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Model development for evidence-based prioritisation of policy action on emerging chemical and microbial drinking water risks

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ABSTRACT

While the burden of disease from well-studied drinking water contaminants is declining, risks from emerging chemical and microbial contaminants arise because of social, technological, demographic and climatological developments. At present, emerging chemical and microbial drinking water contaminants are not assessed in a systematic way, but reactively and incidence based. Furthermore, they are assessed separately despite similar pollution sources. As a result, risks might be addressed ineffectively. Integrated risk assessment approaches are thus needed that elucidate the uncertainties in the risk evaluation of emerging drinking water contaminants, while considering risk assessors' values. This study therefore aimed to (1) construct an assessment hierarchy for the integrated evaluation of the potential risks from emerging chemical and microbial contaminants in drinking water and (2) develop a decision support tool, based on the agreed assessment hierarchy, to quantify (uncertain) risk scores. A multi-actor approach was used to construct the assessment hierarchy, involving chemical and microbial risk assessors, drinking water experts and members of responsible authorities. The concept of value-focused thinking was applied to guide the problem-structuring and model-building process. The development of the decision support tool was done using Decisi-o-rama, an open-source Python library. With the developed decision support tool (uncertain) risk scores can be calculated for emerging chemical and microbial drinking water contaminants, which can be used for the evidence-based prioritisation of actions on emerging chemical and microbial drinking water risks. The decision support tool improves existing prioritisation approaches as it combines uncertain indicator levels with a multi-stakeholder approach and integrated the risk assessment of chemical and microbial contaminants. By applying the concept of value-focused thinking, this study addressed difficulties in evidence-based decision-making related to emerging drinking water contaminants. Suggestions to improve the model were made to guide future research in assisting policy makers to effectively protect public health from emerging drinking water risks.

1. Introduction

1.1. Emerging chemical and microbial drinking water contaminants

The World Health Organization's (WHO) guidelines for drinking water quality include chemical, microbial, radiological and acceptability aspects (like odour, taste and appearance) (WHO, 2011).

However, in terms of the human health impact of drinking water consumption in the Netherlands, chemical and microbial contaminants are the most important to consider as they have been related to diverse health effects, ranging from gastrointestinal diseases to cancer (GBD Risk Factors Collaborators et al., 2015; Landrigan et al., 2017; Prüss-Ustün et al., 2019; Prüss-Ustün et al., 2016).

While the global burden of disease caused by inadequate drinking

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water is declining, new challenges from previously unknown aquatic contaminants are increasing as a result of social, technological, demographic and climatological developments (Lindahl and Grace, 2015; López-Pacheco et al., 2019; van der Aa et al., 2011; Vouga and Greub, 2016). Examples of such emerging aquatic contaminants include ionic liquids (Richardson and Ternes, 2018), per- and polyfluorinated alkyl substances (PFASs) (Thomaidi et al., 2020) and antimicrobial resistant genes (Sanganyado and Gwenzi, 2019). Hence, understanding and preventing the negative impact of contaminants in drinking water (resources) continues to be a global challenge.

1.2. Difficulties in evidence-based decision making of emerging drinking water contaminants

Decision makers (e.g. policy makers) choose which mitigation actions – if any – are needed to protect humans from poor drinking water quality based on the hazard and exposure potential of aquatic contaminants (Schriks et al., 2010; WHO, 2020). This process is known as risk-informed (Aven, 2016) or evidence-based (Clahsen et al., 2020) decision making and is characterised by experts providing decision makers with an evaluation based on available facts and values (Enick, 2007). Here, *values* are defined as “characteristics in virtue of which something is considered valuable” (Wandall, 2004). ‘Epistemic values’ are generally agreed upon by experts in the same field (Enick, 2007; Rijswijk et al., 2014; Wandall, 2004). Contrariwise, ‘non-epistemic values’ are subjective valuations such as the acceptable excess lifetime cancer risk caused by genotoxic carcinogens (e.g. 1 per 100,000 people according to the World Health Organization (WHO) (WHO, 2011)) or the acceptable infection risk caused by pathogens in drinking water (e.g. below 1 per 10,000 persons per year in the Netherlands (Smeets et al., 2009)). Decision makers may add additional non-epistemic values, such as economic or other reasons, to the presented risk-evaluation resulting in the final decision on how to proceed (Aven, 2016).

As emerging contaminants were identified only recently, evidence about their hazard and exposure potential is often scarce and experts frequently disagree on its evaluation (Clahsen et al., 2020; Krayner von Krauss, Casman and Small, 2004). Disagreements might be caused by inconclusive evidence or differences in non-epistemic values and expertise (Biber, 2012; Calow, 2014; Clahsen et al., 2020; Gregory et al., 2012b; Tukker, 2000). As decision making on the risks of contaminants in drinking water should be justifiable to the public, transparent risk-informed decision making is needed (Reichert et al., 2015). There is a need to explain (1) the uncertainties concerning the evidence on which public health decisions are based, and (2) the values and assumptions used by risk assessors (Fawell, 2008; Wandall, 2004).

1.3. Need for joint assessment of chemical and microbial drinking water risks in decision making

Approaches integrating the drinking water risk assessment of chemical and microbial aquatic contaminants are preferred over single-type contaminant approaches, as integrated assessments:

1. Enable policy makers to focus action on those contaminants that pose the highest risk to human health via drinking water (Glassmeyer et al., 2017);
2. Enable the identification of actions that are effective for several types of contaminants (Hou et al., 2019) and
3. Prevent actions where elimination of risk posed by one contaminant is traded off against higher risk posed by another (Mian et al., 2018).

Integrated approaches are rarely published (Olson et al., 2017; Rosen and Roberson, 2007; Spiesman and Speight, 2014) because of differences in risk evaluations (WHO, 2011) and data scarcity (Havelaar et al., 2000; Prüss-Ustün et al., 2011). Microbial risks for drinking water consumption are assessed as the risk of infection, whereas chemical risks

are evaluated by the effect on human health over a lifetime exposure to different concentrations (WHO, 2011). So far, initiatives to achieve integrated risk evaluations for microbial and chemical contaminants in drinking water used the Disability Adjusted Life Years (DALY) approach (Havelaar and Melse, 2003; Havelaar et al., 2000), which is not feasible for emerging contaminants because of lack of data. Thus, integrated frameworks for the assessment of the drinking water risk posed by emerging chemical and microbial contaminants are needed.

1.4. The potential of value-focused thinking to structure contaminant assessment

The concept of value-focused thinking (Keeney, 1996) has proven to be effective in structuring complex interdisciplinary decision problems, such as river quality assessments (Langhans et al., 2013), water supply (Scholten et al., 2017) or endangered species recovery planning (Gregory et al., 2012b), and prioritisation of emerging infectious diseases (Cox et al., 2013). Following the philosophy of ‘value-focused thinking’, the values pertinent to decision making are structured into an objective hierarchy (henceforth ‘assessment hierarchy’) in which the agreed overall objective (e.g., ‘ensuring safe drinking water’) is broken down into sub-objectives (e.g. ‘low microbial/chemical contamination’) that can be further broken down up to a degree of specificity that enables the quantitative assessment (e.g. persistence) of alternatives (e.g. contaminants). The degree of fulfilment of the lowest level sub-objective is then quantified using suitable indicators (e.g. half-life in water or time to first log reduction) (Keeney, 1996; Reichert et al., 2015) (see also Fig. 1).

To compute scores for comparison of alternatives based on the assessment hierarchy, value-focused multi-criteria assessment (MCA) methods, such as multi attribute value theory (MAVT), can be used (Scholten et al., 2017). MCA methods support the decision process with mathematical analysis (Gregory et al., 2012a; Linkov et al., 2006; Scholten et al., 2017), thereby providing a basis for discussion and enabling the quantification of uncertainties within the decision problem (Scholten et al., 2015). MAVT is a specific type of MCA which was developed for analysing assessment hierarchies which are structured using value-focused thinking. MCA methods have been successfully used for complex environmental decisions with conflicting assessment trade-offs (Cox et al., 2013; Havelaar et al., 2010; Khadam and Kaluarachchi, 2003; Langhans et al., 2013; Linkov and Seager, 2011) and are thus used in this study for the integration of microbial and chemical risk evaluation.

1.5. Aim and approach

The aim of this study was twofold, namely (1) to construct an assessment hierarchy for the integrated evaluation of the potential risks from emerging chemical and microbial contaminants in drinking water and (2) to develop a decision support tool based on that agreed assessment hierarchy to quantify (uncertain) risk scores.

A multi-actor approach was used to construct the assessment hierarchy, involving chemical and microbial risk assessors, drinking water experts and members of responsible authorities in the Netherlands. The concept of value-focused thinking was applied to guide the problem structuring and model-building process. Decisi-o-rama (50), an open-source Python library for uncertainty-aware decision analysis, was used to develop the decision support tool.

2. Definitions and concepts

2.1. Terminology in value-focused thinking

Fig. 1 shows the outline of the assessment hierarchy developed in this study. Table 1 provides an overview of the terminology used for different components of the hierarchy.

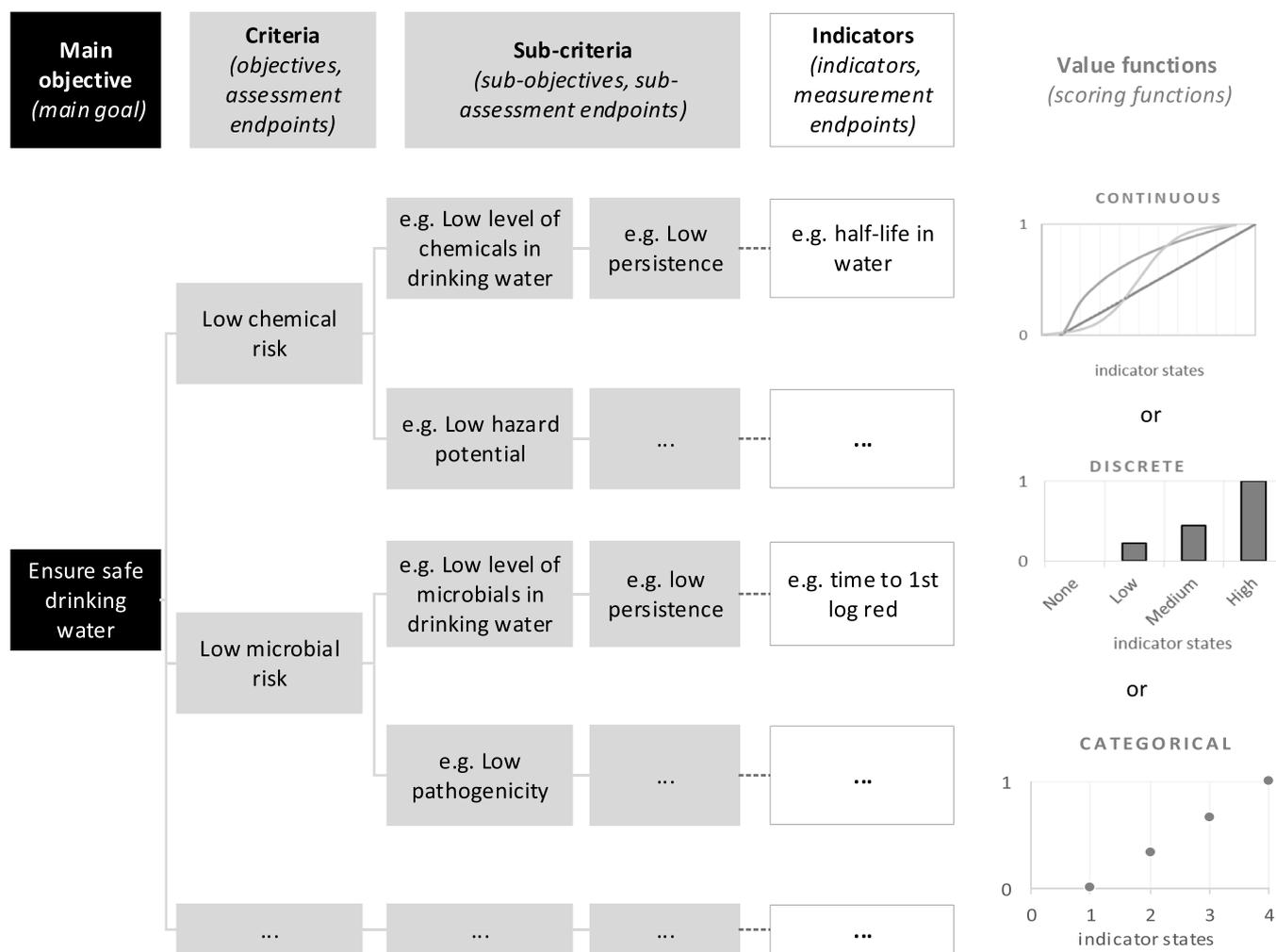


Fig. 1. Example of an assessment hierarchy for the overall objective of ensuring safe drinking water. Each column represents one of the different types of components introduced in Table 1). The first row shows, in bold, the terminology used in this paper to indicate each component, synonyms used in decision science or risk assessment are shown in italic. The components connected with dotted lines represent the indicators which are used to assess the performance of an alternative for a criterion.

2.2. Uncertain risks

In this study, the term ‘uncertainty’ is used to express “knowledge gaps or ambiguities that affect our ability to understand the consequences of decisions” (Gregory et al., 2012a). This includes uncertainties that may be referred to elsewhere as aleatory uncertainties (caused by randomness) and epistemic uncertainties (caused by lack of knowledge). The term ‘risk’ is used to express the possibility of a negative consequence.

The uncertainty in this study refers to the prediction of indicator levels (see Table 1). Therefore, remaining uncertainty in the computed risk scores concerns the ‘uncertain risks’ related to the probability of contaminants being present in drinking water and the possible harm that these could pose to human health.

3. Methodology

An assessment hierarchy was constructed for the overall objective ‘to ensure safe drinking water’. The components of the assessment hierarchy were identified based on (1) a literature review of prioritisation approaches for chemical or microbial risks from drinking water and the criteria and indicators used therein, which were then interlaced with (2) actor consultation before, during, and after two workshops organised for this purpose. Such an iterative approach has proven effective earlier (Bond et al., 2010; Gregory et al., 2012a). Actors were risk assessors,

drinking water experts and members of responsible authorities. Fig. 2 provides an overview of the applied methodology.

3.1. Preliminary list of criteria and indicators from the literature review

A meta-synthesis¹ was performed to compose a preliminary list of criteria and indicators. A meta-synthesis brings together qualitative data from different studies (Atkins et al., 2008). Here, the qualitative data were criteria and indicators used by articles reporting on the prioritisation of chemical and/or microbial risks to drinking water quality. Articles were retrieved² from Scopus® on the 5th of June 2019. Criteria and indicators used by these studies were synthesised into criteria and indicators for the integrated prioritisation of emerging chemical and

¹ A meta-synthesis is also known as a meta-ethnography or a meta-synthetic literature review.

² Search query used: TITLE-ABS ((“contaminant*” OR “pollutant*” OR “substance*” OR “compound*” OR “chemical*” OR “pathogen*” OR “microorganism*” OR “microorganism*” OR “micro-organism” OR “infectious disease*” OR “virus” OR “viri” OR “bacter*” OR “protoz*” OR “component*” OR “agent*” OR “metabolite*”) AND (“prioritising” OR “prioritisation” OR “prioritising” OR “prioritisation” OR “ranking”) AND (“drinking water” OR “tap water” OR “potable water”)) AND PUBYEAR > 2003.

Table 1
Terminology used in this study regarding different components of the objectives hierarchy in Fig. 1 (as indicated in bold on the left).

Term	Definition	Examples	Additional information
Criterion	Used for the different impacts of the contaminant on drinking water.	Persistence, mobility, hazard potential.	In MCA practice, the term <i>objectives</i> is often used instead (Gregory et al., 2012a; Langhans and Lienert, 2016; Scholten et al., 2014).
Alternatives	The different contaminants for which the performance and valuation on the indicators is assessed.	Newly identified aquatic chemical and microbial contaminants, such as ionic liquids (9), and antimicrobial resistant genes (11).	
Indicator	Used to assess the performance of an alternative for a criterion.	Half-life in water (Yost et al., 2017) or time to first log reduction (Mitchell and Akram, 2017) to assess the persistence of chemicals or microbials respectively.	
Value function	A function that covers the degree of fulfilment of the criterion as a function of the associated indicator (s) on a scale from 0 to 1 that is scaled relative to the range of the considered alternatives (Langhans and Lienert, 2016).	Linear, discrete or categorical (see Fig. 1).	In other words, the desirability or degree of fulfilment of one's non-epistemic values with regard to the indicator. This function can take different forms as illustrated in Error! Reference source not found..
Aggregation function	Refers to the mathematical function that is used to express the preferences in terms of trade-offs and interactions between valuations on different indicators. it returns an aggregated value (also scaled from 0 to 1) that can be used to rank alternatives (Linkov and Seager, 2011).	Rank alternatives from highest to lowest expected risk to drinking water quality based on the defined criteria and indicators.	

microbial drinking water risks.

3.2. Actor consultation: construct assessment hierarchy

Two workshops were organised with Dutch risk assessors, drinking water experts and members of responsible authorities with the goal to (1) achieve consensus around terminology, (2) create ownership to facilitate take up of the developed tool by experts/decision makers and (3) have an agreed assessment hierarchy. Participants were selected based on involvement in national and international discussions about emerging chemical or microbial aquatic contaminants. Workshops took place on July 1st 2019 and January 16th 2020, with 25 and 36 participants, respectively (30% overlap, see Supplementary material I for anonymised participant details).

The objective of the first workshop was to review and supplement the preliminary criteria and indicators. Twenty-five participants reviewed the preliminary criteria and indicators, twenty-two of whom attended the workshop and three who were interviewed before or after. The authors used the input from the workshop to construct a first version of the assessment hierarchy.

The objective of the second workshop was to (1) validate and supplement the first version of the assessment hierarchy and (2) investigate the usefulness of the decision support tool. Details of the workshop process are provided in Supplementary material II. After the second workshop, all participants were e-mailed the second version of the assessment hierarchy and invited to provide any remaining suggestions. With these suggestions, a final assessment hierarchy was constructed.

3.3. Decision support tool to compute the risk scores

Using Decisi-o-rama (Chacon-Hurtado and Scholten, 2021) a decision support tool was developed to quantify risk scores based on the agreed assessment hierarchy. Decisi-o-rama is an open-source Python library for uncertainty-aware decision making. It provides a framework to support multi-criteria analysis following value-focused thinking, implementing multi-attribute value and utility theory-based models as commonly used in decision analysis. For details see Chacon-Hurtado and Scholten (2021).

4. Results

4.1. Development of the assessment hierarchy: literature review and actor consultation

A detailed overview of the preliminary criteria and indicators, which were based on the synthesis of the criteria and indicators used by the reviewed prioritisation approaches, is shown for the hazard and exposure potential in Table III.1 and Table III.2, respectively. The preliminary criteria included: acute and chronic potency of the contaminant, severity of the potential health effect caused after short-term and long-term exposure, host sensitivity, removal potential in wastewater treatment plants, the emission potential in the Netherlands, persistence/survival in surface water and the potential to occur in drinking water after treatment. See Error! Reference source not found. for detailed information on the results of the literature review and the synthesis process of the criteria extracted from the literature.

Table 2 provides an overview of the changes and additions made to the preliminary criteria and indicators (Table III.1 and Table III.2) based on the participants' suggestions provided during Workshop 1. The main suggestions, for both chemical and microbial contaminants, were to not distinguish between point and diffuse sources, to not only focus on potential contamination in the Netherlands but in the entire River Basin and to specify the treatment steps included in wastewater and drinking water treatment. Participants' suggestions and the preliminary list of criteria and indicators in Table III.1 and Table III.2 were used to set up a first version of an assessment hierarchy. The development of this first version of the assessment hierarchy was, along with the participants' input, guided by data availability for emerging contaminants. Available models to fill data gaps were used.

Table 3 shows participants' suggestions for the revision of the first version of an assessment hierarchy provided in Workshop 2, which resulted in three revisions, namely (1) the potential of secondary spread was moved up, (2) for microbial contaminants, a distinction was made between acute and chronic exposure, and (3) the criterion 'Potential to take protective actions' was removed. Other suggestions for revision of the hierarchy were outside this study's scope (see Table 3 for explanation). Furthermore, 27 actors performed an intuitive ranking based on hand outs summarizing indicator levels from scientific evidence and their subjective valuation of the evidence and trade-offs between indicators during Workshop 2 (Error! Reference source not found.). The

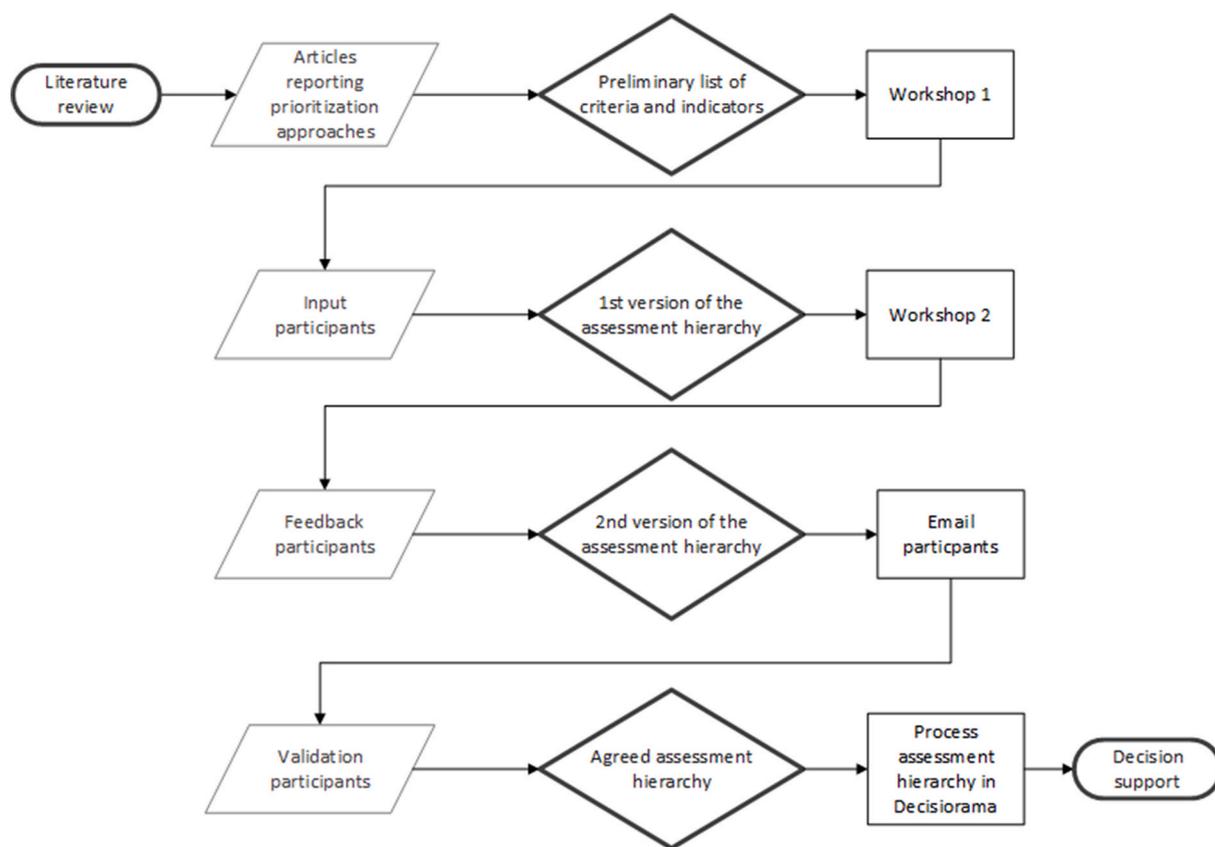


Fig. 2. Overview of the development process of the decision support tool which was developed in Python using the Decisi-o-rama library (see also Section 3.3 and (Chacon-Hurtado and Scholten, 2021)).

high inhomogeneity in the obtained results, shows the usefulness of an the developed decision support tool as it elucidates viewpoints, unknowns and uncertainties, while separating scientific evidence from subjective judgment, thus facilitating more transparent and rational assessments.

After Workshop 2, participants could comment on the second version of the assessment hierarchy via email. One participant responded with a final remark, stating that whether a contaminant is an endocrine disruptor could also be moved up in the hierarchy, namely after being reprotoxic. However, as endocrine disruption is not equal to the carcinogenic, mutagenic and reprotoxic (CMR) potential of a contaminant, the hierarchy was not changed. The participant agreed with this reasoning. The second version of the assessment hierarchy was thus the final version (Fig. 3).

4.2. Final assessment hierarchy

Fig. 3 shows the final assessment hierarchy to ‘ensure safe drinking water’. Four main criteria for both chemical and microbial emerging contaminants were included, namely (1) exposure- and (2) hazard-potential, (3) relevance of drinking water in comparison to other exposure routes, and (4) the potential of human to human spread. Associated sub(sub)-criteria and indicators are shown in Error! Reference source not found. and Error! Reference source not found., respectively, and might be different for chemical and microbial contaminants. For chemical contaminants, indicators are mostly based on physical-chemical properties, whereas for microbial contaminants, known information on similar pathogens was used.

4.2.1. Information sources used to define indicator levels

The basis for indicator level definition is shown for each indicator in Error! Reference source not found. Information sources include existing

estimation models, scientific and grey literature, available data on the drinking water treatment system in the Netherlands and expert judgement.

According to the Dutch Drinking Water Act (van den Berg et al., 2019), Dutch drinking water suppliers must conduct a Quantitative Microbial Risk Assessment (QMRA) for infection by index pathogens (Enterovirus, Campylobacter, Cryptosporidium and Giardia) in order to assess the microbial safety of drinking water. To that end, Dutch drinking water companies using surface water for the production of drinking water collect influent and effluent concentrations of indicator organisms at each treatment step.

The computational tool QMRAspot was used to estimate the parameters of the beta distribution that describes the fraction of indicator organisms which are able to pass a drinking water treatment step (Schijven et al., 2011). For drinking water treatment steps - coagulation, sedimentation, rapid sand filtration, disinfection with UV light (40 mJ/cm²) and activated carbon filtration - parameters were collected from the most recent regular QMRAs of Dutch drinking water suppliers as well as from literature (see Table 4). This information was used to define indicator levels for log red_coa_rf, log red_ac and log red_uv.

4.3. Decision support: risk scores for eight emerging contaminants

The assessment hierarchy introduced in Section 4.2 was operationalised using Decisi-o-rama (Chacon-Hurtado and Scholten, 2021). Table 5 shows the value functions applied. Equation (1) was used as the aggregation function (weighted sum) on each level of the hierarchy to calculate risk scores for the eight contaminants assessed during Workshop 2 (MCR-1 positive *E. coli*, *Legionella longbeachae*, *Norovirus GII. 17*, *Cryptosporidium parvum*, prazosine, perfluorooctanoic acid, 3-(4-tert-Butylphenyl) propanal and minocycline); in which x_i is the indicator i of alternative x and (v_i) is a normalised value function of the indicator i (see

Table 2

Revision of the preliminary criteria and indicators shown in Table III.1 (numbers 1 to 5) and Table III.2 (numbers 6 to 10) based on actor’s suggestions received during Workshop 1. NA = not applicable to any preliminary criterion, thus suggestion to include a new criterion.

Improvement preliminary criterion and/or indicator or addition of new criterion	Suggestion by actor	Related to hazard or exposure potential	Based on plenary discussion or individual suggestion (number of actors raised suggestion)
“Source presence in the Netherlands” was changed to “Source presence in the Netherlands and the River Basin”.	In order to assess the exposure potential of a contaminant via drinking water produced in the Netherlands, one should focus on its potential presence in the River Basin instead of only the Netherlands.	Exposure	Plenary discussion and individual suggestions (7/25)
Distinction between point or diffuse source was removed from the hierarchy.	No distinction between point or diffuse source as (1) point sources might not be treated by WWTP and, (2) diffuse sources might also contain contaminants registered under REACH.	Exposure	Individual suggestions (4/25)
Treatment steps in wastewater and drinking water treatment plant were defined using the Basic Surface Water Purification Process (van Leerdam et al., 2018).	Define treatment steps in wastewater and drinking water treatment plant as this strongly influences the removal efficiency (or even cause an increase of contamination if pathogens regrow).	Exposure	Individual suggestions (6/25)
Criteria/indicators were not revised, as the contaminants’ characteristics that guide removal efficiency are similar in municipal and industrial wastewater treatment.	Make a distinction between industrial and municipal wastewater.	Exposure	Individual suggestions (2/25)
Criteria were not revised; these future contaminants can be included as alternatives.	Include future scenarios (is aquatic contamination by the chemical or microorganism expected to happen in the future?)	Exposure	Individual suggestions (2/25)
New criterion was added	The importance of exposure via drinking water compared to other routes of exposure.	Exposure	Plenary discussion
New criterion was added	Possibility of taking protective measures (e.g. vaccination). Add criterion on authorisation dossier available at ECHA, EFSA, EMA.	Hazard	Plenary discussion
Criteria/indicators were not revised, can be used as information sources to score alternatives.		Exposure	Individual suggestion (1/25)
		Hazard	

Table 2 (continued)

Improvement preliminary criterion and/or indicator or addition of new criterion	Suggestion by actor	Related to hazard or exposure potential	Based on plenary discussion or individual suggestion (number of actors raised suggestion)
Criteria/indicators were not revised as, for chemicals, toxicity is based on QSAR models rather than on toxicity tests.	Add indicator level to distinguish between contaminants that have been tested and shown to be non-toxic and those that have not been tested.		Individual suggestion (1/25)
Criteria/indicators were revised, for chemicals, toxicity is based on QSAR models for chronic health effects.	For chemical contaminants, acute exposure via drinking water is not relevant (concentration is often too low to cause an adverse health effect).	Hazard	Individual suggestion (1/25)
Criteria/indicators were revised. For chemicals, toxicity is based on QSAR models for chronic health effects. No timeframe is included.	The timeframe for chronic exposure via drinking water should be a lifetime.	Hazard	Individual suggestion (4/25)
Textual changes were considered in development hierarchy.	Add ‘in the distribution system’ to the indicator levels.	Exposure	Individual suggestion (1/25)
Textual changes were considered in development hierarchy.	Rephrase ‘common’ to ‘significant’ to indicate the level of expected emission.	Exposure	Individual suggestion (1/25)
Textual changes were considered in development hierarchy.	Remove ‘only in’	Hazard	Individual suggestion (1/25)
Criteria/indicators were not revised, transformation products can be included as alternatives.	The formation of (more toxic) transformation products or metabolites	Hazard	Individual suggestion (1/25)
Criteria/indicators were not revised, this is outside the scope of this study, focus is on individual contaminants.	Include an assessment of the potential risk of a mixture of emerging contaminants in drinking water.	Hazard	Individual suggestion (1/25)

Table 5) and w_i denotes the weight of indicator i . Here, we assumed equal weights for all indicators. The model, including a description of how risk scores were calculated, can be accessed in the form of Python notebooks at https://github.com/j-chacon/Hartmann_contaminants.

$$V(x) = V(x_1, \dots, x_n) = \sum_{i=1}^n w_i v_i(x_i), \text{ where } \sum_{i=1}^n w_i = 1 \quad (1)$$

Fig. 4 shows the calculated risk scores and the scores on the four highest-level criteria (for information on criteria, see Error! Reference source not found.). For all contaminants, drinking water risk scores were found to be medium to low with highest risk scores for MCR-1 positive *E. coli*, *Norovirus GII. 17*, and *Cryptosporidium parvum*. For all eight contaminants, the potential exposure via drinking water was estimated to be medium to high, with the highest estimated exposure for *Cryptosporidium parvum* (see also Section 5.2.3). The hazard potential of all contaminants was found to be medium to low. The calculated risk score for 3-(4-Tert-Butylphenyl) propanal was the most uncertain, because of

Table 3

Actor's suggestions provided during Workshop 2 to improve the first version of the assessment hierarchy (Fig. 3). Suggestions were divided into three categories, namely (1) missing or incorrect criteria, (2) incorrect indicator levels or (3) other remarks related to the assessment hierarchy. NA = not applicable.

Revision	Suggestion by actor	Category
No revision of the assessment hierarchy as this was due to the use of the model Sewage Treatment Plant win (STPwin) model. However, for ionizable compounds the output from STPwin should be reviewed by experts.	The estimated removal percentage for PFOA was too high.	Incorrect indicator levels
No revision of the assessment hierarchy as it was agreed that the fact whether a contaminant is already regulated influences potential actions, but this is outside the scope of this study.	Chemical and microbial contaminants which are already regulated in the Netherlands, should be scored lower.	Missing or incorrect criteria
No revision of the assessment hierarchy was needed. This was discussed with JS after the workshop, indicator levels were adjusted.	Incorrect indicator levels for some of the microbial contaminants.	Incorrect indicator levels
No revision of the assessment hierarchy based on the limited availability of and high diversity within the data on these treatment steps.	Other treatment steps, such as disinfection with ozone, should also be included for the estimation of the reduction efficiency in drinking water treatment systems (next to activated coagulation, rapid filtration, activated carbon and UV disinfection).	Missing or incorrect criteria
For chemical contaminants, no QSAR models were available to assess the acute risk a chemical contaminant poses via drinking water. Therefore, no adjustments were made to the assessment hierarchy for chemical contaminants. However, for microbial contaminants the assessment hierarchy was adjusted to include acute and chronic effects of exposure to the contaminant.	The distinction between health effects after acute or chronic exposure to the contaminant should be included in the model.	Missing or incorrect criteria
The criterion was removed from the assessment hierarchy.	The criterion 'Potential to take protective actions' should be removed.	Missing or incorrect criteria
Assessment hierarchy was not revised as actors agreed that this is outside the scope of this study as it does not concern the risk posed by the contaminant.	Add criterion to assess the public interest of the use of a contaminant. Some actors found this valuable as it influences the possibility of eliminating the use of the contaminant.	Missing or incorrect criteria
Assessment hierarchy was not revised as incidences of the supply chain are outside the scope of this study.	Model is focussed on regular drinking water supply, incidences of error within the supply chain are not considered.	Missing or incorrect criteria
No adjustments were made to the assessment hierarchy, as for emerging contaminants, this information is often unavailable.	Model does not include the concentration in drinking water or source water used for the production of drinking water.	Missing or incorrect criteria
Water solubility was not added to the assessment hierarchy as this is already covered by the Log K _{oc}	Water solubility should be included as an additional indicator for the behaviour	Missing or incorrect criteria

Table 3 (continued)

Revision	Suggestion by actor	Category
No adjustments were made to the assessment hierarchy because of the unavailability of a model for the assessment of the removal in industrial wastewater treatment plants.	in the drinking water treatment plant. Removal in industrial wastewater treatment plant is not included in the model.	Missing or incorrect criteria
No adjustments were made to the assessment hierarchy as risks to ecosystems were outside the scope of this study (not a direct influence on the quality of drinking water).	Potential adverse effects to ecosystems should be included.	Missing or incorrect criteria
No adjustments were made to the assessment as risk perception has no direct influence on the quality of drinking water.	Risk perception of the consumer should be included.	Missing or incorrect criteria
Potential of secondary spread was moved up in the final assessment hierarchy.	Potential of secondary spread is not part of the hazard potential of the contaminant, but increases the overall risk posed by the contaminant to the entire population.	Other remarks related to the assessment hierarchy
Observation, no revision of the assessment hierarchy needed.	Level of uncertainty was considered a reason for action.	Other remarks related to the assessment hierarchy
Preference elicitation in terms of weighing the different criteria was outside the scope of this study, but acknowledged to be very important.	The importance of each criterion is not the same.	Other remarks related to the assessment hierarchy

the uncertain relevance of drinking water as an exposure route. Based on these results, none of the contaminants were estimated to pose a high human health risk via drinking water.

5. Discussion

In this study, a decision support tool was developed for the integrated assessment of potential drinking water risks posed by emerging chemical and microbial aquatic contaminants. This study was initiated because of the need for (1) integrated assessment approaches for chemical and microbial drinking water risks (see Section 1.3), (2) elucidation of uncertainties in evidence-based decision making of emerging drinking water risks (see Section 1.2), and (3) clarification of the values used by risk assessors when evaluating emerging drinking water risks (see Section 1.2). Was the developed decision support tool able to fulfil the identified needs and what are areas for improvement of the model?

5.1. Relevance of the developed decision support tool: comparison to previously published prioritisation approaches

Fig. 4 shows the resulting risk scores for chemical and microbial aquatic contaminants. Risk scores can be used by decision makers and experts to discuss the potential risk that a chemical and microbial emerging contaminant poses to the supply of safe drinking water in the Netherlands. Also, the illustration of the uncertainty in the indicator levels can guide actions, as it points towards the most pressing data gaps, as mentioned by one of the participants of Workshop 2.

None of the published prioritisation approaches for chemical and/or

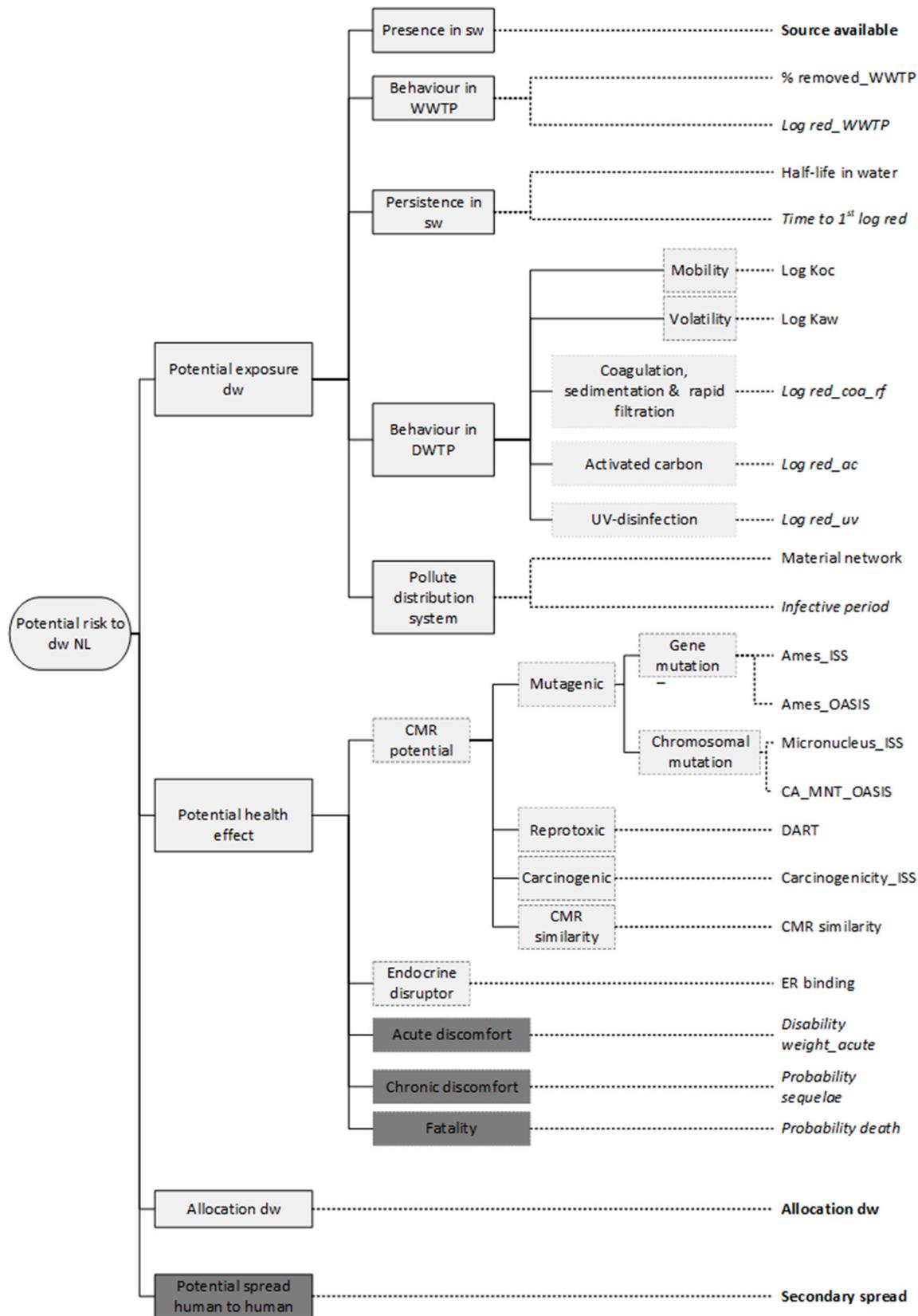


Fig. 3. Agreed assessment hierarchy to evaluate the potential drinking water risk posed by emerging chemical or microbial aquatic contaminants. Boxes reflect four levels of criteria with associated indicators connected via the dotted lines. The indicators in italics were suggested for microbial contaminants, the bold for both chemical and microbial contaminants and the others for chemical contaminants. For detailed information on abbreviations in (sub-)criteria and indicators, see Error! Reference source not found., and Error! Reference source not found., respectively. The criteria that are were added to, or moved within, the hierarchy compared to the first version developed after Workshop 1 and discussed during Workshop 2 () are shown in dark grey.

Table 4

Overview of parameters of the beta distribution that describes the fraction of indicator organisms that are able to pass a drinking water treatment step (Schijven et al., 2011). For different drinking water treatment steps, parameters were collected from data from the last regular QMRAs of Dutch drinking water companies and from literature. Removal efficiency is shown as ¹⁰log reduction. These values can be used to estimate the inactivation efficiency of emerging viruses, bacteria and protozoa by Dutch drinking water companies producing drinking water from surface water.

Treatment step	Parameter	Enteroviruses	Campylobacter	Cryptosporidium	Giardia
Coagulation, sedimentation and rapid sand filtration	α	1.9	1.2	2.1	2.1
	β	12	4	70	70
	Average	-0.86	-0.64	-1.5	-1.5
	Median	-0.92	-0.71	-1.6	-1.6
	5-percentile	-1.6	-1.6	-2.3	-2.3
	95-percentile	-0.51	-0.25	-1.2	-1.2
	Reference	QMRA data	QMRA data	QMRA data	QMRA data
UV-disinfection	α	0.076	1	1	3
	β	25	100000	4000	600
	Average	-2.5	-5	-3.6	-2.3
	Median	-5.6	-5.2	-3.8	-2.4
	5-percentile	-19	-6.3	-4.9	-2.9
	95-percentile	-1.7	-4.5	-3.1	-2
	Reference	Schijven et al. (2011)	Hijnen et al. (2006)	Hijnen et al. (2006)	Hijnen et al. (2006)
Activated carbon filtration	α	-	0.16	0.2	0.2
	β	-	0.84	20	20
	Average	-	-0.8	-2	-2
	Median	-	-1.8	-3	-3
	5-percentile	-	-8	-8	-8
	95-percentile	-	-0.094	-1.3	-1.3
	Reference	-	QMRA data and Hijnen et al. (2009)	Hijnen et al. (2009)	Hijnen et al. (2009)

Table 5

Overview of value functions used to calculate the risk scores for mcr-1-positive *E. coli*, *Legionella longbeachae*, Norovirus GII. 17, *Cryptosporidium parvum*, prazosine, perfluorooctanoic acid, 3-(4-tert-Butylphenyl) propanal and minocycline.

Indicator	Value Function	Based on
Source available	$\frac{1}{3}x$	Assumed linear value function
% removed_WWTP, Time to 1st log red	0.01x	Assumed linear value function
Log red_WWTP, Log red_coa_rf, Log red_ac, Log red_uv half-life in water	$y = 0.0526x$	Assumed linear value function
Log K _{oc}	$\frac{1}{1 + 10^{((\text{LOG}(60) - \text{LOG}(x))/(\text{LOG}(60) - \text{LOG}(40)) * \text{LOG}(2))}}$	Rorije et al. (2011), but here centred around 60 days as half-life for very persistent chemicals in water and 40 days as half-life for persistent chemicals, according to Section 1 European legislation No 1907/2006 on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).
Log Kaw	$\frac{1}{\left(1 + 10^{\left(\frac{-2.7 - x}{-2.7 - (-1.4)} * \text{LOG}(2)\right)}\right)}$	Rorije et al. (2011), but here centred around Log K _{oc} = 2 for very mobile contaminants and Log Kaw = 3 for mobile contaminants.
Material network, Ames_ISS, Ames_OASIS, Micronucleus_ISS, CA_MNT_OASIS, DART, Carcinogenicity_ISS, CMR similarity, Disability weight_acute, Probability sequelae, Probability death, allocation_dw, secondary spread	Y = x	Rorije et al. (2011), but here centred around Log Kaw = -2.7 for very poorly volatile compounds and Log Kaw = -1.4 for poorly volatile compounds. Dichotomous indicator
Infective period	x 0 7 28 365 y 0 0.33333 0.66667 1	WHO (2011)
ER binding	Y = 0.25x-0.25	Approach of Langhans et al. (2013) for discrete variables

microbial risks to drinking water integrated the assessment of emerging chemical and microbial risks and uncertainty awareness in a multi-actor approach (see Section 4.1). Existing prioritisation approaches are limited, especially when it comes to assessing emerging microbial drinking water risks (Hoffman et al., 2009; Olson et al., 2017; Rosen and Roberson, 2007; Spiesman and Speight, 2014). This study illustrates a first attempt at an uncertainty aware semi-quantitative approach suitable for the prioritisation of emerging microbial drinking water contaminants (Olson et al., 2017; Rosen and Roberson, 2007). Also, by

applying the concept of value-focused thinking, this study contributes to transparent decision making in relation to emerging drinking water risks as values and assumptions used by risk assessors were made explicit (Biber, 2012; Calow, 2014; Clahsen et al., 2020; Gregory et al., 2012b; Tukker, 2000).

In terms of emerging chemical drinking water contaminants risks, Clarke et al. (2016) also developed a model which enables the computation of risk scores with uncertain indicator levels. However, this model (Clarke et al. (2016)) is not suitable for the assessment of both microbial

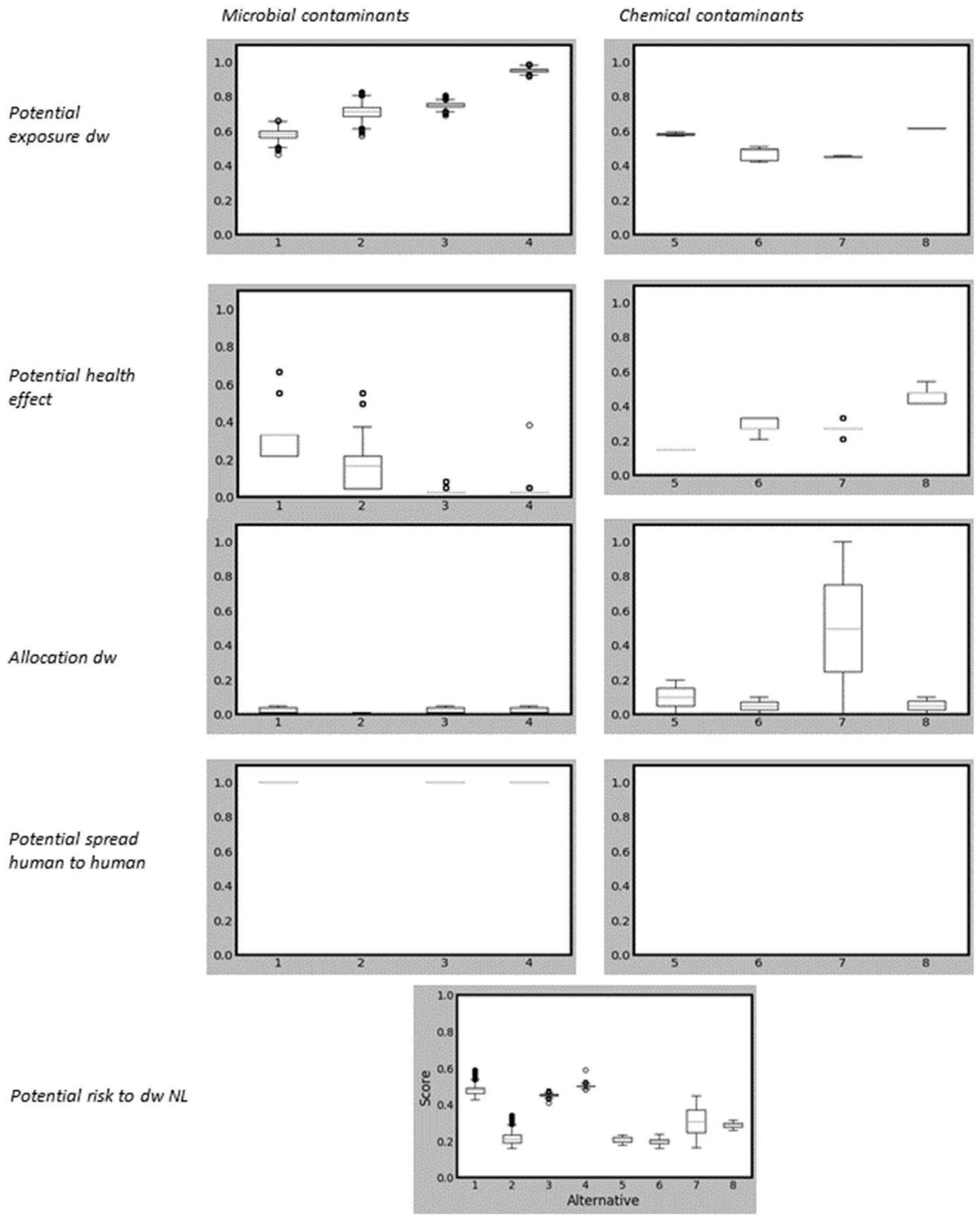


Fig. 4. Calculated risk scores for MCR-1 *E. coli* (=1), *Legionella longbeachae* (=2), Norovirus GII. 17 (=3), *Cryptosporidium parvum* (=4), prazosine (=5), perfluorooctanoic acid (=6), 3-(4-tert-Butylphenyl) propanal (=7) and minocycline (=8) and scores for the four highest level criteria using the developed decision support tool. A score of 1 means high risk, a score of 0 low risk. Potential spread human to human is 0 for all chemical alternatives and *Legionella longbeachae*.

and chemical contaminants nor for emerging risks caused by the use of measured data. Many published prioritisation approaches mentioned data scarcity to be one of the limiting factors in their model (Lapworth et al., 2018; Mian et al., 2018; Sinclair et al., 2006; Spiesman and Speight, 2014; Yost et al., 2017). With the decision support tool developed in this present study, the issue of data scarcity could, at least partly, be resolved and the sources of uncertainty be clarified.

During the development of the decision support tool, the German Environment Agency published a classification approach for potential chemical drinking water risks: persistent, mobile and toxic (PMT) chemicals (Neumann and Schliebner, 2019). Neumann and Schliebner (2019) included the same indicators for mobility and persistence as used in this study (Log K_{oc} , half-life in water), but as a discrete measurement scale. In the present study, sigmoid curved value functions were used, following (Rorije et al., 2011), which gives the model more distinctive power than the Neumann and Schliebner (2019) approach. Another difference between Neumann and Schliebner (2019) and the present study is that Neumann and Schliebner (2019) included the Cramer Classes of the threshold of toxicological concern approach (Mons et al., 2013) to indicate the hazard potential of a contaminant (the T in PMT). Here, Cramer classes are not included. The added value of the use of Cramer Classes to the developed assessment hierarchy could be investigated.

5.2. Areas for improvement of the decision support tool: suggestions for future research

Suggestions for future research to improve the model are structured around the sources of uncertainty in an MCA (Scholten et al., 2015).

5.2.1. Problem framing and structuring

Considering the problem framing and structuring of the model, four areas for improvement were identified. Firstly, microbial and chemical contaminants were used as alternatives, instead of potential actions (Hartmann et al., 2018). The prioritisation of mitigation actions (e.g. additional drinking water treatment steps) instead of addressing single contaminants may also be effective in the pursuit of protecting public health from inadequate drinking water. As an integrated approach to the risk evaluation of drinking water contaminants is needed to prioritise the effectiveness of potential actions, a prioritisation model with mitigation actions as alternatives could be set up using the developed assessment hierarchy and the functionality of portfolio analysis in Decisi-o-rama (Chacon-Hurtado and Scholten, 2021).

Secondly, using a Delphi study when reviewing the literature, might have sped up the process of assessment hierarchy building, as illustrated by Van Schoubroeck et al. (2019).

Thirdly, the focus was on human health risks caused by drinking water quality and thus potential risks to ecosystems were not considered. However, including the potential risks to ecosystems might increase decision makers' leverage for action to be taken when a contaminant is suspected to be both a risk to humans via drinking water and to ecosystems (suggestion by a participant of Workshop 1).

Finally, the criteria 'potential spread human to human' and 'allocation dw' are indirectly related to the risk a contaminant poses via drinking water and thus not part of the hazard and exposure potential of the contaminant. Furthermore, the inclusion of the potential of secondary spread as one of the highest-level criteria increases the risk potential for microbial contaminants compared to all chemical contaminants. This issue might be resolved when preference information is included in the model. For now, two different risk scores can be used by policy makers: one solely based on the hazard and exposure

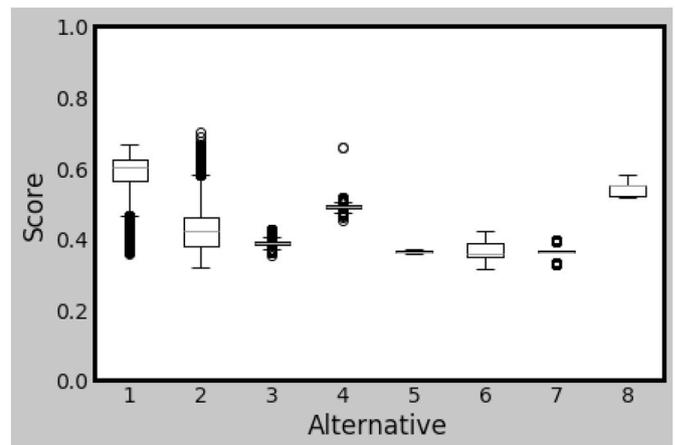


Fig. 5. The calculated risk scores for MCR-1 *E. coli* (=1), *Legionella longbeachae* (=2), Norovirus GII. 17 (=3), *Cryptosporidium parvum* (=4), prazosine (=5), perfluorooctanoic acid (=6), 3-(4-tert-Butylphenyl) propanal (=7) and minocycline (=8) based on only the hazard and exposure potential of the contaminants (leaving out secondary spread and relative importance of the exposure via drinking water). A score of 1 means high risk, a score of 0 low risk.

potential of contaminants in drinking water (ignoring the relevance of drinking water as an exposure route and the potential of secondary spread) (see Fig. 5)³ and one based on all criteria.

5.2.2. The prediction of indicator levels

The indicator for source availability could be improved. Here, source availability is considered a categorical variable and thus measured on a nominal scale. The use of continuous variables is preferred over nominal scales as they have more distinctive power. For chemical contaminants, the indicator could be improved by using emission load to the aquatic environment as indicator (e.g. in kilograms). The information sources shown in Supplementary material VI could be used as a starting point to develop such an indicator. The challenges would be to get information about plant protection products and animal medicines and to deal with emissions both in the Netherlands and upstream countries. For microbial contaminants, alternatives to expert judgment could be considered, such as information from wastewater surveillance systems (Lodder and de Roda Husman, 2020).

5.2.3. The preference model

As preference elicitation was outside the scope of this study, included value functions were based on previous research or assumed to be linear (see Table 5). Also, weights were assumed to be equal in the aggregation function which, furthermore, assumed full compensation between indicators. Future research should focus on preference elicitation to develop value functions and weights that reflect the subjective importance of different criteria and indicators to decision makers more realistically. Also, a sensitivity analysis should be performed to identify further steps in data collection and further model development. The need for an improved preference model can be illustrated by the over-estimated exposure potential of the microbial contaminants (see Fig. 4, especially for *Cryptosporidium parvum* (Nic Lochlainn et al., 2018)). A recent study by Wood et al. (2020) illustrated the challenges faced with similar preference elicitation.

³ To construct Fig. 5, the following adjustments to the code have to be made: Line 88 of `hierarchy_chemicals.py` with `children = [[6, 15]]`, and Line 82 of `hierarchy_pathogens.py` with `children = [[9,13]]`.

6. Conclusion

A decision support tool was developed for the integrated risk assessment of emerging chemical and microbial contaminants in drinking water using actor consultation and following the concept of value-focused thinking. With the decision support tool risk scores can be quantified for chemical and microbial contaminants for which evidence of their hazard and exposure potential is scarce. The contaminants to be ranked can be any list of aquatic contaminants that might influence the quality of drinking water. Information about these contaminants could for example be extracted from the scientific literature (Hartmann et al., 2019) or, in the case of chemical contaminants, from registration databases (such as the registration, evaluation, authorisation and restriction of chemicals (REACH) database). The computed risk scores and their associated uncertainty can be used for risk-based prioritisation of action on emerging chemical and microbial risks to drinking water. The value-focused approach applied in this study was thus able to address prevailing difficulties in evidence-based decision-making of emerging drinking water contaminants and to bridge varying disciplinary views.

As well as calculating risk scores, the developed assessment hierarchy also helps one to visualise the different information sources available for the assessment of emerging drinking water contaminants and its sources of uncertainty. The decision support tool was found to be an improvement on previously published prioritisation approaches as it is the first to be suitable for emerging risks, to combine uncertainty awareness with a multi-stakeholder approach and to integrate the assessment of chemical and microbial risks into one approach. Suggestions to improve the tool were made, such as the inclusion of preference information, more accurate prediction of indicator levels, and the possibility of prioritising mitigation actions instead of single contaminants. This study thereby guides future research in assisting policy makers to effectively protect public health from emerging risks to drinking water.

Credit author statement

Julia Hartmann: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing. **Juan Carlos Chacon-Hurtado:** Methodology, Software, Investigation, Formal analysis, Data Curation, Writing - Review & Editing. **Eric Verbruggen:** Methodology, Software, Investigation, Writing - Review & Editing. **Jack Schijven:** Methodology, Software, Investigation, Writing - Review & Editing. **Emiel Rorije:** Methodology, Formal analysis, Investigation, Writing - Review & Editing. **Susanne Wuijts:** Conceptualization, Investigation, Methodology, Writing - Review & Editing, Supervision, Funding acquisition. **Ana Maria de Roda Husman:** Conceptualization, Investigation, Methodology, Writing - Review & Editing, Supervision, Funding acquisition. **Jan Peter van der Hoek:** Conceptualization, Investigation, Methodology, Writing - Review & Editing, Supervision, Funding acquisition. **Lisa Scholten:** Conceptualization, Investigation, Methodology, Writing - Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2021.112902>.

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