the average removal rate of pharmaceuticals was obtained from the rapport by Moermond et al. (2016).

The information for the growth criteria was primarily obtained from a literature review study about regrowth of pathogenic microorganisms in the distribution network (Van der Wielen & Van der Kooij, 2009) in combination with scientific literature. Venglovsky et al. (2006) discuss which pathogens can be found in animal manure and other bio-solids, which was used to determine the score on the remobilization criterion. The average removal rate of microbial contaminants in different tanks of a simple wastewater treatment plant was found on the website of the Global Water Pathogen Project (Naughton & Rousselot, 2017; Oakley, 2018). Lastly, to determine whether a microorganisms is emitted by point or diffuse sources, the EZIP database was used (Van der Giessen, Van de Giessen, & Braks, 2010) with additional information from scientific literature on individual pathogens.

Main implications

The final step in this study was to evaluate the main implications of integrating climate change into a prioritization method on a possible ranking of emerging contaminants. To do this, the ranking shown above was used as an example. The aim of the current paragraph is to provide a more general picture of the impact of climate change on the exposure potential of contaminants.

An important consequence of the climate change criteria was that microbial contaminants became more important in terms of exposure potential due to the increasing temperatures in surface water and the distribution network. Bacteria and protozoa that are able to multiply in nutrient-poor water of 25 °C clearly stood out. The criteria related to temperature increase were clearly very important for the order of the ranking.

Related to the increased temperature, chemical substances were ranked higher in case they are present in certain products which are expected to be used more, such as plant protection products (herbicides, fungicides, insecticides, etc.), veterinary medicines and certain human pharmaceuticals. However, due to the relatively low weight of this criterion, it has a smaller impact on the increased risk of these substances. As a result of the selection made, the ranking in Figure 7 only included one substance (anti-inflammatory drug Diclofenac) which is expected to be used more.

In addition, chemical and microbial contaminants that can be both remobilized (runoff or resuspension) and discharged by combined sewer overflow after a (heavy) rainfall event received a relatively high score. This led to an more emphasis on contaminants that are affected by increased precipitation.

As a consequence of more droughts, the overall dilution capacity of the aquatic environment decreases, which means that all contaminants are diluted less and all concentrations thus increase. Contaminants from point sources received a slightly higher weight from the experts, but there is no clear difference between the risk of contaminants from point sources and diffuse sources. A possible explanation for this small difference could be that point sources have a high impact but are more easily regulated during dry periods, while diffuse sources likely emit fewer contaminants in times of drought but are harder to regulate.

Discussion

The aim of this study was to assess the added value of integrating climate change in a prioritization method for emerging risks to Dutch drinking water quality. The evaluation of the integrated prioritization method showed that climate change has an impact on the exposure potential of emerging contaminants (ECs), and that not all contaminants are affected to the same extent. Therefore, it is important to take climate change criteria into account when emerging risks are prioritized. Using scientific literature and expert knowledge, this study demonstrated: I) what the most dominant effects of climate change are on water quality in the Netherlands, II) which effects require further research and III) which effects are advised to include in a prioritization method for emerging risks to drinking water.

However, the qualitative nature of the study and the uncertainties in the prioritization method made it difficult to deduce quantifiable claims about the magnitude of the impact of climate change on water quality. The main point of improvement is to develop a more quantitative prioritization method that incorporates criteria with more extensive scoring possibilities instead of dichotomous scoring (Eisenführ et al., 2010; Langhans et al., 2013). Using criteria with only two scoring levels (0 or 1) might present an oversimplification, but formulating quantitative criteria requires a lot of time and substantive knowledge in both the chemical and microbiological fields. Nonetheless, the focus of this research was not on the actual content of the criteria, but to provide insight on whether it has added value to include climate change criteria in a prioritization method for emerging risks to drinking water quality and which criteria could be considered.

Uncertainty in the MCDA framework

Although attempts have been made to develop a transparent and systematic prioritization method with the Multi-Criteria Decision Analysis (MCDA), multiple sources of uncertainty remain inherently present in a prioritization method that relies to some extent on subjective values (Eisenführ et al., 2010). The uncertainties can be classified into three categories, namely problem framing and structuring, score prediction and method development (Scholten et al., 2015).

Problem framing and structuring

The first source of uncertainty is the framing and structuring of the problem, which means that the way an issue and its boundary conditions are defined (unintentionally) influences the answer. In other words, different decisions can be taken for similar problems depending on the problem framing (Scholten et al., 2015). Thorough problem structuring reduces the risk of irrelevant answers or solutions that solve the wrong problem (Belton & Stewart, 2010).

The first important part of problem structuring is to clearly state the alternatives of the prioritization method, which in this study were the ECs, defined as a newly discovered chemical substance or pathogenic microorganism, which poses a new threat to public health through the exposure to drinking water (Hartmann et al., 2018). The prioritization method is designed to rank any possible list of chemical or microbial contaminants. In this thesis, a prioritization was made of a selection of ECs taken from already existing lists of potentially problematic substances or microorganisms (Environmental Protection Agency, 2016; Van Leerdam et al., 2018). The use of a relatively small selection can lead to selection bias, but since the ranking in this study was only used as an example, this has no significant consequences for the evaluation. In further research, a promising possibility would be to rank contaminants that are discussed in early warning papers in scientific literature (Hartmann et al., 2019).

A second issue with problem structuring is the formulation of the criteria. To minimize the uncertainties regarding the criteria, an attempt was made to formulate the criteria with quantifiable sub-objectives, namely a log K_{ow} between 1.0 and 4.5 for remobilization and >40% removal for combined sewer overflow. In cases where quantification was not possible, the sub-objectives were formulated as specifically as possible to avoid ambiguity. Synergies between criteria were not considered in this study to avoid complexity, and the focus was on direct effects of climate change. Future research could also include mixture interactions or indirect effects, for example increased biodegradation (Boxall et al., 2008; Schriks et al., 2010).

The problem framing in this study is based on the Multi-Criteria Decision Analysis (MCDA) framework, to structure the research in a transparent and systematic way. MCDA studies combine technical information with subjective values from experts. In this context, the feedback from experts during the consultation session and online survey was very important. To prevent framing bias, the consultation session started with individual brainstorming without giving much introductory information in advance, to ensure that ideas from the researchers were not imposed on the experts. Also, the subsequent group discussions made individual or disciplinary biases more explicit (Krueger et al., 2012).

Furthermore, the use of an online survey for elicitation of the criteria weights gave the opportunity to ask standardized and highly structured questions. However, since the respondents carried out the survey remotely, it was not possible to discuss their answers with the experts. In follow-up research, it would be beneficial to organize a second consultation session once the final set of criteria is formulated, to discuss the individual reasoning behind the criteria weights and to evaluate whether a possible ranking of contaminants is consistent with the expectations of the experts.

Score prediction

Scholten et al. (2015) argue that the second source of uncertainty concerns scoring the alternatives. To establish a ranking of ECs, each contaminant is scored on all criteria. However, scoring can be difficult for emerging contaminants because it is not always clear what the physico-chemical properties of the contaminant are and how it behaves in the environment, in treatment plants or in the drinking water distribution network. The scoring of the microbial contaminants required in general more effort than of chemicals, because a lot of information about pathogens is unknown, highly uncertain or very dependent on specific circumstances. The criteria scores often depend on other models or experimental data, which all entail a certain degree of uncertainty.

Moreover, the current prioritization method is very simplified, because it only has two possible scoring levels for each criterion. To improve the method, the scoring functions of the criteria should be based on continuous ranges, discrete states or multiple scoring levels. Langhans et al. (2013) advise to use, whenever possible, continuous scoring functions, which should be supplemented with an uncertainty assessment. In addition, the effects of climate change will likely be non-linear (Noyes et al., 2009), which increases the need for continuous scoring function, because these functions make it possible to take thresholds and tipping points into account.

Method design

A third source of uncertainty discussed by Scholten et al. (2015) is the uncertainty arising from the components of the method, especially the technical choices. The main uncertainties are related to the literature review, the expert knowledge elicitation process and the score aggregation method.

With an eye on time efficiency, the literature review performed in this study was very concise, since it only considered scientific review articles. The information in review articles has already been bundled by other researchers, which increases the chance of biased or omitted information. However, the review articles provided a lot of information, and additional important information was supplemented by the experts during the consultation session.

The criteria weights presented in this study were calculated with the tradeoffs given by fourteen respondents. Although the group consisted of experts with a diverse background, expertise and current field of work, a more robust analysis could be performed if a larger group of experts were to participate. The low coefficient of concordance and the radar chart in Figure 5 showed that the level of agreement among the surveyed experts was rather low. An additional consultation session can help to make clear where these differences in judgment come from and to possibly reach a higher degree of consensus.

The criteria weights are highly dependent on the accuracy and consistency of the experts' responses, and therefore weights elicitation will most likely be accompanied by uncertainty and biases (Krueger et al., 2012; Scholten et al., 2015). In this study, the expert elicitation was performed with the pairwise comparison technique, which is considered relatively reliable in comparison with other elicitation techniques (Hansen & Ombler, 2008; Tayyar & Durmu, 2017). Nevertheless, the criteria weights might differ when another group of experts is questioned, for example experts with different scientific backgrounds or from other countries (Papadopoulos et al., 2015).

On the other hand, a concise analysis on the individual criteria weights showed that the ranking of the contaminants does not significantly differ when different weights are used in the prioritization. There are minor changes in the total scores of the contaminants, but no changes in the order of the ranking. The combined weights of the experts with a microbiological background do not give a different ranking than the weights of the weights of the chemistry experts. Prioritizing the contaminants with criteria with equal weights (all $\frac{1}{7}$) would also not lead to a different ranking. In short, the criteria weights show which criteria are more or less important according to a group of experts, but the weights do not have a significant effect on the ranking of the contaminants.

Lastly, the common additive aggregation function was used in this study to calculate the total score of the alternatives. The additive aggregation function uses the weighted arithmetic mean. An important condition for using additive aggregation is the independence of the criteria. Three main types of independences are discussed by Eisenführ et al. (2010), namely mutual preferential independence, additive independence and difference independence. These independence principles dictate that one particular criterion must have no effect on the score on another criterion, and the criteria are not allowed to be complementary nor supplementary.

Attempts have been made to take independency into account as much as possible during the development of the prioritization method, but a certain degree of dependence could not be eliminated. For example, whether a contaminant can grow in warmer surface warmer determines to a large extent if a contaminant can grow in a warmer distribution network. In addition, the fact whether a contaminant is emitted by a point or diffuse source is implicit or explicit assessed in various criteria.

In follow-up research into integrating climate change in a prioritization method for emerging risks, it is recommended to pay more attention to increasing the independency of the criteria. To achieve this, it could also be beneficial to set up a hierarchal structure with higher- and lower-level criteria, which makes it easier to validate the completeness and redundancy of the criteria (Eisenführ et al., 2010). Lastly, a different type of aggregation function could be used to calculate the alternative scores, see Eisenführ et al. (2010) and Scholten et al. (2015) for possible alternatives.

Suggestions for future research

In addition to the amendments related to the MCDA as presented in the paragraphs above, there are three suggestions for future research topics, concerning the identification of additional climate change criteria, the specification to the river basin level and the inclusion of uncertainty elicitation.

The current study has identified multiple criteria that relate climate change to the occurrence of ECs in surface or drinking water, but not all of these criteria were actually included in the final criteria set. The main reason for this was the large uncertainty in the magnitude of the impact of climate change on the environment. More in-depth research into the excluded criteria could result in incorporating these criteria into the prioritization method. For example, more information is required about freshwater acidification and the effects of climate change on nutrient enrichment and dissolved oxygen. Additionally, the impact of salinity might become more relevant if more drinking water were to be produced from sea water or in specific drinking water production sites with relatively high salinity levels.

A second suggestion for future research into a prioritization method for emerging risks to drinking water quality is to specify the method to a single river basin. The current study had a generic approach to develop a prioritization method for the Netherlands in assistance of national policy. A river basin prioritization method provides the opportunity to specify the criteria, weights and scoring functions to the situation in that particular river basin. Also, the hydrological, environmental and land use situation can vary greatly between different aquatic systems, which in turn have an effect on the climate change criteria. A ranking of ECs on river basin level could be interesting for policy makers of, for example, drinking water companies or water boards that are active in one specific river basin.

An example of a criterion that could be incorporated in a river basin prioritization method is the 'decreased flow velocity' criterion. The flow rate is an important factor for the residence time of a contaminant in surface water. Longer residence times could lead to increased degradation, assimilation, adsorption, complexation and settling (Delpla et al., 2009; Wuijts et al., 2013). If the prioritization method is specified to a river basin, the flow velocity effect could be quantified. Wuijts et al. (2013) argue that this is an important issue to take into account when it comes to water quality, particularly in rivers with very low flow rates during drought, such as the Meuse.

A final suggestion for future research would be to include a form of uncertainty elicitation into the criteria weighting process. Many scientific articles have argued that uncertainty can be encountered by using weight distributions (Krueger et al., 2012; O'Hagan, 2019; Page et al., 2012; Scholten, 2013). In this study, the criteria weights are not documented as weight distributions, because the uncertainty of the experts must be asked very accurately, preferably in a situation where the answers of the expert can be immediately reflected. These requirements make uncertainty elicitation a highly time-consuming exercise, which could not be performed within the timeframe of this study.

The transparency of the prioritization method is likely increased in case this uncertainty is explicitly incorporated. In future research, the expert elicitation process could include uncertainty elicitation, which results in a (subjective) weight distribution. The importance of the criteria is then not represented by a single weight value, but by a probability or fuzzy distribution (Krueger et al., 2012). Although experts usually find it difficult to specify their level of uncertainty, uncertainty distributions provide the opportunity to include to some extent the complexities of 'real world' environmental challenges (Page et al., 2012).

Relevance

To the best of the author's knowledge, this is the first study that incorporated the effects of climate change in a prioritization method for emerging risks to the production of safe drinking water, although there is scientific consensus that climate change has a major impact on water quality (Jiménez Cisneros et al., 2014). The results of this research have implications for long-term policymaking. The integration of climate change criteria in a prioritization method for emerging risks to drinking water quality supports more futureproof policy and promotes the proactive identification of ECs of potential high concern.

The goal of proactive identification is in line with the scope of the PS-DRINK project of the RIVM, where this study was part of. Within the PS-DRINK project, a risk-based prioritization method is designed with exposure and hazard criteria. The main objective of this prioritization method is to identify chemical and microbial contaminants with the highest potential exposure via the production of safe drinking water in the Netherlands (RIVM, 2016). The climate change criteria formulated in this study can complement the exposure criteria of the main prioritization method.

The identification of ECs of high concern with the prioritization method provides policymakers the opportunity to respond faster to potential contaminations (Dulio et al., 2018; Hartmann et al., 2018). By ranking a list of early signals of contaminants in the aquatic environment in scientific literature, proactive action can be implemented to prevent or minimize the exposure to potentially hazardous ECs (Hartmann et al., 2019). Examples of proactive action are the installation of monitoring schemes, the possibility of research into the toxicity of the EC, or the tracing of the source of the pollution.

In the Netherlands, a policy program is implemented to reduce the amount of pharmaceutical residues in water (Rijksoverheid, 2019). The climate change criteria formulated in this study suggest that other groups of contaminants might become more important in the future due to the increasing temperature and precipitation. An integrated prioritization method with exposure, hazard and climate change criteria could show that a policy program like the one for reducing pharmaceutical residues in the aquatic environment might also be productive for other contaminant groups.

The current prioritization method is specified to the Dutch drinking water supply, but the results might be relevant to countries or regions with a comparable climate (a temperate climate without dry season) and similar level of prosperity, for example France, West Germany, the United Kingdom and New Zealand (Peel, Finlayson, & McMahon, 2007). Moreover, this study describes a transparent and systematic approach which can be repeated for every region with a region-specific climate scenario and local experts. Lastly, currently only drinking water produced with surface water is considered, but a similar approach might be used to evaluate the impact of climate change on the occurrence of ECs in groundwater, which is relatively underexposed in scientific literature compared to surface water (Lapworth et al., 2018).

Conclusion

This study has evaluated the added value of integrating climate change criteria in a prioritization method for emerging chemical and microbial risks to Dutch drinking water quality. The formulated climate change criteria suggest that the exposure potential of certain contaminants increases if the W_H scenario is considered. Therefore, it is recommended to integrate climate change in a prioritization method if the prioritization is intended to support long-term policy on monitoring of emerging contaminants.

According to the prioritization method designed in this study, the most dominant effect of climate change on water quality are the increased air temperature and increased precipitation. As a result of an increased average temperature of 3.7 °C, pathogens that are able to grow in nutrient-poor conditions with relatively high water temperatures are likely to pose an increased threat to Dutch drinking water. Also, chemical substances that are present in certain products (plant protection products, veterinary medicines and certain pharmaceuticals) are ranked higher because they are expected to be used more in response to a warming climate.

Due to a substantial increase in the average winter precipitation (30%) and maximum hourly rainfall intensity in summer (22 to 45%), contaminants that can be transported to the main river system by runoff, resuspension or combined sewer overflows pose a higher threat to drinking water in the Netherlands. A decreasing amount of average rainfall in summer (–23%) will most likely lead to a lower dilution capacity of the aquatic system, which impacts all contaminants that are present in the rivers and lakes.

The climate scenario predicts that the summers in the Netherlands will become much drier. This will likely increase the concentration of all contaminants. Additionally, the criteria weights of the drought criteria suggest that reduced dilution is slightly more important for contaminants that are emitted by point sources, there is no significant difference with contaminants from diffuse sources.

The criteria related to nutrient loading, dissolved oxygen concentration, freshwater acidification and salinization were excluded from the prioritization method mainly because the direction and magnitude of change in Dutch surface water bodies is uncertain. However, in case more information about these subjects becomes available, it could be considered to include them as climate change criteria in the prioritization method.

An important next step in the development of prioritization methods with integrated climate change criteria is to quantify the criteria as much as possible. This study showed which effects of climate change are important to consider in a prioritization of emerging contaminants in surface and drinking water, but it raised the question of the magnitude of these effects. The quantification of the criteria is expected to increase the agility of the method and provides the opportunity to deal with thresholds and tipping points.

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Appendixes

Appendix 1	List of articles found during scientific literature review
Appendix 2	List of experts that participated in consultation session and online survey
Appendix 3	Preliminary list of criteria as presented during the expert consultation session

Appendix 1

Table A1. List of articles found in scientific literature review. General information of the articles is presented and the last column displays the relevance to this study.

#	Authors	Year	Title	Journal (# of citations)	Topics	Relevance
1.	Ahmed, T., Scholz, M., Al-Faraj, F., Niaz, W.	2016	Water-Related Impacts of Climate Change on Agriculture and Subsequently on Public Health: A Review for Generalists with Particular Reference to Pakistan	International Journal of Environmental Research and Public Health (4)	Environmental management; developing countries; waterborne diseases	Included, although focus on Pakistan or countries with similar environmental conditions
2.	Anawar, H.M.	2013	Impact of climate change on acid mine drainage generation and contaminant transport in water ecosystems of semi-arid and arid mining areas	Physics and Chemistry of the Earth (24)	Mining waste; sulphide oxidation; contaminant transport	Included, although the majority of the article is very specific on acid mine drainage
3.	Carere, M., Miniero, R., Cicero, M.R.	2011	Potential effects of climate change on the chemical quality of aquatic biota	Trends in Analytical Chemistry (20)	Bioavailability; Contaminant distribution and partitioning; Bioaccumulation	Included, extensive discussion on diverse effects of climate change on aquatic environment and biota
4.	Delpla, I., Jung, A.-V., Baures, E., Clement, M., Thomas, O.	2009	Impacts of climate change on surface water quality in relation to drinking water production	Environment International (313)	Physicochemical parameters; micropollutants; biological parameters; drinking water	Included, comprehensive overview of climate change impacts
5.	Hamilton, A.T., Stamp, J.D., Bierwagen, B.G.	2010	Vulnerability of biological metrics and multimetric indices to effects of climate change	Journal of the North American Benthological Society (17)	Benthic macroinvertebrates; ecological condition; temperature sensitivity	Excluded, only studies the effects on macroinvertebrates

6.	Johnson, A.C., Acreman, M.C., Dunbar, M.J., (...), Williams, R.J.	2009	The British river of the future: How climate change and human activity might affect two contrasting river ecosystems in England	Science of the Total Environment (93)	Modelling water quality; phytoplankton; nutrient, organic and biological concentrations	Included, discusses the modelled effects of climate change scenarios on river characteristics
7.	Lake, P.S.	2003	Ecological effects of perturbation by drought in flowing waters	Freshwater Biology (625)	Ecology of droughts; water quality deterioration	Included, explains the consequences of droughts, although main focus on aquatic organisms
8.	Lipczynska-Kochany, E.	2018	Effect of climate change on humic substances and associated impacts on the quality of surface water and groundwater: A review	Science of the Total Environment (5)	Humic substances; Dissolved organic matter; Microbial growth	Included, considers impact on humic substances and resulting water quality effects
9.	Miller, J.D., Hutchins, M.	2017	The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom	Journal of Hydrology: Regional Studies (22)	Urban water environment; Flood risk; Confidence levels	Included, although it combines climate change impacts with urbanization
10.	Misra, A.K.	2013	Climate change impact, mitigation and adaptation strategies for agricultural and water resources, in Ganga Plain (India)	Mitigation and Adaptation Strategies for Global Change (15)	Agriculture; Hydro-climatic changes; River morphology	Excluded, does not specify the effects on surface water quality
11.	Mosley, L.M.	2015	Drought impacts on the water quality of freshwater systems; review and integration	Earth Science Reviews (76)	Hydrological effects of drought; Key drivers of water quality change	Included, comprehensive overview of impact of drought on water quality

12.	Park, J.-H., Duan, L., Kim, B., Mitchell, M.J., Shibata, H.	2010	Potential effects of climate change and variability on watershed biogeochemical processes and water quality in Northeast Asia	Environment International (97)	Biogeochemical processes; Mountainous watersheds; Extreme precipitation	Included, although it is rather specific for mountainous areas
13.	Pinkney, A.E., Driscoll, C.T., Evers, D.C., (...), Sparling, D.W.	2015	Interactive effects of climate change with nutrients, mercury, and freshwater acidification on key taxa in the North Atlantic Landscape Conservation Cooperative region	Integrated Environmental Assessment and Management (8)	Acidification; Eutrophication; Estuarine hypoxia	Included, study on interactive effects on aquatic environment, although a focus on wildlife
14.	Rehana, S., Mujumdar, P.P.	2013	Impact of climate change on regional water resources	Journal of the Indian Institute of Science (0)	Hydrologic impacts; Uncertainty modelling	Included, discusses hydrologic impacts of climate change on water quality
15.	Ritson, J.P., Graham, N.J.D., Templeton, M.R., (...), Freeman, C.	2014	The impact of climate change on the treatability of dissolved organic matter (DOM) in upland water supplies: A UK perspective	Science of the Total Environment (73)	Dissolved organic matter; Water treatment processes; Physicochemical properties	Included, comprehensive overview of changes under future climate conditions, with focus on dissolved organic matter
16.	Soh, Y.C., Roddick, F., Van Leeuwen, J.	2008	The future of water in Australia: The potential effects of climate change and ozone depletion on Australian water quality, quantity and treatability	Environmentalist (18)	Freshwater resources; Link climate change and ozone depletion; Biogeochemical cycle; Aquatic ecosystems; Natural organic matter	Included, although rather specific on Australia

17.	Teshager, A.D., Gassman, P.W., Schoof, J.T., Secchi, S.	2016	Assessment of impact of agricultural and climate change scenarios on watershed water quantity and quality, and crop production	Hydrology and Earth System Sciences (17)	Agricultural land use change; Scenario modelling	Excluded, modelled effects in combination with agricultural land use change
18.	Wade, S.D., Rance, J., Reynard, N.	2013	The UK Climate Change Risk Assessment 2012: Assessing the Impacts on Water Resources to Inform Policy Makers	Water Resource Management (27)	Climate change risk metrics; Risk assessment; Environmental policy	Included, comprehensive overview of climate change impacts and its consequences
19.	Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M., Wade, A.J.	2009	A review of the potential impacts of climate change on surface water quality	Hydrological Science Journal (411)	Mobility and dilution of contaminants; Physicochemical aspects; Ecological status	Included, comprehensive overview with in-depth effects on water quality
20.	Xia, X.-H., Wu, Q., Mou, X.-L.	2012	Advances in impacts of climate change on surface water quality	Advances in Water Science (16)		Excluded, written in Chinese
21.	Young, I., Smith, B.A., Fazil, A.	2015	A systematic review and meta-analysis of the effects of extreme weather events and other weather-related variables on Cryptosporidium and Giardia in fresh surface waters	Journal of Water and Health (15)	Occurrence and concentration; Input for QMRA	Included, although rather specific on the two pathogens

Appendix 2

Table A2. List of experts who are consulted during the consultation session (in alphabetical order), with their area of expertise and the organization where they are employed. The last column shows which experts responded to the online elicitation survey.

Name	**Chemical (CH) or microbial (MB) expertise**	**Organization**	**Online elicitation?**
M. van der Aa	CH	RIVM	Yes
G. Bakker	MB	Vitens	Yes
M. Dingemans	CH	KWR	
A. Fischer	CH	Evides	Yes
E. van der Grinten	MB	RIVM	
J.P. van der Hoek	CH	TU Delft/Waternet	Yes
D. ten Hulscher	CH	Rijkswaterstaat	Yes
L. Keltjens	CH	Aqualab Zuid	Yes
G. de Kloe	CH	Aqualab Zuid	
A. Knezev	MB	Het Waterlaboratorium	Yes
M. Kretzschmar	MB	RIVM	
C. Moermond	CH	RIVM	Yes
R. van der Oost	CH	Waternet	
A.M.de Roda Husman	MB	RIVM	
A. Roosma	MB	Vitens	Yes
R. Sjerps	CH	Oasen	Yes
T. Slootweg	CH	Het Waterlaboratorium	
G. Stroomberg	CH	RIWA Rijn	
H. Timmer	CH	Oasen	Yes
E. Verbruggen	CH	RIVM	
L. Vissers	MB	Aqualab Zuid	Yes
A. van Wezel	CH	University of Amsterdam	
P. van der Wielen	MB	KWR	Yes
S. Wuijts	CH	RIVM	Yes

Appendix 3

Table A3. List of criteria as presented during the expert consultation session. The list consists of eight criteria, displayed with a concise description and scoring categories.

National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Climate change

Criterion	Indicator	
	Description	**Range/categories**
Run-off	Is the contaminant remobilized when a flooding event occurs?	• Yes, and it is likely that the contaminant is distributed to the main river system • Yes, but it is unlikely that the contaminant is distributed to the main river system • The effect is uncertain • No effect
Dilution capacity	Does the concentration of the contaminant increase when a drought occurs?	• Yes, the contaminant is (mainly) discharged by point sources • No effect
Flow velocity	Does a decrease in flow velocity affect the concentration of the contaminant? Think of processes such as assimilation, adsorption or complexation.	• Yes, it is likely that the concentration will increase • Yes, it is likely that the concentration will decrease • The effect is uncertain • No effect
Nutrient enrichment	Does a higher level of nutrient availability affect the concentration of the contaminant?	• Yes, it is likely that the concentration will increase • Yes, it is likely that the concentration will decrease • The effect is uncertain • No effect

National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Climate change

Criterion	Indicator	
	Description	Range/categories
pH level	Does a lower pH-level affect the concentration of the contaminant?	• Yes, it is likely that the concentration will increase • Yes, it is likely that the concentration will decrease • The effect is uncertain • No effect
Salt water intrusion	Does a higher salinity affect the concentration of the contaminant?	• Yes, it is likely that the concentration will increase • Yes, it is likely that the concentration will decrease • The effect is uncertain • No effect
Higher water temperature	Does a higher surface water temperature of 2 °C affect the concentration of the contaminant?	• Yes, it is likely that the concentration will increase • Yes, it is likely that the concentration will decrease • The effect is uncertain • No effect
Oxygen availability	Does a lower concentration of dissolved oxygen affect the concentration of the contaminant?	• Yes, it is likely that the concentration will increase • Yes, it is likely that the concentration will decrease • The effect is uncertain • No effect