Being prepared for the drinking water contaminants of tomorrow

An interdisciplinary approach for the proactive risk governance of emerging chemical and microbial drinking water contaminants

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DOI
10.4233/uuid:666aa030-557f-4a68-bf6e-8a464a3f0b9c

Publication date
2022

Document Version
Final published version

Citation (APA)
Hartmann, J. (2022). *Being prepared for the drinking water contaminants of tomorrow: An interdisciplinary approach for the proactive risk governance of emerging chemical and microbial drinking water contaminants*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:666aa030-557f-4a68-bf6e-8a464a3f0b9c

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Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Friday 8 July 2022 at 12:30 o'clock

by

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This research was funded by *the RIVM Strategic Research Project PS-DRINK (S/121014)*.

Keywords: drinking water; emerging contaminants; pathogens; chemical; microbial; early warning

Printed by: Ridderprint | www.ridderprint.nl

Cover design: ©evelienjagtman.com

An electronic version of this dissertation is available at http://repository.tudelft.nl/.

ISBN 978-94-6384-335-5

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation/acronym	***Explanation***
DWD	Drinking water Directive
DALY	Disability Adjusted Life Years
EC	European Commission
ECHA	European Chemicals Agency
EFSA	European Food Safety Authority
GenX	GenX is a technology used in the production of coatings. In the GenX technology, two compounds are being used which are both PFASs.
HBGV	Health Based Guideline Value(s)
IRGC	International Risk Governance Council
MCR-1	mobilized colistin resistance gene
NOAELs	No Observed Adverse Effect Levels
PFASs	per- and polyfluoroalkyl substances
PFC	Perfluorinated compounds
PFOA	Perfluoroctanooic acid
SDG	Sustainable Development Goal
UN	United Nations
WFD	Water Framework Directive
WHO	World Health Organisation

SUMMARY

“Access to safe drinking water is a fundamental human need and, therefore, a basic human right. Contaminated water jeopardizes both the physical and social health of all people”: such is the importance of safe drinking water, as stated by Kofi Annan, former Secretary-General of the United Nations, on World Water Day 2001.

While some countries are still struggling to protect their citizens from well-known drinking water contaminants, potential new drinking water risks from newly-identified chemical and microbial aquatic contaminants are appearing globally. The increasing detection of these emerging contaminants has been advanced by a combination of social, technological, regulatory, climatological and demographic developments. Recent examples of emerging contaminants are perfluoroalkyl and polyfluoroalkyl substances (PFAS), sapoviruses, pharmaceuticals and colistin resistant bacteria.

Whether emerging aquatic contaminants are a concern for drinking water safety depends on their exposure and hazard potential, which is influenced by a range of various determinants, including their mobility, toxicity and persistence in the environment, the severity and duration of the health effects caused by the contaminant, and the possibility for, and efficacy of, protective measures. Evidence, however, of these determinants is often limited. The challenge of protecting public health from emerging drinking water contaminants, therefore, does not only relate to identifying emerging contaminants as soon as possible, but also to prioritising the impact on human health which these contaminants have when evidence on their exposure and hazard potential is limited. Once identified and assessed, the challenge of effective risk communication under uncertainty needs to be dealt with as well. In this dissertation, an integrated approach to facilitate the early warning of, and communication on, emerging chemical and microbial drinking water contaminants has been developed.

Literature review

This dissertation addresses three gaps in the scientific literature. The first relates to the integrated assessment of emerging chemical and microbial drinking water contaminants. Literature on risk-based prioritisation approaches for emerging chemical and microbial drinking water contaminants has focussed almost exclusively on the assessment of either chemical or microbial contaminants. This has occurred despite the fact that (1) the pollution sources of, and potential mitigation actions against, chemical and microbial drinking water contaminants overlap enormously and (2) chemical and microbial contaminants can interact in drinking water (resources) and influence each other’s presence.

The second knowledge gap is the lack of methodological approaches that enable the proactive identification of potential new risks to drinking water safety and tackle the vicious circle of ‘no monitoring means no data, and no data means no regulations’. These approaches are needed urgently as scientific research has shown that it takes about 15 years after the first scientific study which mentions the presence of a contaminant in the environment, for the issue to peak in scientific attention and regulatory action.

The third knowledge gap relates to the communication on emerging drinking water risks to the general public. In the Netherlands, risk communication on drinking water contaminants often states that a hazardous chemical or microbial contaminant has been detected in drinking water but that no risk is associated with the presence of that contaminant as the doses do not exceed safety limits. Risk communication research indicates that consumers often misunderstand this kind of risk statement. There is limited scientific evidence on how to effectively communicate the (absence of) risks associated with emerging contaminants in drinking water.

Research aim and questions

To close these three identified knowledge gaps, the following research aim was defined:

To improve the risk governance of emerging chemical and microbial drinking water contaminants

The research aim was broken down into the following research questions:

- *I. What are the weaknesses in the current risk governance approaches for the identification of, and manner of dealing with, unregulated compounds in drinking water and its resources?*
- *II. How do we develop a method for the early identification of potential emerging chemical and microbial risks in drinking water (resources)?*
- *III. Is the developed methodology effective for the early identification of emerging chemical and microbial drinking water contaminants?*
- *IV. How do we prioritise microbial and chemical contaminants based on the risk they present to drinking water quality?*
- *V. How do we effectively communicate about emerging chemical and microbial drinking water risks to the public?*

Research strategy

The research strategy was based on concepts which originated in different scientific disciplines (e.g. toxicology, microbiology/ infectious diseases, risk assessment, data science, operations research and communication science). This resulted in a diverse set of research methods, including desk research, a field study, expert consultation sessions and a survey.

Desk research

The research in this dissertation was guided by a comparative analysis of risk governance approaches for the chemical contaminant Perfluorooctanoic acid (PFOA) in drinking water (resources) in the Netherlands, Germany, Switzerland and the state of Minnesota (research question 1, Chapter 2). Using quality indicators for effective risk governance, areas for improvement were identified. Furthermore, a methodology based on literature mining was developed to find the first report of a potential emerging chemical and microbial drinking water contaminant in the scientific literature (research question 2, Chapter 3). The efficacy of this methodology was validated with two retrospective cases of emerging drinking water contaminants (one chemical and one microbial) (research question 3, Chapter 3).

Field study

A field study was performed to investigate the efficacy of literature mining for early warning purposes, on top of the retrospective validation (research question 3, Chapter 4). Two sampling campaigns were set up based on the application of the text mining methodology to recent literature. Samples of Dutch municipal and industrial wastewater, surface water and drinking water were collected between May and October 2019.

Expert consultation

A decision support tool was developed to guide the integrated prioritisation of emerging chemical and aquatic contaminant's potential risk to drinking water safety. The decision support tool was developed using the philosophy of value-focused thinking, expert consultation sessions and an open-source Python library for uncertainty-aware decision analyses (research question 4, Chapter 5). Experts consulted included chemical and microbial risk assessors, drinking water experts and members of responsible authorities. Expert consultation sessions took place in July 2019 and January 2020.

Survey

A risk communication strategy for emerging drinking water contaminants was developed based on consumers' information needs (research question 5, Chapter 6). The efficacy was assessed with an online survey (N = 510). Data collection was performed in May 2020.

Major findings and their theoretical implications

The findings of the desk research and the validation of the text mining methodology illustrated that the main area for improvement in current risk governance approaches to emerging drinking water contaminants is the more timely identification of potential new chemical and microbial aquatic contaminants. Available information sources are not sufficiently structurally consulted.

The field study showed that literature mining is valuable in this regard, as four out of six contaminants were detected for the first time in surface water or wastewater in the Netherlands.

The results of expert consultation sessions indicated that the prevailing difficulties in integrated and evidence-based decision-making in regard to emerging chemical and microbial drinking water contaminants can be tackled by using a value-focused approach and an uncertainty-aware decision support tool. These prevailing issues include data scarcity and varying risk assessment methods.

Finally, the survey showed that risk communication about emerging drinking water contaminants could be improved by tailoring communication strategies to consumers' information needs. The results provide insight into, for instance, the importance of concerns about contaminants and the acceptance of norms when it comes to the effectiveness of communication about drinking water safety. This is in contrast to what is often thought by experts, who consider knowledge to be the major factor of influence.

Relevance for drinking water suppliers, policy makers and researchers

Based on the findings presented in this dissertation, suggestions for improving the risk governance of emerging contaminants in the Netherlands were made:

- Drinking water suppliers should consider combining literature mining with the risk-based prioritisation of contaminants when designing monitoring campaigns considering both microbial and chemical contaminants.
- Stakeholders of the Dutch drinking water sector (e.g. water authorities, drinking water companies and research institutes) should start a structural alert platform for the early warning of chemical and microbial drinking water risks. Such to be established structural alert platform would be invited to use the developed text mining and prioritisation methodology to structure the identification and integrated assessment of emerging drinking water risks.
- All actors communicating on emerging contaminants in drinking water to consumers are invited to tailor their risk communication towards the identified information needs of consumers.

To better understand the implications of the presented results, further research is suggested to:

- extend the text mining methodology to other information sources, such as media articles.
- further improve the effectiveness of the text mining methodology for identifying early signals of emerging drinking water risks by, for example, including semantic relationships in the methodology. Extension of the methodology to other environmental compartments, such as soil and air, is also deemed relevant.
- use the presented value-focused thinking approach to develop a decision support tool for emerging drinking water contaminants that also takes into account consumer’s concerns about a contaminant, and to extend the decision support tool to other exposure routes, such as food, or to prioritise mitigation measures instead of contaminants.

With the development of the integrated approach, this dissertation has tackled some of the key challenges of protecting human health from emerging environmental risks and has taken a first step towards the more structured, integrated and proactive risk governance of emerging chemical and microbial drinking water contaminants.

SAMENVATTING (IN DUTCH)

“Toegang tot veilig drinkwater is een primaire menselijke behoefte en dus ook een fundamenteel mensenrecht. Verontreinigd water brengt zowel de fysieke als de sociale gezondheid van mensen in gevaar”, het belang van veilig drinkwater zoals omschreven door Kofi Annan, voormalig Secretaris-Generaal van de Verenigde Naties op Wereldwaterdag, 2001.

Terwijl sommige landen nog moeite hebben met het beschermen van de volksgezondheid tegen bekende drinkwaterrisico’s, komen er wereldwijd potentieel nieuwe drinkwaterrisico’s op ten gevolge van recent geïdentificeerde chemische stoffen en micro-organismen. Het opkomen van deze verontreinigingen wordt veroorzaakt door een combinatie van sociale, technologische, klimatologische en demografische ontwikkelingen. Recente voorbeelden zijn poly- en perfluoralkylstoffen (PFAS), sapovirussen, geneesmiddelen en colistine-resistente bacteriën.

Óf recent in water geïdentificeerde chemische stoffen en micro-organismen een probleem vormen voor de productie van veilig drinkwater, hangt af van twee aspecten: hun blootstellingspotentieel, dat is de mate waarin de contaminant tot het drinkwater doordringt en hun hazardpotentieel, dat is hoe gevaarlijk de contaminant kan zijn voor de mens. Deze aspecten worden bepaald door een combinatie van eigenschappen van de contaminant, zoals diens mobiliteit, virulentie, resistentie en persistentie in het milieu, de ernst en duur van de door de contaminant veroorzaakte gezondheidseffecten, de mogelijkheid om beschermende maatregelen te nemen en de effectiviteit ervan. Voor opkomende contaminanten is de informatie over deze eigenschappen vaak beperkt voorhanden.

Als het gaat om het beschermen van de volksgezondheid voor opkomende drinkwaterrisico’s ligt de uitdaging dus niet alleen bij het vroegtijdig identificeren van opkomende stoffen en micro-organismen in water, maar ook bij het prioriteren van de respons op die verontreinigingen aan de hand van beperkte informatie. Eenmaal geïdentificeerd en beoordeeld, blijft het een uitdaging om over onzekere risico’s te communiceren. In dit proefschrift is een integrale methode ontwikkeld voor het vroegtijdig signaleren en beoordelen van, en communiceren over, opkomende stoffen en micro-organismen in drinkwater(bronnen).

Literatuuroverzicht

Dit proefschrift adresseert drie kennishiaten. De eerste is gerelateerd aan de integrale beoordeling van opkomende stoffen en micro-organismen in drinkwater(bronnen). Wetenschappelijke risico-gebaseerde prioriteringsmodellen voor opkomende stoffen en micro-organismen zijn vrijwel allemaal gericht op de beoordeling van óf chemische stoffen óf micro-organismen. Dit terwijl (1) de verontreinigingsbronnen voor, en potentiële mitigerende maatregelen tegen, stoffen en micro-organismen in drinkwater(bronnen) overlappen, en (2) chemische stoffen en micro-organismen in drinkwater(bronnen) met elkaar kunnen interageren wat hun aanwezigheid en beschikbaarheid kan beïnvloeden.

De tweede kennishiaat is het gebrek aan methoden die de proactieve identificatie van potentiële nieuwe drinkwaterrisico’s mogelijk maken en die de vicieuze cirkel van “gebrek aan monitoring leidt tot gebrek aan data, en gebrek aan data leidt tot gebrek aan regulering” doorbreken. Dit soort methoden zijn nodig aangezien onderzoek heeft laten zien dat het ongeveer 15 jaar duurt van de eerste wetenschappelijke studie die de aanwezigheid van een milieuverontreiniging rapporteert en het effect op de mens en/of milieu duidelijk maakt, totdat de aandacht voor de verontreiniging zijn hoogtepunt bereikt en regulering volgt.

De derde kennishiaat is gerelateerd aan de communicatie over opkomende drinkwaterrisico’s. In Nederland omvat risicocommunicatie over verontreinigingen in drinkwater vaak uitspraken als “een chemische stof of micro-organisme is aangetroffen in drinkwater, maar dit vormt geen risico voor de volksgezondheid, omdat de concentratie onder de veilige grenswaarde ligt”. Onderzoek heeft echter aangetoond dat burgers dit soort uitspraken vaak niet goed begrijpen. Er is beperkt wetenschappelijk bewijs voor strategieën voor het effectief communiceren over opkomende drinkwaterrisico’s.

Onderzoeksdoel en -vragen

Het volgende onderzoeksdoel is gedefinieerd om de genoemde kennishiaten op te vullen:

Het verbeteren van de risico governance van opkomende chemische stoffen en micro-organismen in drinkwater.

Dit onderzoeksdoel is uitgesplitst in de volgende onderzoeksvragen:

I. *Wat zijn beperkingen van huidige toegepaste risico governance benaderingen bij het identificeren en beoordelen van ongereguleerde verontreinigingen in drinkwater(bronnen)?*
II. *Hoe kunnen we een methode ontwikkelen voor het vroegtijdig identificeren van mogelijke opkomende chemische en microbiologische drinkwaterrisico’s?*
III. *Is de ontwikkelde methode effectief voor het vroegtijdig identificeren van opkomende chemische en microbiologische drinkwaterrisico’s?*
IV. *Hoe kunnen we chemische en microbiologische contaminanten prioriteren op basis van het risico dat ze vormen voor de drinkwatervoorziening?*
V. *Hoe kunnen we effectief communiceren over opkomende chemische en microbiologische drinkwaterrisico’s?*

Onderzoeksstrategie

De toegepaste onderzoeksstrategie is opgezet aan de hand van concepten uit verschillende wetenschappelijke disciplines, zoals toxicologie, microbiologie/ infectieziekten, risicobeoordeling, datawetenschappen, operationeel onderzoek en communicatiewetenschappen. Dit resulteerde in een verscheidenheid aan toegepaste onderzoeksmethoden, namelijk: deskresearch, veldonderzoek, expert consulatie en een vragenlijstonderzoek.

Deskresearch

De eerste stap in dit proefschrift was het analyseren en vergelijken van de risico governance benaderingen toegepast voor de chemische stof perfluoroctaanzuur (PFOA) in drinkwater in Nederland, Duitsland, Zwitserland en de Amerikaanse staat Minnesota (onderzoeksvraag 1, hoofdstuk 2). Op basis van kwaliteitsindicatoren voor effectieve risico governance benaderingen, zijn verbeterpunten geïdentificeerd. Vervolgens is een methode ontwikkeld waarmee met behulp van automatische tekstanalysetechnieken (textmining) het eerste signaal in de wetenschappelijke literatuur van een mogelijk opkomend drinkwaterrisico kan worden opgepikt (onderzoeksvraag 2, hoofdstuk 3). De effectiviteit van de textmining methode is gevalideerd aan de hand van twee retrospectieve casussen, één chemische casus en één microbiologische casus (onderzoeksvraag 3, hoofdstuk 3).

Veldonderzoek

De effectiviteit van de textmining methode is naast de retrospectieve validatie, ook gevalideerd met behulp van veldonderzoek (onderzoeksvraag 3, hoofdstuk 4). Twee monitoringscampagnes zijn opgezet op basis van het toepassen van de textmining methode op recente wetenschappelijke literatuur. Tijdens dit veldonderzoek zijn tussen mei en oktober 2019 monsters genomen van Nederlands huishoudelijk en industrieel afvalwater, oppervlaktewater en drinkwater.

Expert consulatie

Een beslissingsondersteunend model is ontwikkeld om opkomende stoffen en micro-organismen integraal te kunnen prioriteren. Daarbij is uitgegaan van het mogelijke risico dat deze contaminanten vormen voor de Nederlandse drinkwatervoorziening. Dit computermodel is ontwikkeld met behulp van de zogenaamde ‘value-focused thinking’ filosofie, expert consultatie sessies en een vrij verkrijgbare Python code (onderzoeksvraag 4, hoofdstuk 5). Bij de ‘value-focused’ thinking filosofie, ligt de nadruk op het specificeren van fundamentele doelen en subdoelen binnen het besluitvormingsproces. De gebruikte Python code biedt de mogelijkheid om onzekerheden in onder andere de data mee te nemen in het besluitvormingsproces. Geconsulteerde experts waren risicobeoordelaars van chemische stoffen en infectieziekten, drinkwaterexperts en beleidsmedewerkers. De expert consultatie sessies vonden plaats in juli 2019 en januari 2020.

Vragenlijstonderzoek

Met de informatiebehoefte van de burger als uitgangspunt is een risicocommunicatie strategie voor opkomende drinkwatercontaminanten ontwikkeld (onderzoeksvraag 5, hoofdstuk 6). De effectiviteit van deze strategie werd getest aan de hand van een online vragenlijst die is voorgelegd aan een burgerpanel (N = 510). Dataverzameling vond plaats in mei 2020.

Belangrijkste resultaten en hun theoretische implicaties

De resultaten van het deskresearch en de validatie van de tekstmining methode lieten zien dat vroegtijdige identificatie van mogelijke nieuwe risico’s het belangrijkste verbeterpunt is in de huidige risico governance van opkomende drinkwatercontaminanten. Beschikbare informatiebronnen worden nog niet structureel geraadpleegd.

Bovendien bleek uit het veldonderzoek dat tekstmining van wetenschappelijke literatuur waardevol is voor het vroegtijdig identificeren van opkomende drinkwatercontaminanten. Vier van de zes in oppervlaktewater en afvalwater gedetecteerde contaminanten werden immers nog niet eerder gemonitord in Nederland.

Verder lieten de resultaten van de expert consultatie sessies zien dat de grootste belemmeringen om opkomende drinkwatercontaminanten geïntegreerd en op bewijs gebaseerd te kunnen prioriteren overbrugd kunnen worden door een ‘value-focused’ benadering en het gebruiken van een computermodel waarin onzekerheden in de onderliggende data kunnen worden meegewogen.

De resultaten van de vragenlijst lieten tenslotte zien dat de effectiviteit van de risicocommunicatie over opkomende drinkwatercontaminanten verbeterd kan worden door de informatiebehoefte van burgers als uitgangspunt te nemen. De resultaten geven bijvoorbeeld inzicht in het belang van het meenemen van zorgen rondom drinkwatercontaminanten en normacceptatie. Dit is in tegenstelling tot wat er vaak wordt gedacht door experts, die kennis als belangrijkste factor voor de effectiviteit van risicocommunicatie bestempelen.

Relevantie voor drinkwaterbedrijven, beleidsmakers en onderzoekers

De volgende suggesties voor het verbeteren van de risico governance van opkomende drinkwatercontaminanten in Nederland kunnen worden gedaan op basis van de resultaten in dit proefschrift, namelijk:

- Drinkwaterbedrijven en waterbeheerders wordt geadviseerd om, bij het opzetten van monitoringscampagnes, de combinatie van de textmining methode en de risico gebaseerde prioritering van contaminanten in water mee te nemen.
- Belanghebbenden van de Nederlandse drinkwatersector (zoals relevante overheden, drinkwaterbedrijven en onderzoeksinstituten) wordt geadviseerd een signaleringsoverleg te starten voor de vroegtijdige identificatie en beoordeling van mogelijke nieuwe chemische en microbiologische drinkwaterrisico’s. Dit signaleringsoverleg zou de textmining methode als ook het ontwikkelde prioriteringsmodel kunnen gebruiken om de geïntegreerde identificatie en beoordeling van chemische en microbiologische drinkwatercontaminanten te structureren.
- Alle partijen die communiceren over opkomende drinkwaterrisico’s zouden hun risicocommunicatie aan moeten passen aan de informatiebehoefte van de burger.

Om de implicaties van het gepresenteerde onderzoek beter te doorgronden, worden onderzoekers uitgenodigd om:

- de textmining methode uit te breiden naar andere informatiebronnen, zoals nieuwsartikelen.

- de effectiviteit van textmining als early warning methode voor opkomende drinkwaterrisico's verder te verbeteren. Dit zou bijvoorbeeld kunnen door het meenemen van semantische relaties. Het uitbreiden van de methode naar andere milieucompartimenten, zoals bodem en lucht, is ook relevant.
- De aanpak, zoals gevolgd bij het opzetten van het prioriteringsmodel, te gebruiken voor het opzetten van een prioriteringsmodel voor opkomende drinkwaterrisico's waarbij de zorgen van burgers over contaminanten ook worden meegenomen. Ook zou eenzelfde aanpak gebruikt kunnen worden om een prioriteringsmodel voor andere blootstellingsroutes op te zetten, zoals voedsel, of voor het prioriteren van mogelijke maatregelen in plaats van contaminanten.

Met de ontwikkeling van een integrale aanpak voor het vroegtijdig signaleren en beoordelen van en communiceren over opkomende stoffen en micro-organismen in drinkwater(bronnen), heeft dit proefschrift een aantal uitdagingen in het beschermen van de volksgezondheid voor opkomende drinkwaterrisico's overwonnen. Hiermee is een eerste stap gezet richting een meer gestructureerde, integrale en proactieve benadering voor de risico governance van opkomende chemische en microbiologische drinkwaterrisico's.

1 INTRODUCTION

Having access to safe water for drinking, cooking and maintaining personal hygiene is one of the most important prerequisites for a healthy life [22]. In some parts of the world, the unlimited access to safe water is seen as a matter of course, but for roughly 30% of the world's population it represents an everyday struggle [23]. The United Nations (UN) is determined to overcome this inequality by adopting Sustainable Development Goal 6 (SDG 6). SDG 6 includes eight targets, including Target 6.1 which states that safe drinking water should be accessible and affordable for all humans by 2030. The Protocol on Water and Health, a pan-European agreement linking water management and the prevention of water-related diseases in Europe, plays an important role in operationalising SDG 6 by providing practical tools and guidance from lessons learnt [24]. The implementation of Target 6.1 in Europe is also included in Article 16 of the revised European Drinking Water Directive which came into force in January 2021. Although progress has been made over the past years to ensure safe drinking water for all [22], water quantity and water quality issues still stand in the way [25].

It might be hard to imagine that we face water scarcity on our blue planet whose surface is 71% water, but only 3% of that water is freshwater and less than 0.5% of it is accessible to humans as a drinking water resource [26]. At the time of writing, more than 2 billion people are living in regions which experience water stress and this number continues to rise due to the consequences of climate change [27]. Water scarcity will thus remain a major limiting factor in achieving Target 6.1 [25]. Another key limiting factor is the deteriorating quality of our limited drinking water resources because of anthropogenic pollution [23, 28].

Both water quality and quantity issues present not only a struggle for countries that have trouble with achieving Target 6.1. In the Netherlands, for example, nearly all citizens have access to clean and safe drinking water and sanitary facilities (Target 6.1). However, in terms of improving water quality by eliminating dumping and minimising the release of hazardous chemicals and materials (Target 6.3) for example, there is still work to be done [29-31]. Minimising the release of hazardous chemicals is difficult for several reasons, one of which being the vast amount of chemicals used every day and the fact that it is not always known which of these are hazardous to humans and/or the environment. Another challenge involves the promotion of resistant pathogens that emerge upon contact with hazardous chemicals and materials e.g. heavy metals [32].

Currently, 100 million chemicals are registered in the Chemical Abstracts Service (CAS) database [33]. The risk posed by most of these chemicals is unknown, in fact only for a very small number of these chemicals, and an even smaller number of their transformation products and metabolites, presented risks to the environment and humans are known. Furthermore, chemicals are not the only contaminants being released into the aquatic environment by human activities. Microbial contaminants are also released via, for example, human wastewater discharges (included in Target 6.3) and include bacteria, protozoa, algae, fungi and viruses.

Not all microbial contaminants are disease causing or pathogenic, just as not all chemicals are toxic, but some bacteria, viruses or protozoa can cause severe acute, and chronic, health effects via drinking water. Again, just as is the case for chemicals, we have not identified all the microbial contaminants that are present in the aquatic environment and new microbial contaminants emerge every day [34]. Accepting the uncertainty of not knowing the entire chemical and microbial composition of our drinking water resources, raises the question as to how we can effectively protect drinking water safety.

A common approach to this end is the identification of new aquatic contaminants through screening efforts. This approach is rather ad-hoc and reactive as mitigation actions are only taken when the contaminants have already reached the drinking water resource. In addition, once identified, mitigation actions should focus on the contaminants which pose the highest threat to public health via drinking water, but this is challenging, as newly-identified aquatic contaminants are different by nature, evidence about their hazard and exposure potential is often scarce, and experts can disagree on the evaluation of their disease potential. In this dissertation, an integrated approach is developed to tackle these challenges, focussing on drinking water production in the European context, specifically on drinking water production in the Netherlands. When using the results and conclusions of this dissertation in other countries, the context in those countries should be taken into account.

1.1 Sources for chemical and microbial pollution of drinking water

Both groundwater and surface water are used as drinking water resources around the world and both are susceptible to chemical and microbial pollution caused by human activities [35]. In this dissertation, surface water as a drinking water resource includes rivers and lakes. Chemical pollution is the release of manmade (or anthropogenic) chemicals and their metabolites into the environment. Drinking water resources can also be contaminated with naturally-occurring chemicals (such as arsenic [36]). Microbial pollution refers to the occurrence of bacteria, viruses and protozoa, of which some might be disease causing, which are then referred to as pathogens. Microbial pollution occurs, for instance, due to the release of domestic or agricultural wastewater, recreation, animal excretion, but it can also originate from the environment itself. Both anthropogenic and naturally occurring chemical and microbial aquatic contaminants can present a threat to environmental and human health.

Groundwater is influenced by human activities on, and in, the (sub-)soil and through its connection with surface water [37]. Anthropogenic pollution of surface water, such as rivers and lakes, occurs due to 1) the discharge of municipal and industrial wastewater, 2) run-off from agricultural land and urban areas, 3) direct contamination by animal (e.g. from fish or birds) or human excretion, sweat or saliva , 4) (illegal) waste dumps, 5) sewage overflows, 6) waterbed pollution and 7) recreation and shipping [38-40]. Once in the environment, contaminants might persist for days, weeks and even months, and travel far from their initial source of pollution. The impact of human activities on surface water quality occurs directly after pollution, whereas the impact of chemical and microbial environmental pollution on groundwater quality can take years to manifest because of the ground passage barrier. The chemical and microbial pollution of drinking water can also occur during treatment (e.g. disinfection by-products) or distribution (e.g. regrowth of microbial contaminants in distribution systems) [41, 42]. Figure 1-1 shows an overview of the different sources of chemical and microbial pollution of drinking water in the Netherlands. For more information on drinking water production in the Netherlands, see Section 1.5.

Figure 1-1 reveals the large overlap between chemical and microbial drinking water pollution sources. For some contaminants pollution sources are obvious, the accidental emissions of contaminants from industrial sites, for example, are often associated with the emission of chemical contaminants (e.g. the accidental release of pyrazole in the Meuse in 2015 [43]). Others are less obvious, such as the industrial pollution which leads to the contamination of the aquatic environment with pathogens. An example of the later was the accidental release of poliovirus from a vaccine-producing company in Belgium [44]. The same applies to illegal waste dumps, which often raise concerns about the leaching of chemicals. But, in some cases, microbial contaminants might also leach out of the waste. An example of this occurs when the waste of synthetic drug production is mixed with manure and then illegally dumped on soil (e.g. [45]).

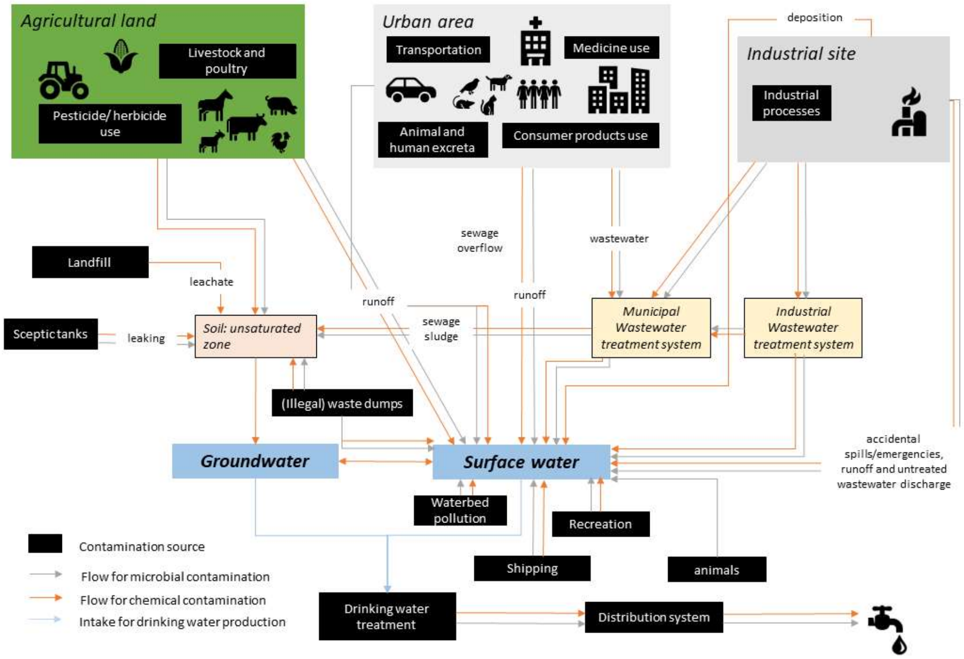

__Figure 1-1 Overview of the different sources of chemical and microbial pollution of drinking water in the Netherlands. Surface water includes lakes and rivers.__

Besides having similar pollution sources, it's also worth mentioning that chemical and microbial contaminants can both originate from, and interact in, the aquatic environment or the drinking water supply system, thereby increasing or decreasing each other's presence [46]. Examples of such interactions include 1) the influence of antimicrobial pharmaceuticals on the rise of antimicrobial resistant microbial contaminants [46], 2) the increase in Legionnaires' disease caused by *Legionella* *pneumophila* in drinking water distribution systems as a result of the presence of lead and iron in the water [47], and 3) the degradation of chemicals by microbial contaminants in the water [48].

Based on the large overlap between chemical and microbial drinking water pollution sources and the interaction between chemical and microbial contaminants, approaches which integrate the risk assessment of chemical and microbial aquatic contaminants are preferred over single-type contaminant approaches [49]. Integrated assessments enable the identification of actions that are effective for several types of chemical and microbial contaminants [50] and prevent actions where the elimination of risk posed by one contaminant is traded off against the higher risk posed by another [41], thereby allowing for the effective use of scarce public resources [51]. Despite all of this, integrated approaches are rarely published [52-54].

1.2 Well-known versus emerging drinking water contaminants

The potential health effects posed by some manmade, and naturally-occurring, chemical and microbial contaminants in drinking water have been well-studied [55]. Examples of these include arsenic [56] and *Cryptosporidium* [57]. How the risks posed by chemical and microbial drinking water contaminants are assessed in the Netherlands is explained in Section 1.4.2.

Over the last decades, more and more, previously unknown, microbial and chemical aquatic contaminants are causes of concern for scientists, drinking water suppliers and regulators. Recent examples are the group of Polyfluorinated Alkyl Substances (PFAS) [58] and sapoviruses [59].

PFAS is a group of manmade chemicals which have been used in many industrial applications since the 1940s. Perfluorooctane sulphonic acid (PFOS) and Perfluorooctanoic acid (PFOA) were the most used members of the PFAS group, but were phased out because of their persistence in the environment, their bioaccumulative properties and their toxicity (also known as PBT properties). In the Netherlands, and many other countries, PFOA was replaced by the industry with 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)-propanoic acid (HFPO-DA trade name GenX) in 2012 [60]. HFPO-DA, and other replacements of PFOS and PFOA, are molecules with shorter chains of carbon atoms than the originally used PFAS. These shorter chain molecules were considered less hazardous as they are less likely to bioaccumulate.

However, recent evidence has shown that the shorter chain replacements are of particular concern in terms of drinking water quality, as some of them are also persistent and toxic, as well as mobile in the environment [60]. The mobility is due to their hydrophilic properties, which also makes them more resistant to drinking water treatment systems. HFPO-DA is indeed detected in Dutch drinking water and its resources [61]. In July 2019, HFPO-DA was categorised a Substance of Very High Concern by the European Chemicals Agency (ECHA) [62]. This shows that this new category of substances with PMT properties can be cause for a similar level of concern as chemicals with PBT properties [60]; this is also illustrated by the inclusion of a legal limit for PFAS in drinking water in the revised European Drinking Water Directive. Whether this legal limit is stringent enough to protect human health is under discussion following a recent report drawn up by the European Food Safety Authority (EFSA) [63].

An example of microbial aquatic contaminants that are cause for increasing concern related to drinking water safety are sapoviruses. The gastroenteritis caused by exposure to sapoviruses in drinking water is similar to the one caused by noroviruses [59]. Sapoviruses are not newly discovered but due to the improvement of analytical techniques (see for more details Section 1.3.1) they can now be analysed in drinking water related outbreaks and sporadic cases. A rising number of publications shows the increasing role of sapoviruses in drinking water to be a public health concern, as was reviewed by Kauppinen et al. [59]. However, though linked to acute gastroenteritis in 2010 from drinking water exposure [64] sapovirus is still not always included in waterborne outbreak investigations and often the causative agent remains unidentified as was seen, for example, in a large recent outbreak in Northern Greece [65]. Novel approaches should not just be developed [66] but also adopted in outbreak investigations; monitoring programs for the prevention of the microbial contamination of drinking water should also be implemented.

PFAS and sapoviruses, and other contaminants for which recent scientific and/or public concern has been expressed, are referred to in the scientific literature as: emerging contaminants [67], emerging substances [68], contaminants of emerging concern [69], emerging pollutants [70] or emerging pathogens [71]. As is the case with sapoviruses, these contaminants are not necessarily restricted to recently emerged contaminants, but also to the rising concern that scientists and/or policy makers have had recently about their presence in the environment. This might be because these contaminants have only recently been detected, or are newly emitted or produced, or because their presence in the environment had not been considered a human or environmental health risk until new scientific evidence on their toxicity or pathogenicity was published [72-74]. An overview of the terminology and definitions used by various international organisations and partnerships is given in Table 1-1.

Table 1.1 illustrates the diversity in definitions of emerging chemical and microbial contaminants. A review of the scientific literature in January 2017 revealed that the main criteria used to define a pathogen as an emerging pathogen are 1) an expanded geographical and/or host range [72, 82-95], 2) an increased incidence [72, 84-86, 88-91, 96, 97] and/or 3) recently being discovered/recognised [72, 84, 87, 88, 90, 91]. The most important criteria to define a chemical as an emerging contaminant were: 1) recently being detected in the environment [37, 73, 98-105], 2) being unregulated [16, 103, 106-120] and 3) being a potential threat to the environment and living organisms [16, 98-100, 102-104, 106, 109, 111, 115, 119, 121-123] (or a combination thereof). These criteria show the overlap as well as the differences between the definitions used for emerging chemical and microbial contaminants.

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Table 1-1 Terminology used by different international organizations and partnerships to indicate new or emerging chemical and microbial contaminants.

Terminology	Definition *(used by organization/partnership)*
Emerging substances	Substances that have been detected in the environment, but which are currently not included in routine monitoring programs at EU level and whose fate, behaviour and (eco)toxicological effects are not well understood. *The NORMAN Network (Network of reference laboratories, research centres and related organisations for monitoring of emerging environmental substances) [75]*
Emerging pollutants	Pollutants that are currently not included in routine monitoring programs at the European level and which may be candidates for future regulation, depending on research on their (eco)toxicity, potential health effects and public perception and on monitoring data regarding their occurrence in the various environmental compartments. *The NORMAN Network (Network of reference laboratories, research centres and related organisations for monitoring of emerging environmental substances) [75]*
	Any synthetic or naturally-occurring chemical or any microorganism that is not commonly monitored or regulated in the environment with potentially known or suspected adverse ecological and human health effects. *UNESCO (the United Nations Educational, Scientific and Cultural Organization) [76]*
	Substances that have the potential to enter the environment and cause adverse ecological and human health effects, but are still largely unregulated and whose fate and potential effects are poorly understood. *The Joint Research Centre of the European Commission [77, 78]*
Emerging pathogens	Pathogens that have newly appeared in a population or have existed but are rapidly increasing in incidence or geographic range. *The United States Environment Protection Agency (US EPA) (based on the definition of the National Institute of Allergy and Infectious Diseases) [79]*
	Emerging pathogens are those that have appeared in a human population for the first time, or have occurred previously but are increasing in incidence or expanding into areas where they have not previously been reported, usually over the last 20 years. *The World Health Organization (WHO) [80]*
Emerging risk	A risk resulting from a newly identified hazard to which a significant exposure may occur, or from an unexpected new or increased significant exposure and/or susceptibility to a known hazard. *European Food Safety Agency (EFSA) [81]*

In this dissertation the term *emerging contaminant* will be used to refer to both chemical and microbial contaminants that pose a potential new or increased risk to public health via drinking water. The risk might be real, expected or perceived:

- A *real risk* occurs when the contaminant is known to be present in drinking water at disease causing levels. As evidence on the hazard and exposure potential of emerging contaminants is often missing, the related risk often starts out as an expected one.
- An *expected risk* occurs when new evidence is published on either the presence of the contaminant in drinking water or its resource, or on its toxicity or pathogenicity. Additional research is needed to identify the real risk that the contaminant might pose to humans via drinking water.
- A *perceived risk* occurs when a drinking water contaminant is present which might not affect the physical safety of drinking water but does influence the consumer's perception of the safety of that drinking water [124]. These contaminants are also of interest to drinking water suppliers and policy makers, as consumers who perceive their drinking water as unsafe will look for alternatives, such as bottled water or sodas, which is undesirable from both public health and sustainability perspectives [124-127].

1.3 Increasing issue of emerging chemical and microbial drinking water contaminants

Detection of emerging contaminants in drinking water and its resources is expected to increase in the future due to different technological, demographic, societal, regulatory and climatological developments. Each of these developments and how they might influence the increasing detection of emerging contaminants in drinking water (resources) is clarified in Sections 1.3.1 to 1.3.5. Many of these developments will not only result in the increased detection of emerging contaminants in drinking water resources, but also in other environmental compartments, such as soil and air.

1.3.1 Technological developments

Technological advances in analytical techniques that have been achieved over the past years have enabled the detection of chemicals and microbial contaminants in drinking water which, until recently, remained undetected [128, 129]. The first relevant development in this regard is that analytical methods for known (groups) of contaminants have become more sensitive [130, 131]. Another important development in the field of analytical chemistry is the rise of nontarget or unknown analytical methods. With traditional analytical techniques the analyst had to know what contaminant to look for in the water sample, but with nontarget analytical methods, a water sample can be analysed for a wide range of unknown chemical contaminants [128]. A final significant technological development related to the detection of emerging chemical contaminants in the aquatic environment, is the rise of effect-directed analytical methods [132]. Using effect-directed analyses, the presence of unknown contaminants in a water sample can be traced back by the biological response that the water sample induces.

In regard to the technological advances made in the field of analytical microbiology which are relevant to the detection of emerging pathogens, the trend towards molecular techniques instead of approaches that rely on identification through culturing or microscopy is promising [129]. Another relevant development, is the use of next-generation sequencing (NGS) [133], a technique which allows for a very high number of parallel sequencing results to be achieved in a short amount of time. NGS can be used to define the genomes or target regions of DNA and RNA, which is a valuable tool in the identification of emerging pathogens, including waterborne pathogens. Mass Spectrometry (MS) has also proved to be useful for the identification of microbial contaminants in water samples and detection of microbial waterborne threats [134].

While all of these novel analytical methods still have their obstacles (e.g. too costly or time-consuming or problematic for water matrices), it is evident that they will spur the detection of emerging chemical and microbial contaminants in drinking water and its resources. As well as advances in analytical techniques, advances in water treatment approaches could also lead to emerging contaminants in drinking water. The advanced oxidation processes used for drinking water treatment [135] and wastewater treatment [136] are good examples of this, as they could lead to the formation of, yet unknown, unwanted transformation products or resistant pathogens. Another relevant example in this regard is the recovery of wastewater for reuse in cooling towers, as part of a more circular economy approach, which might increase the growth of legionella bacteria [137].

1.3.2 Demographic and societal changes

The changing size or characteristics of the human population, also referred to as demographic change, can increase the concentration of emerging contaminants in drinking water resources. For example, a growing and ageing population will consume more pharmaceuticals which could end up in surface water through municipal wastewater discharges [138, 139]. Also, the corona pandemic has shown us that when a high number of people are not immune to a pathogen, then the infection risk increases which, in turn, leads to an increase of the pathogen in wastewater discharges to surface water [140].

Demographic changes might also induce societal change, which could increase the detection of emerging chemical and microbial aquatic contaminants. One such example is the increase of industrial activities in developing economies around the world where often limited environmental protection policies are in place [141]. Another is the increasing use of certain household cleaning and disinfection products as a result of cultural changes or for infectious disease prevention [142].

1.3.3 Globalisation

We live in a highly globalised world, which means that humans as well as consumer products travel around the globe. This increase in global travel increases the spread of pathogens which can enter the aquatic environment via municipal wastewater [143]. It also increases shipping, which is a potential pollution source for chemical and microbial aquatic contaminants (see Figure 1-1). The exact influence of globalisation on environmental quality remains unknown [144].

1.3.4 Regulatory changes

In Europe, the production and use of industrial chemicals has been regulated by the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation since December 18th 2006. Also, the Classification, Labelling and

Packaging (CLP) Regulation ((EC) No 1272/2008) is in place to determine whether a substance or mixture displays properties that should lead to a hazardous classification. Biocidal products are regulated by the Biocides Directive (Directive 98/8/EC). For pharmaceuticals, the European Medicines Agency (EMA) evaluates and monitors medicines within the European Union (EU) and the European Economic Area (EEA).

Regulators might determine that a specific chemical (or group of chemicals) need(s) to be phased out because of its/their hazardous properties (e.g. persistence in the environment and their human and/or environmental toxicity). In that case, the industry will innovate their industrial processes and look for chemicals with similar properties that can be used to replace the phased-out chemical(s). History has taught us, that in some cases this leads to the use of even riskier chemicals. The replacement of toxic contaminants with even more toxic ones is also known as *regrettable substitution* [70]. A recent example of regrettable substitution was the replacement of Bisphenol A, a suspected endocrine disruptor, in children's consumer products, by Bisphenol S. Several studies have shown Bisphenol S to also have worrying toxicology properties [145]. These and other regrettable substitutions could be the emerging drinking water contaminants of tomorrow.

To the best of my knowledge, no regulatory changes have led or are expected to lead to the emergence of new aquatic pathogens.

1.3.5 Climate change

The master thesis by van der Sluis [146], performed in the context of this dissertation, reviewed the scientific literature for processes in which climate change could impact the chemical and microbial quality of surface water. The worst-case Dutch climate change scenario (W_H) of the Royal Netherlands Meteorological Institute (KNMI) was used to determine which of the identified processes are expected to be most dominant for the Dutch context. The W_H scenario considers a high global temperature rise of 3.5 °C in 2085 compared to the reference period (1981-2010). The major consequences of climate change for the weather conditions in the Netherlands are anticipated to be increased precipitation events, with milder winters and hotter summers [147]. The results and conclusions presented in the master thesis are included here to illustrate the potential impact of climate change on the increasing detection of drinking water contaminants in the future.

Van der Sluis [146] concluded that the most dominant effects of climate change on Dutch surface water resources were increasing air temperature, which results in an increasing water temperature, and increasing episodes of rainfall and other precipitation. The increasing water temperature creates a favourable environment for pathogens that grow in relatively high water temperatures. These pathogens are thus likely to pose an increased threat to Dutch drinking water in the future [148]. Also, chemical substances that are present in certain products (e.g. plant protection products, veterinary medicines and certain pharmaceuticals) are expected to be increasingly detected in drinking water resources as their use increases in response to a warming climate.

Another dominant effect relates to the annual changes in precipitation. Due to a substantial rise in average winter precipitation (30%) and maximum hourly rainfall intensity in the summer (22 to 45%), contaminants that can be transported to the main river system by runoff, resuspension, or combined sewage overflow, will pose a higher threat to drinking water in the Netherlands. A decreasing amount of average rainfall in the summer (minus 23%) will lead to a lower dilution capacity of surface water, resulting in increasing concentrations of contaminants in drinking water resources.

Other relevant effects of a changing climate on water quality were found to be nutrient loading, dissolved oxygen concentration, freshwater acidification and salinization. However, the direction and magnitude of their impact on the presence of chemical and microbial contaminants in Dutch drinking water resources is uncertain.

The impact of climate change on the detection of emerging contaminants in drinking water and its resources is already noticeable in the Netherlands. In 2015, for example, an emerging chemical contaminant, later identified as pyrazole, was detected in high concentrations in the Meuse, a river used for the production of drinking water in the south of the Netherlands [149]. Pyrazole was discharged via industrial wastewater into the Meuse because of a malfunctioning wastewater treatment plant. The level of the concentrations was strongly affected by the low river discharge of the Meuse following a long-lasting drought [150]. Also, Nichols et al. [150] analysed rainfall around drinking water related outbreak events in England and Wales and provided evidence that both very low rainfall, as well as heavy rainfall events, can lead to drinking water outbreaks. In regard to the effects of climate change on the microbial quality of groundwater, Schijven and de Roda Husman [148] reported no climate effects in wells where the pumping rate was the determining factor for the groundwater table and flow rate.

1.4 Risk governance of emerging drinking water contaminants

Risk governance in the context of this dissertation refers to the identification, appraisal, management, and communication of information regarding potential emerging chemical and microbial risks to drinking water quality [126, 151]. To illustrate the risk governance process of emerging drinking water contaminants, the framework of the International Risk Governance Council (IRGC) was used, a framework which has proven applicable to the risk governance of emerging chemical and microbial risks on earlier occasions [152, 153].

The five steps of the risk governance process, and what they entail, are described in Table 1-2. A few current issues with the risk identification and assessment of, and risk communication on, emerging chemical and microbial drinking water contaminants are discussed in Sections 1.4.1 to 1.4.3.

Table 1-2 A description of the five steps of the risk governance process, based on Table 2-3 of Hartmann et al. [126].

Steps of the Risk Governance process of emerging contaminants in drinking water	Description of the steps
Identification of emerging contaminants	The processes and information sources used during the identification of potential emerging chemical and microbial risks to drinking water quality.
Risk appraisal a. Hazard assessment (HA) b. Exposure assessment (EA) c. Concern assessment (CA)	The risk assessment based on the intrinsic properties of the identified contaminant, and the measure of exposure, combined with the assessment of associations and perceived consequences that stakeholders might associate with the contaminant [151].
Risk acceptance	The evaluation of whether the identified risk is "acceptable", "tolerable" or "intolerable" [151].
Risk management	The development and implementation of measures taken to avoid, decrease, transfer or retain the risk posed by the identified contaminant [151].
Risk communication	Assisting the public in understanding the risk assessment results and risk management decisions [154].

1.4.1 Risk identification of emerging contaminants

In terms of the identification of emerging chemical contaminants, there is a common understanding between scientists and regulators that we are caught in a vicious circle in which "no regulation means limited monitoring of a contaminant, no monitoring means no data, and no data means no regulation" [33]. Also, developing and implementing regulation takes time. Scientific research has shown that it takes about 15 years between the first scientific study mentioning the presence of a contaminant in the environment for the issue to peak in scientific attention and regulatory action [155]. The period between the first scientific publication to the time at which it reaches the peak of scientific attention and regulatory action has been referred to as the 'period of emergence of concern' [155, 156]. Shortening the period of emergence of concern can accelerate the introduction of regulatory actions to control chemical contaminants in the environment and thus limit environmental effects.

Although research, in this regard, has focussed specifically at the emergence of concern about chemical contaminants [155, 156], similar conclusions can be drawn for emerging microbial contaminants [156]. Specific pathogens have been shown (in retrospect) to be present in the environment and linked to human sources long before the disease that they cause had gained attention (e.g. the Aichi Virus [157, 158]).

1.4.2 Risk assessment of chemical and microbial drinking water contaminants in the Netherlands

To protect human health from the chemical and microbial pollution of drinking water, legal standards have been included in the Dutch Drinking Water Act (2015) for a selection of chemical and microbial contaminants. Legal standards for chemical and microbial contaminants in drinking water are different in terms of how they are derived and as to what it means when the standard is met. This is explained in detail in Section 1.4.2.1 for chemicals and in Section 1.4.2.2 for microbial contaminants.

The differences in the nature of legal standards for, and the monitoring of, chemical and microbial drinking water contaminants can be traced back to a few fundamental differences between them (based on World Health Organization [55]):

- The risk posed by chemical contaminants in drinking water is often related to long-term exposure, during which a chemical accumulates in the human body up to a level that can induce a health effect. Pathogens do not accumulate in the body. Repeated exposure to the same pathogen may even lead to immunity.
- The health effect associated with the exposure to chemicals in drinking water can occur years after exposure (e.g. cancer), whereas for pathogens the human health effect may manifest within days after exposure. There are, however, some pathogens which can induce both acute and long-term or chronic health effects, which means in this case that related health effects are not only present days or weeks after exposure but may last for years (e.g. long-term effects from Legionnaires' disease, also referred to as sequelae).
- Pathogens can multiply in the distribution system of drinking water, which can lead to recontamination of drinking water after drinking water treatment. Chemicals cannot multiply, but can be transformed into sometimes more hazardous transformation products and metabolites.
- The risk assessment for chemicals is based on animal studies or on studies with cell lines, whereas the risk assessment for pathogens is often based on information on health effects in humans (including results from volunteer studies or outbreaks). This difference is partly due to the fact that pathogens induce a health effect in humans that manifests hours to weeks after the subject has been exposed to them in drinking water. For chemicals, the health effect caused by the exposure to the chemical can happen years after exposure (e.g. for carcinogenic chemicals).
- Risk monitoring for chemicals in drinking water is most commonly based on risk-based water quality targets (a maximum concentration in drinking water or intake water), whereas standards for microbial contaminants can also be based on performance targets. These performance targets assist in choosing and controlling measures to prevent pathogens from breaching the barriers of source protection, treatment and distribution systems, and prevent growth within the distribution system.
- Risk assessment for chemicals is often done in a contaminant for contaminant manner (with a few exceptions), whereas pathogens are mostly assessed and monitored as groups with similar properties (viruses, bacteria and parasites).

1.4.2.1 Chemical risk assessment for Dutch drinking water

Legal standard setting for chemicals in drinking water in the Netherlands starts with a risk assessment of that chemical by the Dutch National Institute for Public Health and the Environment (RIVM). The RIVM will propose a health-based guideline value, or health-based limit, to the Ministry of Infrastructure and Water Management

(IenW). This health-based guideline value represents the concentration in drinking water that does not adversely affect human health even over a lifetime consumption of that drinking water [127]. The ministry will set the legal standard based on the proposal by the RIVM, but will also take into account the technical and economic feasibility of that limit value, societal concerns and the protection of drinking water resources for future generations. The legal standard is then used to monitor the safety of Dutch drinking water according to the Dutch Drinking Water Act (2015). This section will focus on the risk assessment process used by the RIVM to calculate a health-based guideline value.

Risk assessment of chemicals in drinking water differs for threshold and non-threshold chemicals [127, 159]. In the case of threshold chemicals, a level of exposure is assumed below which no adverse health effect occurs. For non-threshold chemicals (genotoxic carcinogens), however, no such level exists as exposure to one additional molecule can cause cancer by inducing DNA mutations [160].

For threshold chemicals, the level below which no adverse health effect occurs is often based on a 'no observed effect' level found in animal toxicity testing. Using Uncertainty Factors, this level is then extrapolated to humans [127, 159, 161, 162]. For non-threshold chemicals, a theoretically acceptable excess lifetime cancer risk is used to determine acceptable levels in drinking water (e.g. 1 excess case of cancer per 100,000 people according to the WHO [159]) [127]. For both threshold and non-threshold chemicals, a tolerable daily intake (TDI) per kilogram bodyweight is calculated. De Poorter et al. [163] can be consulted for details on how the RIVM derives a TDI.

The TDI is multiplied by a standard body weight (70 kg in the Netherlands) and the relative importance of drinking water compared to other exposure routes (e.g. air or food). Twenty percent allocation is the standard allocation percentage for exposure by consumption of drinking water in the Netherlands [11, 127]. This allocation percentage can be as high as 80 percent if drinking water is the most important exposure route (e.g. in the case of disinfection by-products) and can be reduced to as low as 2 percent (e.g. for artificial sweeteners) when another route, e.g. food, is known to be the dominant route [55, 127]. The height of the resulting health-based guideline value (HBGV) is greatly affected by these differences in allocation percentage [127]. As a final step to determine acceptable levels in drinking water, the estimated daily intake of drinking water is taken into consideration (e.g. 2 litres in the Netherlands) [127, 159, 161, 162]. The following equation summarizes the calculation of the HBGV for drinking water:

$$HBGV = \frac{Tolerable\ Daily\ intake \times standard\ body\ weight\ \times allocation\%}{Daily\ consumption\ of\ drinking\ water}$$

With regard to emerging chemical contaminants, toxicity data might be unreliable or insufficient. Therefore, health-based guideline values need to be determined using other approaches. The threshold of toxicological concern (TTC) approach is such an alternative approach [11, 18, 127, 164, 165]. The TTC is based on the idea that contaminants with similar structures have similar toxic properties [11, 18, 127, 164, 165]. The use of the TTC approach and related approaches to derive HBGVs has been explained in depth elsewhere [11, 164, 166]. HBGVs may differ between countries when, for instance, risk assessments are based on contaminant specific toxicity data (e.g. use of different standard body weights or different exposure allocations to drinking water) or when the TTC approach is used (with different threshold values used for different classes) [126, 167, 168].

1.4.2.2 Microbial risk assessment for Dutch drinking water

According to the Dutch Drinking Water Act [169], 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. The microbial risk assessment for Dutch drinking water is founded upon a health-based outcome target that states that viruses, bacteria and protozoa are acceptable in drinking water up to concentrations that cause infection in less than 1 in 10,000 consumers of unboiled tap water per year.

Because the concentration of pathogens equal to the mentioned health outcome target is typically too low to be measured in the final product drinking water, index pathogens and indicators are measured in source water. Indicator organisms have similar characteristics to the index pathogens, and are thus assumed to respond to drinking water treatment processes similarly to the index pathogens. Appropriate indicator organisms are chosen based on the fact that these are present in higher numbers in the water. Using QMRA, the concentration measured in the source water can be used to calculate the possible risk posed by exposure to the pathogen in drinking water. QMRA has four stages, namely the hazard identification, the corresponding dose-response relationship, exposure assessment and risk characterisation. The hazard identification is done in the source water in combination with the efficiency of the various treatment steps. Using this information, the possible exposure to microbial contaminants can be estimated. The exposure assessment is combined with the dose-response relation for the pathogen to estimate the possible risk [170].

1.4.3 Risk communication on emerging contaminants in Dutch drinking water

The World Health Organization (WHO) has defined safe tap water as water that *does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages* [55]. Next to this physical aspect of safe drinking water, the safety of tap water as perceived by consumers is also crucial because consumers who perceive tap water to be unsafe will search for alternatives to drink, e.g. bottled water or sodas, which, as mentioned before, is undesirable from sustainability and health perspectives [124, 171, 172]. Therefore, even if the presence of emerging contaminants in drinking water does not pose a risk to the physical safety of drinking water, it might still influence the perceived safety. Effective risk communication is thus crucial.

In the Netherlands, risk communication on drinking water contaminants often states that a hazardous chemical or microbial contaminant has been detected in drinking water but that no risk is associated with the presence of that contaminant as the doses do not exceed safety limits. Risk communication research indicates that consumers often misunderstand this kind of risk statements [127, 173, 174].

Although there is published research on the risk communication on emerging contaminants in drinking water, there is limited evidence on effective communication strategies for emerging contaminants in drinking water [175].

1.5 Drinking water production in the Netherlands and its regulatory context

The research presented in this dissertation was conducted for the Netherlands where ten companies ensure the production and supply of safe and clean drinking water to almost all citizens. Also, some recreational parks, breweries, and saunas have their own drinking water intake and supply system.

Both surface water and groundwater are used for drinking water production in the Netherlands. Groundwater is used for 58% of the Dutch drinking water production, 35% is produced from surface water, 6% from riverbank filtration and 1% from natural dune water [30, 176]. The rivers Rhine and Meuse and the lake IJsselmeer are the main surface water resources in the Netherlands [30, 176]. Dutch drinking water is of very high quality due to the use of preventive risk assessment and risk management from source to tap, good asset management, and the application of a multi-barrier approach in drinking water treatment [169, 170, 176, 177]. Emerging contaminants in drinking water (resources) have led to substantial regulatory challenges and media attention, despite the high quality of drinking water in the Netherlands [61, 126, 176, 178].

The responsibility for the safety and sustainability of drinking water in the Netherlands rests with the Ministry of Infrastructure and Water Management (IenW) as is stated by the *Dutch Drinking Water Act (2015)*. The quality of drinking water is dependent on the quality of drinking water resources. These are influenced, among other things (see Section 1.1), by municipal and industrial wastewater discharges. The chemical and microbial quality of industrial and municipal wastewater discharges, surface water, groundwater and drinking water are all regulated. Table 1-3 shows European directives and the derived Dutch regulations on chemical and microbial contaminants in drinking water, surface water, municipal and industrial wastewater and groundwater based on Table 1.1 of Wuijts [157]. This table illustrates the difference between regulatory frameworks in the Netherlands for the chemical and microbial quality of surface water and groundwater. Although the guidelines for drinking water quality by the World Health Organization (WHO) [55] are not included in Table 1-3, it should be noted that this and other WHO reports have exerted great influence on both European as well as Dutch regulations on drinking water and surface water quality.

Table 1-3 European and Dutch regulations which are relevant for chemical and microbial contaminants in drinking water, surface water, municipal and industrial wastewater and groundwater using Table 1.1 of Wuijts [179].

	Relevant regulations for chemical contaminants		**Relevant regulations for microbial contaminants**	
	European	*Netherlands*	*European*	*Netherlands*
Drinking water quality	Drinking Water Directive (DWD) (EU) 2020/2184 (revision of 98/83/EC)	Dutch Drinking Water Act (2015)	Drinking Water Directive (DWD) (EU) 2020/2184 (revision of 98/83/EC)	Dutch Drinking Water Act (2015)
Surface water quality	Water Framework Directive (EU) 2000/60/EG	Water Act (2009)*	Water Framework Directive (EU) 2000/60/EG**	
		Water Quality Requirements and Monitoring Decree (2009)		
	Priority Substances Directive (EU) 2013/39/EU			
			Bathing Water Directive (EU) 2006/7/EC	Decree on hygiene and safety of bathing establishments and swimming facilities
Municipal and industrial wastewater effluent quality	Urban Waste Water Directive (EU) 91/271/EEC	Water Act (2009) (for discharges to surface water)*	Urban Waste Water Directive (EU) 91/271/EEC	Water Act (2009) (for discharges to surface water)*
		Environmental Protection Act (1979) (for discharges to the sewer)*		Environmental Protection Act (1979) (for discharges to the sewer)*
		General Provisions Act Wabo (2009) (for discharges to the sewer)*		General Provisions Act Wabo (2009) (for discharges to the sewer)*
Groundwater quality	Groundwater Directive (EU) 2006/118/EC	Environmental Protection Act (1979)*		Environmental Protection Act (1979)*
		Fertiliser Act (1986)		
		Pesticides and Biocides Act (2007)		
		Soil Protection Act (2017)		
		Water Act (2009)		

* These regulations will be collected into the Environment and Planning Act by 2022 (planning still under discussion)

** Directive 75/440/EEG, which included microbiological parameters, was transferred to the Water Framework Directive (EU) 2000/60/EG

On a European level, the protection of drinking water resources is regulated by the *Water Framework Directive (WFD) (2000/60/EG)*, which was introduced in 2000. The objective of this Directive is to present an all-encompassing framework for the protection of rivers and lakes, coastal waters and groundwater for now and for future generations. One of the new requirements from the Directive compared to previous Directives, is the obligation of Member States to create river basin districts and draw up river basin management plans for these districts. Another new obligation imposed by the WFD on Member States was that drinking water resources should be included in Protected Areas Registers by Member States. The river basin management plans should include the characterisation and assessment of impacts on river basin districts, environmental monitoring, setting of environmental objectives and monitoring and measuring plans.

Under the WFD, in the Priority Substance Directive (2013/39/EU), a list of priority substances and groups of substances is included for which environmental quality standards are set. These substances include certain plant protection products, biocides and metals. Monitoring of these priority substances is required within the river basin management plans. Furthermore, so-called watch lists consisting of chemicals that might be included in the list of priority substances in the future should also be monitored. These can include emerging contaminants. The first Watch List (WL) was established in March 2015 and was updated in June 2018. A proposal for the third Watch List was published by the European Commission in 2020 [180]. Next to monitoring these substances, Member States can, within river basin districts, incorporate more substances in the monitoring plan based on the hazards that are expected to be found in the river basin district that may impact water quality.

Next to the *Water Framework Directive*, the *Drinking Water Directive (DWD)* (*Council Directive (EU) 2020/2184, revision of 98/83/EC)* is in place in Europe, and implemented in the Dutch Drinking Water Act (2015). The DWD is aimed at safeguarding the quality of water intended for human consumption (either tap water or bottled water) by stating the essential quality standards at the European level. Member States are free to determine more stringent quality standards. Amongst other influences, the *Drinking Water Directive* is founded on the risk-based approach stipulated by the World Health Organization (WHO) in combination with the precautionary principle. In the Netherlands, the precautionary principle for chemical emerging contaminants is implemented by including a general threshold value (or signalling parameter) of 1 μg/L for unregulated anthropogenic compounds in surface water and groundwater used for the production of drinking water [6]. The threshold value was set at 1 μg/L more than 20 years ago, based upon the detection limit at that time, and serves as a catalyst to initiate research on possible health risks. Today, the detection limit for most anthropogenic substances is 0.1 μg/L or even lower. However, van der Aa et al. [11] concluded that 1.0 μg/L is safe for most contaminants, but for a limited number of highly hazardous contaminants a stricter value would be necessary. Next to the signalling parameter, a signalling value of 0.1 μg/L is in place for water used for the production of drinking water as stated in the Dutch Water Quality Requirements and Monitoring Decree (2009).

Up to January 12th 2021, the DWD 98/83/EC put the European Member States under an obligation to frequently test, monitor and report 48 microbiological, chemical and indicator parameters and to provide regular information to consumers about the quality of their drinking water. The revised DWD came into force on January 12th 2021. Member States have two years to implement the revision into their national legislation. Some of the revisions made are relevant to the issue of emerging contaminants in drinking water resources, namely: the inclusion of endocrine disruptors and PFAS, as well as microplastics, and a preventive approach favouring actions to reduce pollution at source by introducing the "risk-based monitoring approach". This is based on an in-depth analysis of the whole water cycle, from source to distribution.

1.6 Societal relevance

At present, emerging chemical and microbial drinking water risks are not assessed in a systematic way, but in a rather reactive and incidence-based way (see Sections 1.2, 1.4 and 1.5). In addition, the assessment of chemical and microbial drinking water contaminants is done separately despite similar pollution sources (see Section 1.2) and drivers of risk (see Section 1.3). As a result, risks might not be addressed early enough leading to human health risks and potential expensive control measures. Furthermore, it should be taken into account that, despite the fact that the presence of emerging contaminants in drinking water might not affect the physical safety of drinking water, consumer perception of drinking water quality can still be affected. Therefore, including public risk perception in assessing emerging contaminants is warranted [181, 182].

1.7 Scientific relevance: knowledge gaps

Based on the information provided in the previous sections, three knowledge gaps can be identified regarding the risk governance of emerging chemical and microbial drinking water contaminants:

1. Despite the need for integrated risk assessments of emerging chemical and microbial drinking water contaminants (see Section 1.1), these are rarely published [52-54] (see Section 1.1). This is probably due to data scarcity and differences in risk evaluation methods applied (see Section 1.4.2).
2. There are no approaches that enable the proactive identification of potential new risks to drinking water safety and tackle the vicious circle of "no monitoring means no data, and no data means no regulations" [33]. There are also none that reduce the period of emergence of concern [155] (see Section 1.4).
3. There is lack of scientific evidence on how to effectively communicate the (absence of) risk associated with emerging contaminants in drinking water (Section 1.4.3).

1.8 Research aim and research questions

To take the first steps toward closing the identified knowledge gaps (Section 1.7), the overarching research aim of this dissertation is:

To improve the risk governance of emerging chemical and microbial drinking water contaminants

Here, improving means making the process more effective in ensuring drinking water safety. This eventually is also expected to improve the efficiency of the risk governance process as more effective risk governance of emerging drinking water contaminants might prevent the need for costly mitigation actions. This dissertation will not go into the legitimacy of the risk governance process.

It is hypothesised that the overarching research aim can be accomplished by developing and applying an integrated approach to the identification, assessment of and communication on emerging chemical and microbial drinking water risks. To this end, the following research questions are formulated:

I. *What are the weaknesses in the current risk governance approaches for the identification of, and manner of dealing with, unregulated compounds in drinking water and its resources?*
II. *How do we develop a method for the early identification of potential emerging chemical and microbial risks in drinking water (resources)?*
III. *Is the developed methodology effective for the early identification of emerging chemical and microbial drinking water contaminants?*
IV. *How do we prioritise microbial and chemical contaminants based on the risk they present to drinking water quality?*
V. *How do we effectively communicate about emerging chemical and microbial drinking water risks to the public?*

1.9 The structure of this dissertation

This dissertation opens in **Chapter 1** with background information on drinking water safety and its assessment, the research aim and questions, as well as its societal and scientific relevance.

In **Chapter 2** a range of policy approaches used for the risk governance of emerging contaminants in drinking water and its resources in the Netherlands, Germany, Switzerland and the state of Minnesota in the United States are compared in order to find weaknesses. To overcome the identified weaknesses, a methodology for the early identification of potential emerging chemical and microbial drinking water risks is developed using literature mining. The development of this semi-automated methodology is discussed in **Chapter 3**. The effectiveness of the methodology for early warning purposes is assessed in **Chapter 4**.

A decision support tool is developed in **Chapter 5** to assist policy makers and drinking water companies in targeting action at those contaminants that pose the highest threat to public health via drinking water. The challenge of improving the risk communication on emerging drinking water contaminants is ad.dressed in **Chapter 6**.

Chapter 7 includes a general discussion on the contribution of this dissertation to the overall research aim – to improve the risk governance of chemical and microbial drinking water contaminants. Besides discussing the relevance of this dissertation in the light of other research done in the field of emerging drinking water contaminants and presenting a general conclusion, suggestions for scientists, policy makers and drinking water suppliers are made to improve the future risk governance of emerging chemical and microbial contaminants in drinking water and its resources.

Table 1-4 shows the research questions analysed in Chapters 2 to 6. To answer those research questions a highly interdisciplinary approach is followed. Chapters 2 to 6 each use concepts originating from different scientific disciplines, including, next to chemical and microbial risk assessment, data science (**Chapter 3**), analytical chemistry and microbiology (**Chapter 4**), operations research (**Chapter 5**) and communication science (**Chapter 6**). Detailed background information to these concepts is included in each chapter.

Table 1-4 Analysed research question per chapter in this dissertation.

Chapter	Analysed research question
2	What are the weaknesses in the current risk governance approaches for the identification of, and manner of dealing with, unregulated compounds in drinking water and its resources?
3	How do we develop a method for the early identification of potential emerging chemical and microbial risks in drinking water (resources)?
4	Is the developed methodology effective for the early identification of emerging chemical and microbial drinking water contaminants?
5	How do we prioritise microbial and chemical contaminants based on the risk for drinking water quality?
6	How do we effectively communicate about emerging chemical and microbial drinking water risks to the public?

2 RISK GOVERNANCE OF EMERGING DRINKING WATER CONTAMINANTS: ANALYSING CURRENT PRACTICES

Abstract

The presence of emerging contaminants in the aquatic environment may affect human health via exposure to drinking water. And, even if some of these emerging contaminants are not a threat to human health, their presence might still influence the public perception of drinking water quality. Over the last decades, much research has been done on emerging contaminants in the aquatic environment, most of which has focused on the identification of emerging contaminants and the characterisation of their toxic potential. However, only limited information is available on if, and how, scientific information is implemented in current policy approaches. The opportunities for science to contribute to the policy of emerging contaminants in drinking water have, therefore, not yet been identified.

In this chapter[1], a comparative analysis was performed of current approaches to the risk governance of emerging chemical contaminants in drinking water (resources) to identify any areas for improvement. The policy approaches used in the Netherlands, Germany, Switzerland and the state of Minnesota were analysed using the International Risk Governance Council framework as a normative concept. Quality indicators for the analysis were selected based on recent literature. Information sources used were scientific literature, policy documents, and newspaper articles.

Subsequently, suggestions for future research for proactive risk governance are given. Suggestions include the development of systematic analytical approaches to various information sources so that potential emerging contaminants to drinking water quality can be identified quickly. In addition, an investigation into the possibility and benefit of including the public concern about emerging contaminants into the risk governance process was encouraged.

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[1] This chapter is based on Hartmann J, van der Aa M, Wuijts S, de Roda Husman AM, van der Hoek JP. Risk governance of potential emerging risks to drinking water quality: Analysing current practices. Environmental Science & Policy. 2018;84:97-104

2.1 Introduction

Human activities affect the chemical and microbial composition of the aquatic environment. The effects on water quality may be both direct and indirect. Direct effects include the release of anthropogenic chemicals into freshwater resources as a result of industrial and municipal wastewater discharges [114]. An example of an indirect effect is the positive correlation between the temperature increase caused by climate change and pathogen survival in aquifers [183]. Because of demographic and environmental changes such as rapid urbanisation and extreme rainfall, the intensity and number of these direct and indirect effects is expected to increase [141, 184].

Newly recognised potential hazards in the aquatic environment are often referred to as emerging contaminants and may be of both microbial and chemical nature. In this study, we focus on emerging chemical contaminants. The presence of emerging chemical contaminants in the aquatic environment may be a threat to human health, as water resources are being used for recreation as well as food and drinking water production. In addition, even if some of these emerging contaminants were not of concern from a public health point of view, their presence might still influence the public perception of drinking water quality [18]. Negative risk perception of drinking water quality might lead consumers to search for alternatives to tap water. Alternatives include bottled water and sweetened beverages, which are related to sustainability issues and in some cases even human health concerns [125, 171, 172]. Therefore, emerging contaminants are defined here as any chemical compound that may pose a new, or increased, threat to public health through the exposure to drinking water. The threat might be real, perceived or expected.

In regard to drinking water production, it is the emerging chemical contaminants found in groundwater [37], and surface water resources [114] that are of particular concern. Examples include pharmaceuticals, personal care products, and microplastics [185]. Technological advances in analytical techniques will enable the detection of even more contaminants in the future. Thus, the effective risk governance of emerging contaminants in drinking water and its resources is and will remain very important in order to protect public health.

Over the past years, much research has focused on emerging contaminants in the aquatic environment [130]. Studied topics include: the identification of emerging contaminants through screening efforts [186], the prioritisation of monitoring programmes [187], and the investigation into the toxicological potential of emerging contaminants [35, 188]. The risk management of emerging contaminants in drinking water [189], and in the environment in general, has also been studied [100]. However, as far as we understand, any research into the risk governance of emerging contaminants in drinking water and if, and how, scientific knowledge is implemented into current policy approaches has not yet been published.

This paper describes a comparative analysis of a range of existing policy approaches to the risk governance of emerging contaminants in drinking water and its resources. The objective is to identify areas in current risk governance approaches that are suitable for improvement and make suggestions for future scientific research, which will add to the proactive risk governance of emerging contaminants in drinking water.

2.2 Analytical approach

2.2.1 The IRGC risk governance framework

In this study, the risk governance framework issued by the International Risk Governance Council (IRGC) was used as a normative concept. Risk governance refers to the identification, assessment, management, and communication of potential chemical risks to drinking water quality [151]. The IRGC framework was chosen because of its proven applicability to the risk governance of emerging chemical and microbial risks [152, 153].

The IRGC risk governance framework consists of five elements: pre-assessment, risk appraisal, risk evaluation, risk management and risk communication. We redefined two steps of the five elements to make them more readily applicable to the governance of drinking water contaminants. Pre-assessment and risk evaluation were redefined into identification of emerging contaminants and risk acceptance respectively.

2.2.2 Selected countries and state

Transboundary differences in a river catchment area were examined using the policy approaches for emerging contaminants in drinking water employed by the Netherlands, Germany and Switzerland, countries which all lie within the Rhine River catchment area. The Rhine is a multifunctional river that is used for transportation purposes, power generation, and urban sanitation, while at the same time providing drinking water for 25 million people [190]. These characteristics make the Rhine highly susceptible to the influence of emerging contaminants and thus interesting for the purpose of this paper.

Minnesota is one of the few jurisdictions which has a specific programme in place aiming explicitly at the identification and risk assessment of emerging contaminants in drinking water (The Minnesota Department of Health Contaminants of Emerging Concern (MDH CEC) program) (http://www.health.state.mn.us/cec). Therefore, the policy approaches used in the Netherlands, Germany and Switzerland were compared to the approach used in the state of Minnesota (the United States of America). This programme has also been analysed by Naidu et al. [122].

2.2.3 Quality indicators

For the analysis of the risk governance process, suggestions for best practice in the governance of emerging contaminants proposed by Naidu et al. [100] and Naidu et al. [122] were used for defining quality indicators. The suggestions for best practice that were considered were (1) the integration of science into policymaking, (2) the acceptance of the risk governance process by all stakeholders, (3) the defensibility of decisions made, and (4) the consideration of other factors as well as public health-risk reduction when choosing remediation strategies.

Number 2 was not used as a direct indicator. To analyse the acceptance levels of all the relevant stakeholders during the risk governance process required having insight into which stakeholders were involved in the process first. However, this information was not available. We therefore evaluated the stakeholders who were involved in each of the five elements of the risk governance process.

Furthermore, the defensibility of decisions made (3) can be ensured by creating transparency. Indeed, transparency is stated by the IRGC [151] and the Organisation for Economic Co-operation and Development (OECD) [191] as one of the principles of good governance. We therefore chose to assess transparency as a quality indicator. Transparency was evaluated upon the sharing of information with involved stakeholders during all elements of the risk governance process.

2.2.4 Incidences of PFOA in drinking water or its resources

Four incidences of the same emerging contaminant in drinking water resources and/or treated drinking water were assessed. The emerging contaminant of choice was Perfluorooctanoic acid (PFOA). Additional information on PFOA is included in Textbox 2-1.

PFOA is an anthropogenic chemical, which belongs to the group of per- and poly-fluorinated compounds. PFOA is hydrophobic, oleophobic, and hydrophilic due to its completely fluorinated carbon chain and carboxylic group. Because of these characteristics, PFOA has been widely used in many products over the past decades, for instance in the production of polytetrafluoroethylene and paints [4, 5] and is ubiquitously found in the aquatic environment [10]. PFOA has also been detected in drinking water [14] and shown to have adverse human health effects, such as on the reproductive system [15, 16]. Consequently, PFOA has been identified as a potential risk to drinking water quality [5].

Textbox 2-1 Additional information on the emerging contaminant Perfluorooctanoic acid (PFOA).

Table 2-1 shows the selected incidences of PFOA in drinking water per country/state. From now on, these incidences of pollution will be referred to as cases. A description of each case can be found in Textbox 2-2.

Table 2-1 Overview of the selected incidences of PFOA contamination of drinking water resources and/or treated water.

Case	Method by which the contaminant was identified	When identified	Source of pollution	Time of pollution	References
PFOA in the rivers Ruhr and Möhne, Germany	A scientific publication	2006	Soil improver containing industrial waste	Not known	[1-3]
PFOA in Dordrecht, the Netherlands	A publication of an investigation into the same polluter in the United States	2016	Industrial wastewater	1970-2012	[7, 8]
PFOA in Basel, Switzerland	Target monitoring of drinking water for per- and poly-fluorinated compounds	2011	Not known	Not known	[12, 13]
MDH response to new health advisory Environmental Protection Agency (EPA), Minnesota	A publication of lower health advisory level by the EPA	2016*	Industrial waste	Not known	[17, 192]

*First discovery of contaminated groundwater was in 2002 [192].

The selected German case is the first major incidence of detected high PFOA concentrations in a drinking water resource [1-3]. In 2006, a scientific publication revealed elevated levels of several PFCs in the Ruhr and Möhne, which resulted in PFOA concentrations of up to 0.5 µg/L in drinking water. The pollution was found to be the result of a soil improver used in agriculture, which encompassed industrial waste containing PFCs [1]. No Health Based Guideline Values (HBGVs) for PFOA exposure via drinking water had been derived at that time.

The selected Dutch case is the investigation into possible contaminated groundwater near the city of Dordrecht, which had been used for the production of drinking water. The groundwater was found to be polluted by PFOA as the result of industrial wastewater discharges and subsequent infiltration into groundwater in the period of 1970-2012 [7, 8]. The identification of the possible pollution in 2015 was initiated by the publication of an investigation into the same polluter in the United States.

For Switzerland, the elevated levels of PFOA in drinking water as detected in the Canton of Basel in 2011 were selected as case [12, 13]. These elevated levels were identified in a monitoring program initiated by the Canton of Basel, which specifically aimed at detecting PFCs.

Finally, the response in Minnesota to the recent publication of new and lower drinking water health advisories (70 p.p.t.) for PFOA by the US Environmental Protection Agency (EPA) was selected as the case for the state of Minnesota [17].

Textbox 2-2 A description of each of the analysed incidences of PFOA in Chapter 2.

2.2.5 Risk communication

In risk communication, two different models of communication can be distinguished, described by Ramirez-Andreotta et al. [193] as the technical and the cultural models. The technical model uses one-way communication to inform the public, change behaviour and assure people of the acceptability of the risk as determined by experts. In contrast, the cultural model is based on two-way communication and includes the opinions of the affected public in the risk assessment element.

In this study, the type of communication model used in the different cases was determined. Furthermore, a quantitative analysis of the risk communication process during the four selected cases was performed. During this process, we assumed that less media coverage meant that there would be less tumult in the affected society, and thus less public concern. Although it is recognised that the relationship between news media coverage and public opinion is a dynamic process, studies have shown that information on risks provided by news media may influence public risk perception [194]. The analysis was therefore based on the number of published newspaper articles before, during and after the incident of pollution. Newspaper articles were searched in LexisNexis® using search strings listed in Table 2-2.

Table 2-2 Search strings for LexisNexis® search on published newspaper articles on incidences of PFOA in drinking water (resources). For more information on the selected incidences, see Textbox 2-2.

Case of	**Search criteria**	**Start date**	**End date**	**Database**
Germany	(PFOA AND trinkwasser) OR (PFT AND trinkwasser) OR (Perfluor! AND trinkwasser)	01-01-2005	01-01-2008	German Language news
The Netherlands	(PFOA AND drinkwater) OR (PFT AND drinkwater) OR (Perfluor! AND drinkwater) OR (PFC AND drinkwater)	01-01-2000	01-06-2017	Dutch Language news
Minnesota, US	(PFOA AND drinking water) OR (PFT AND drinking water) OR (Perfluor! AND drinking water) OR (PFC AND drinking water) OR (EPA AND PFOA) AND (Minnesota W/3 water)	01-01-2016	01-06-2017	Midwest Regional Stories Midwest Regional Stories - Most Recent Two Weeks Minnesota News Sources Newsbank - Minnesota News Sources
Switzerland	(PFOA AND trinkwasser) OR (PFT AND trinkwasser) OR (Perfluor! AND trinkwasser)	01-01-2010	01-01-2014	Swiss newspapers available in LexisNexis®

Figure 2-1 is a graphical representation of the analytical approach used in this study. The comparative analysis of the risk acceptance, risk management and risk communication approaches is illustrated by the selected cases (see paragraph 2.4).

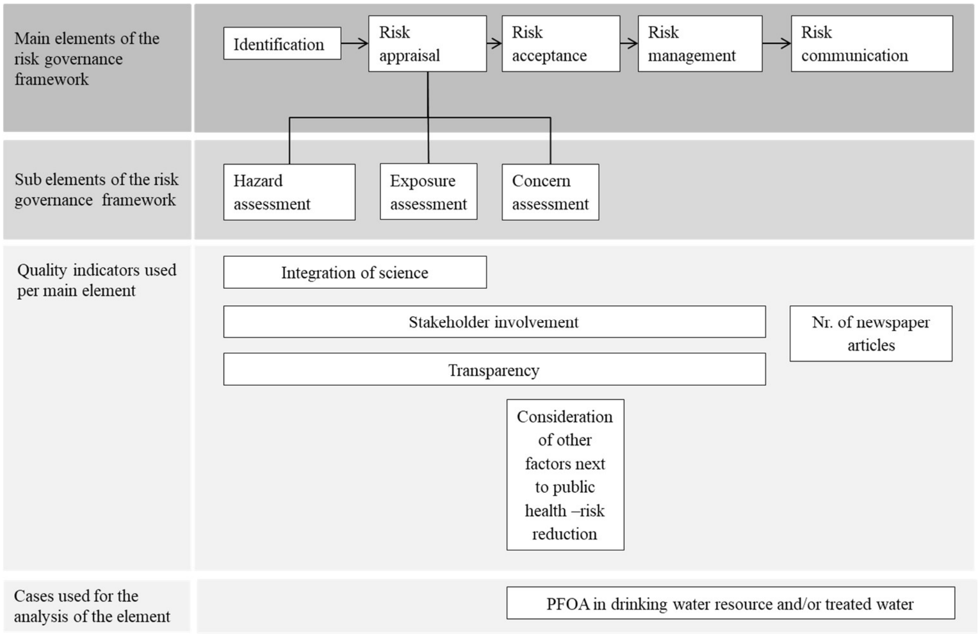

Figure 2-1 Graphical representation of the analytical approach used in this study.

In Table 2-3, a short description of what the main elements are based on and the key questions used for the interpretation of the quality indicators are shown.

2.3 Results

The results of the comparative analysis will be described per element of the risk governance framework as shown in Figure 2-1. The evaluation of one of the quality indicators, namely stakeholder involvement, is described separately for practical reasons.

2.3.1 Identification of emerging contaminants

In Minnesota, the first step in the identification process of possible emerging contaminants in drinking water was voluntary nomination by stakeholders via the website of the MDH CEC program.[2] By November 2016, state government agencies, advocacy organisations, and citizens had nominated 117 contaminants [195]. Nominations were mostly based on monitoring studies or studies that revealed new toxicity data (Katie Nyquist, personal communication). Nominated contaminants were selected for further review if (1) they were, or potentially could be, found in surface water or groundwater in Minnesota (2) there were no Health Based Guidance Values (HBGVs) in Minnesota (3) they posed a real or perceived health threat, or (4) there was new or changing health or exposure information [196]. A list of nominated contaminants including argumentation for nomination (if available) and whether the contaminant was selected for further review was published on the MDH CEC webpage.

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[2] http://www.health.state.mn.us/divs/eh/risk/guidance/dwec/nominate.cfm

Table 2-3 A short description of the main steps of the Risk Governance framework of the IRGC and the key questions used for the interpretation of the quality indicators used for the comparative analysis of four incidences of PFOA in drinking water (resources).

Steps of the Risk Governance framework of emerging contaminants in drinking water	Description of the step of the Risk Governance framework (IRGC [151])	Quality indicators (Naidu et al. [100]) and (Naidu et al. [122])	Key questions for the evaluation of the regulatory frameworks based on the quality indicators
Identification of emerging contaminants	The processes and information sources used during the identification of potential emerging risks to drinking water quality.	- Integration of science - Stakeholder involvement - Transparency	What information sources are used? Which stakeholders are involved? Is all information available to relevant stakeholders?
Risk appraisal a. Hazard assessment (HA) b. Exposure assessment (EA) c. Concern assessment (CA)	The combination of the risk assessment based on the intrinsic properties of the identified contaminant and the measure of exposure as well as the assessment of associations and perceived consequences that stakeholders might associate with the contaminant [151].	- Integration of science - Stakeholder involvement - Transparency	What is the scientific basis for the HA and EA? Which stakeholders are involved in the HA, EA, and CA? Is all information available to relevant stakeholders?
Risk acceptance	The evaluation of whether the identified risk is “acceptable”, “tolerable” or “intolerable” [151].	- Consideration of other factors next to public health-risk reduction - Stakeholder involvement - Transparency	What other factors (next to public health risk) are taken into account when evaluating the need for action? Which stakeholders are involved?
Risk management	The development and implementation of measures taken to avoid, decrease, transfer or retain the risk posed by the identified contaminant [151].	- Stakeholder involvement - Transparency	Which stakeholders are involved? Who is responsible for the risk management?
Risk communication	Assisting the public in understanding the risk assessment results and risk management decisions [154].	- Number of newspaper articles	What is the trend in the public concern about the contaminant during the selected case studies?

In Switzerland, Germany and the Netherlands, identification of emerging contaminants was mainly based on the monitoring of drinking water (resources) and the screening efforts made by drinking water suppliers as well as national government agencies [2, 11, 165, 197]. Details on the trigger values used can be found in Textbox 2-3. The identification process was less transparent compared to that of Minnesota, as not all monitoring and screening data were publicly available.

Scientific literature [3] and media articles were also found to be sources for the identification of possible emerging contaminants to drinking water. However, none of the analysed policy approaches appeared to contain formal procedures for any evaluation of these information sources to be made.

In the Netherlands, a general threshold value (or signalling value) of 1 μg/L was used for unregulated anthropogenic compounds in surface water, groundwater and drinking water [6]. The threshold value was set at 1 μg/L more than 20 years ago based upon the detection limit at that time and served as a catalyst to initiate research on possible health risks. Today, the detection limit for most anthropogenic substances is 0.1 μg/L. The Dutch National Institute of Public Health (RIVM) recently assessed whether the threshold value should be set at a lower value [11]. The assessment was based on the potential human health impact via exposure to drinking water of 42 unregulated anthropogenic substances recently detected in drinking water (resources) (based on Schriks et al. [18] and Baken and Sjerps [19]). It was found that the Health Based Guideline Value (HBGV) for drinking water was below 1 μg/L for only the two substances PFOA and PFOS. For these perfluorinated compounds, quality standards are proposed in the recent proposal for a revision of the Council Directive 98/83/EC on the Quality of Water Intended for Human Consumption [20]. In the Dutch policy evaluation it was concluded that the threshold value of 1 μg/L serves well as a as a pragmatic approach and catalyst to initiate an obligatory research on possible health risks. Important part of this approach are elaborate screening and risk based monitoring programs that focus on all emerging contaminants in the water supply chain, also at lower concentration levels [11].

In Switzerland and Germany, no such signalling value was used. However, in the Rhine River catchment area a system is in place called AQUALARM. AQUALARM is a cooperation between seven international stakeholders, among which Swiss (Canton Basel's environment and energy agency), Dutch (Rijkswaterstaat, which is part of the Dutch Ministry of Infrastructure and the Environment), and German (several regional government agencies in Düsseldorf, Mainz und Wiesbaden) stakeholders, who monitor the water quality of the Rhine. Here, the laboratories used a threshold value of 3 μg/L for unregulated anthropogenic organic polar and non-polar compounds [21].

Textbox 2-3 Details on the trigger values used in Switzerland, Germany and the Netherlands for identification of emerging contaminants

2.3.2 Risk appraisal

In the Netherlands, Germany and Switzerland, the aim of the hazard assessment was to determine whether there was a need to develop HBGVs and whether it was feasible to do so. In the MDH CEC program, the hazard and exposure assessments were merely two of the factors that were taken into account by the MDH CEC program staff when evaluating the need for developing HBGVs. Other factors that were taken into account include the need for and feasibility of developing HBGVs [196].

2.3.2.1 Hazard assessment

The potential risk posed by the contaminants selected for review in the MDH CEC program was evaluated by scoring the contaminant using relevant potency and exposure data. The method used for scoring the contaminants was described extensively in a recent review by Lewandowski et al. [196]. The hazard assessment was based on a combination of scoring available threshold toxicity data (e.g. no observed adverse effect levels) and non-threshold toxicity data (e.g. cancer classifications from the International Agency for Research on Cancer) into one potency score.

In the Netherlands, the hazard assessment of unregulated contaminants found in drinking water (resources) was compound-specific and highly dependent on the availability and reliability of toxicity data. When reliable and sufficient toxicity data were available, these were used to derive a Tolerable Daily Intake (or comparable) value, which was then used to calculate a HBGV for the contaminant in drinking water. Also, HBGVs derived by other national or international organisations were considered for evaluation (e.g. by the German Environment Agency) [11]. In Switzerland, a similar approach was used [165].

However, in relation to emerging contaminants, toxicity data are often insufficient or unreliable. In those cases, experts in the Netherlands and Switzerland were able to use the Threshold of Toxicological Concern (TTC) or the Read-Across approach. The TTC was first developed by the U.S. Food and Drug Administration and is considered to be a level of human exposure below which negligible risk is expected even though toxicity data are unavailable [164]. The TTC approach allocates chemicals to five different chemical groups based on their chemical structure [168].

For some compounds the TTC approach is not applicable, e.g. inorganic compounds, proteins, and steroids, as is described by the European Food Safety Agency [167]. If the identified emerging contaminant belongs to one of these groups, the Read-Across-approach can be used instead of the TTC-approach [198, 199]. The use of the TTC approach to determine safe levels in drinking water has been explained in depth elsewhere for the Netherlands [11] and Switzerland [165, 198].

Although the Netherlands and Switzerland used similar approaches during the hazard assessment element, several differences can be identified. Different standard body weights (70 vs. 60 kg), exposure allocations to drinking water (20% vs. 100%), and human exposure threshold values for the different classes in the TTC approach (European Food Safety Agency [167] vs. International Life Sciences Institute [168]) were used. These differences resulted in diverse HBGVs.

In Germany, the hazard assessment of emerging contaminants with insufficient or unreliable toxicity data was based on a scheme of health related indication values that was first published in 2003 by the German Environment Agency. The scheme consists of four possible health related indication values, namely 0.1, 0.3, 1, and 3 µg/L. Health related indication values increase with sufficient and reliable toxicity data, and decrease with the severity and irreversibility of the toxic endpoints, as described by Dieter [200].

2.3.2.2 Exposure assessment

The exposure assessment in Minnesota was based on diverse exposure-related data that are combined into three indicators for potential exposure via drinking water intake. These indicators include persistency (e.g. log K_{ow}, biodegradability), emission and disposal rates (wastewater and industrial releases), and a measure of occurrence (detected concentrations in different waterbodies and drinking water).

The scores as well as the data they are based on are not published on the MDH website.

The exposure assessments performed in the Netherlands, Germany and Switzerland were very similar to one another. Preferably, concentrations of the contaminant in treated drinking water were used. When unavailable, concentrations in the drinking water resource were used. The expected concentration in drinking water can then be calculated using estimated removal rates by the drinking water treatment system.

2.3.2.3 Concern assessment

The IRGC (2012) has suggested relevant factors for the concern assessment, such as the assessment of perceptions associated with the hazard and the relationship between the perception and behaviour.

In three out of four cases (not in the Swiss case), public meetings were held. It was unclear to the authors whether a formal concern assessment of all stakeholders had taken place during the public meetings, as no minutes of these meetings were available. Also, in Minnesota, the opportunity for anyone to nominate a contaminant could be interpreted as part of the concern assessment. However, these concerns and the assessment of potential concern during the public meetings, do not appear to have had any influence on the further decision-making and risk management steps to be taken. None of the analysed policy approaches seem to have formal procedures in place for the concern assessment.

2.3.3 Risk acceptance and risk management

Risk management is the combination of actions taken to avoid, decrease or retain the potential risk posed by a hazard. The need and choice of risk reduction measures is based on the outcome of the risk acceptance element.

The risk acceptance element is based on the decision of the involved stakeholders on whether an identified risk is *acceptable* (no measures need to be taken), *tolerable* (risk reduction measures are needed), or *intolerable* (should be avoided) [151]. The IRGC framework is unclear about who to involve and not involve in the concern assessment and risk acceptance element respectively. It was thus decided that, in this study, the concern assessment would include the assessment of public associations with the hazard. In contrast, the risk acceptance element included only the risk evaluation of professionals.

In the selected Dutch case no measures could be taken to reduce or eliminate the risk, as the source of pollution had already been eliminated and exposure to it had gone on since 2012 [7]. Also, considering the fact that the company had phased out the PFOA on a voluntary basis, no relevant risk management steps initiated by Dutch government agencies could be pointed out. The risk acceptance process and the resulting risk management steps in the remaining cases are described below. Also, flowcharts of the risk management processes can be found in the Appendices for Chapter 2.

No measures were taken in the Swiss case, where the drinking water treatment system was able to remove PFOA. The risk of PFOA in drinking water was thus considered acceptable. During the German and Minnesotan case, the threat posed by PFOA was considered intolerable, because the drinking water treatment system in place was not able to remove PFOA from the resource water. However, by adding activated carbon to the drinking water treatment system, the potential risk posed by PFOA moved from being intolerable to tolerable [2].

In all selected cases, the decision as to whether the posed risk by PFOA was acceptable, tolerable or intolerable was solely based on the ability of the drinking water treatment system to remove PFOA and thus on the human health impact. No other aspects, such as economic implications, were taken into consideration. This illustrates the need for the timely identification of emerging contaminants to drinking water quality and the inclusion of the risk acceptance element as soon as possible after identification.

2.3.4 Risk communication

The technical risk communication model was used in all selected cases. The communication was one-way in order to induce protective behaviour (in the German and Minnesotan case) or to reassure people that the drinking water was safe despite the presence of PFOA (in the Swiss and Dutch case).

Figure 2-2 shows the number of articles published per month about PFOA in drinking water in German newspapers from January 2005 to January 2008 (N = 137). The articles were divided based upon publication in national or regional newspapers, as the selected cases were local incidents of PFOA contamination. Also, a timeline of the most important risk communication incidences by local, regional or national government agencies is shown (based on Kleeschulte et al. [2]). Before May 2006 and after June 2007, no articles about PFOA in drinking water were published in Germany. This indicates that the articles shown in Figure 2-2 are a reaction to the incidence of PFOA in the Rivers Ruhr and Möhne. A clear decline in newspaper articles can be seen after August 2006 indicating a decrease in public concern. This is based on our assumption that lower media coverage indicates lower public concern.

Figure 2-3 illustrates the number of articles about PFOA in drinking water published in Dutch newspapers from January 2015 to May 2017 (N = 50). In contrast to the German case, there was no clear decline in the number of newspaper articles after the last communication incidence. This indicates no decline in public concern. This is in line with the fact that, in the Netherlands, research has been focussing on the potential health effects of the alternative for PFOA that has been used by industry since 2012 [201, 202]. However, it is recognised that differences in the type of incidence, such as other routes of exposure to PFOA (e.g. via air in the Dutch case), as well as the timing of the incident, might have also contributed to the differences in media coverage.

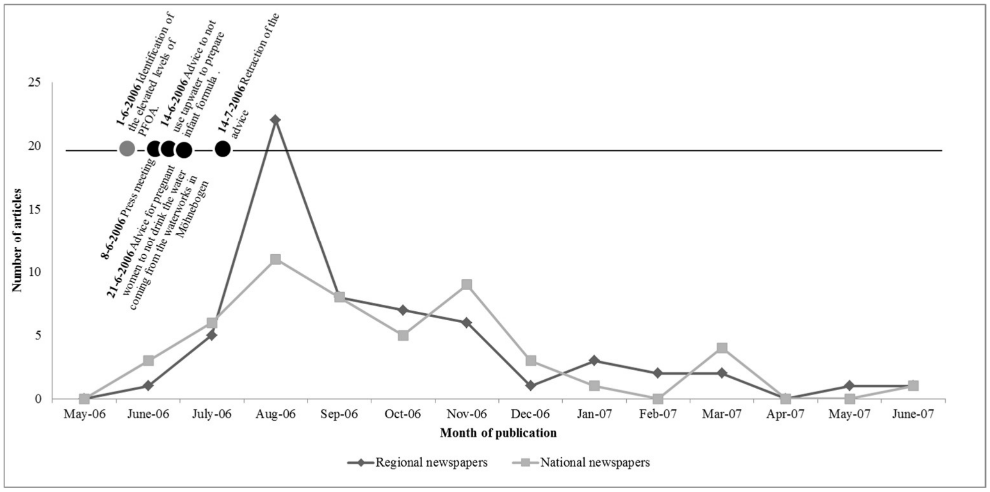


Figure 2-2 Number of published articles about PFOA in drinking water per month in Germany (May 2006 to June 2007) in relation to important risk communication event times during the selected German case.

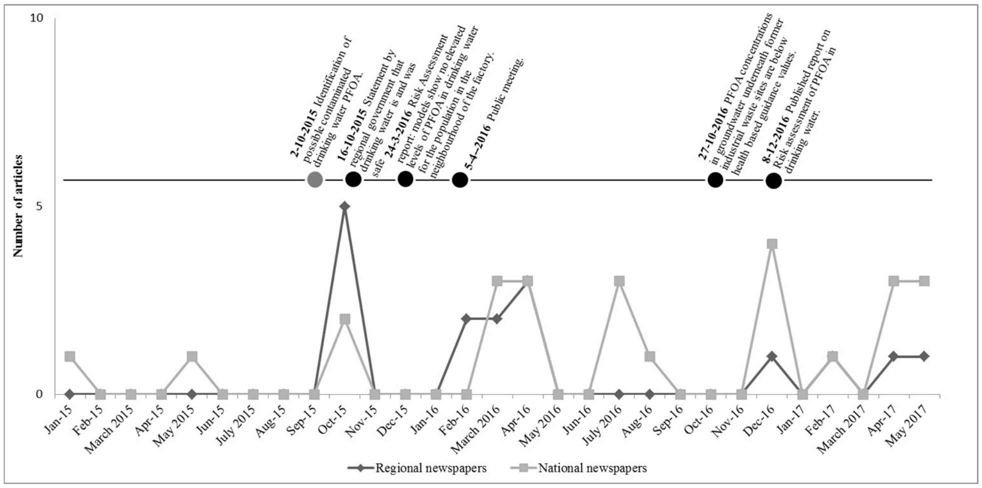


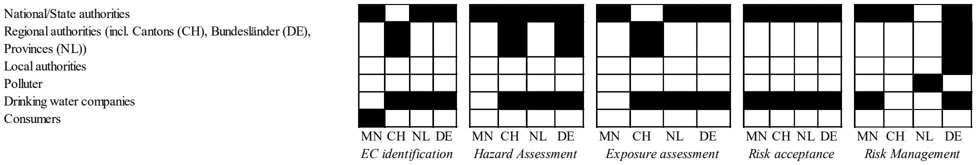
Figure 2-3 Number of published articles about PFOA in drinking water per month in Dutch newspapers (January 2015 to May 2017) in relation to important risk communication events during the selected case.

No results that correlated to the selected Swiss case were found between October 2010 and January 2014. Also, the search for articles about PFOA in drinking water between January 2016 and June 2017 in Minnesotan newspapers resulted in only two articles. This indicated low to no public concern in the Minnesotan and Swiss case.

The presented cases show the influence that risk communication has on public concern about an emerging contaminant. Comparing the German and Dutch case illustrates the need for timely risk communication.

2.3.5 Stakeholder involvement

Figure 2-4 shows the range of stakeholders involved in the selected risk governance approaches to emerging contaminants in drinking water. In this analysis, stakeholders were defined as all those parties, which had an interest in the matter of emerging contaminants in drinking water. The risk appraisal element is divided into its sub elements. However, as the concern assessment element was not represented in either of the analysed policy approaches, it is not shown in Figure 2-4.



	EC identification				Hazard Assessment				Exposure assessment				Risk acceptance				Risk Management			
	MN	CH	NL	DE	MN	CH	NL	DE	MN	CH	NL	DE	MN	CH	NL	DE	MN	CH	NL	DE
National/State authorities	■	□	■	■	■	■	■	■	■	□	■	■	■	■	■	■	■	■	□	■
Regional authorities (incl. Cantons (CH), Bundesländer (DE), Provinces (NL))	□	■	□	□	□	■	□	■	□	■	□	□	□	□	□	□	□	□	□	■
Local authorities	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■
Polluter	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	□
Drinking water companies	□	■	■	■	□	■	■	■	□	■	■	■	■	■	■	■	■	□	□	■
Consumers	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□

Figure 2-4 Stakeholders involved in the risk governance of emerging contaminants in drinking water in Minnesota, Switzerland, the Netherlands and Germany.

The analysis of the involved stakeholders in Minnesota in the identification element of the risk governance process is based on the list of nominated contaminants published by the MDH CEC program [195]. As mentioned in Paragraph 2.3.1, the identification of emerging contaminants in Switzerland, Germany and the Netherlands is mainly based on monitoring and screening efforts by regional and national government agencies [11, 165, 203]. Therefore, these stakeholders are shown in Figure 2-4.

The involved stakeholders shown for the hazard and exposure assessment are based on the following references for Minnesota ([196], Switzerland [165, 204] , Germany [197, 203], and for the Netherlands [11]. The stakeholders involved in the risk acceptance and management of the case studies are based on the references shown in Table 2-1.

2.4 Areas identified for improvement

This study has shown that, with regard to proactive risk governance, a key area for improvement in the risk governance of emerging contaminants is their timely identification. Timely identification enables appropriate risk management options to be taken, allows other factors as well as public health to be included in deliberating the need for risk remediation measures, and can positively influence risk communication as was illustrated by the selected cases.

The identification process used by the MDH CEC program appeared to be more proactive, as identification was based on the nomination of contaminants and not necessarily on monitoring data. However, the main reasons for contaminants to be nominated in the MDH CEC program came from screening and monitoring data or from studies that revealed new toxicity data. Therefore, it can be concluded that the information sources used in the selected risk governance approaches are comparable. However, based on recent scientific literature, several additional information sources could be used by government agencies for the timely identification of possible emerging contaminants.

Firstly, the use of product registration under REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals [205]) for the identification of persistent, mobile, and toxic contaminants has been suggested by Reemtsma et al. [206] and Arp et al. [207]. This could be a valuable added classification of chemicals next to the persistent, bioaccumulative, and toxic-chemicals, by which physical-chemical properties indicate the possible threat a compound poses to drinking water quality. The use of other product registration databases besides REACH is also encouraged, such as the Biocidal Products Regulation.

Secondly, analysing driving forces behind current emerging contaminants in drinking water could be valuable. Driving forces in this case relate to social, economic, technical and political processes that have initiated drinking water contamination in the past. Correlating driving forces to risks has been done for infectious disease threats in Europe [208] and chemical risks to biodiversity [209]. Finding relevant driving forces for chemical and microbial risks to drinking water quality can result in proactive risk governance by enabling timely interventions on relevant drivers.

Thirdly, the systematic review of newspaper articles could accelerate the identification of possible emerging contaminants. This was illustrated by the Dutch case. Investigation into the same polluter in the United States started already in 2001 [210]. Therefore, systematic analysis of international newspaper articles would have accelerated the identification of the possible PFOA contamination near Dordrecht. However, to make the analysis of international news relevant, the chance of false positives has to be minimised. Well-structured analytical approaches, such as the media monitoring approach by Alomar et al. [211], are thus needed.

An additional area for improvement could be expanding the range of involved stakeholders by including consumers in the risk governance process. Participatory governance has been shown to positively influence stakeholder acceptance [193, 212]. However, who to involve and not to involve still needs critical reflection and further study.

Also, in terms of transparency, the results show that not all information is publicly available. Making monitoring data on micropollutants publicly available could positively influence risk perception since studies have suggested that people evaluate drinking water quality based on their expectations [181]. By sharing monitoring data, expectations can be managed. It is recognised that in order to make this kind of information understandable for non-experts, thorough explanation is needed.

Finally, harmonisation of the hazard assessment is encouraged for contaminants with limited toxicity data. Different approaches are shown to result in very different HBGVs, which impedes risk communication as communication on chemical drinking water contaminants is mainly based on water quality standards [213]. A harmonised shift from chemical specific risk assessment to assessing groups of chemicals based on their modes of action and physical-chemical properties is suggested [189]. This will enable the timely hazard assessment of contaminants with limited toxicological information.

2.5 Limitations

Some limitations of this study have to be considered. Firstly, it is recognised that the selected cases are considerably different from one another, both in terms of the size of the affected population and in terms of the knowledge level on human health effects of PFOA. These differences may have had an effect on the differences in the risk management and risk communication processes. In addition, the analyses of which stakeholders were involved in the risk assessment, risk management and risk communication elements of the risk governance process were based on the selected cases. The overview of the involved stakeholders in these elements, as shown in Figure 2-4, is therefore specific for the selected case and may not be representative for each incident of an emerging contaminant in a drinking water resource.

Furthermore, the LexisNexis® database is limited in terms of included newspapers, which may have affected the results. Also, the framing of the risk event by news media was not taken into account. Recent literature shows that the framing of risk communication in case of emerging contaminants in drinking water can have a positive and negative effect on risk perception [175]. Therefore, further analysis of the risk communication during the selected cases is considered valuable.

Finally, the analysis focused on policy approaches and did not include voluntary actions taken by drinking water companies or other involved stakeholders.

2.6 Conclusions

The IRGC framework with a few modifications was found to be a valuable instrument for identifying areas for improvement in current risk governance approaches for emerging contaminants to drinking water quality. A key area for improvement was found to be the timely identification of and subsequent communication on emerging contaminants in drinking water. Similar results have been found for the risk communication on infectious diseases [152].

2.7 Future research suggestions

Based on the areas identified for improvement, the following suggestions for future scientific research that will add to the proactive risk governance of emerging contaminants in drinking water can be made:

- The development of systematic analytical approaches for the timely identification of emerging contaminants to drinking water quality using product registration databases, news media, drivers of risk, and scientific literature is encouraged.
- The possibility and benefits of integrating the concern assessment into the risk governance process of emerging contaminants in drinking water and improving transparency by sharing monitoring data should be investigated.
- The risk communication process and consequent public risk perception and risk behaviour that took place in past incidences of emerging contaminants in drinking water should be further analysed.

3 EARLY IDENTIFICATION OF EMERGING CONTAMINANTS IN DRINKING WATER RESOURCES WITH LITERATURE MINING

Abstract

Recent research has shown that it takes about 15 years from the time of the first scientific study mentioning the presence of a contaminant in the environment for the issue to peak in scientific attention and regulatory action. One possible factor influencing this lengthy period is that the first article becomes lost in the vast number of publications.

In this chapter[3], we therefore developed a methodology using literature mining to identify the first scientific study which reports the presence of a contaminant in the aquatic environment. The developed semi-automated methodology enables health and environment agencies to inform policy makers about contaminants in the aquatic environment that could be significant for public and environmental health in national, international and river basin settings. The methodology thereby assists the proactive governance of emerging contaminants in the aquatic environment. This was illustrated by a retrospective analysis of the period of emergence in the Netherlands of: (1) perfluorooctanoic acid in surface water, and (2) biological industrial wastewater treatment systems as potential infection sources for Legionnaires´ disease.

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[3] This chapter is based on Hartmann J, Wuijts S, van der Hoek JP, de Roda Husman AM. Use of literature mining for early identification of emerging contaminants in freshwater resources. Environmental Evidence. 2019;8(1):33.

3.1 Background

Human activities result in the release of contaminants into the aquatic environment. Anthropogenic sources contaminating the aquatic environment include the effluents of municipal wastewater treatment plants (WWTPs), industrial wastewater discharges, as well as runoff from agricultural land and urban areas [141]. Moreover, demographic, social and climatological changes aggravate the impact of human activities on the aquatic environment. Examples of these changes are the increased volumes and changed composition of wastewater caused by urbanisation and the decreasing dilution capacities of receiving water bodies due to droughts which results in higher concentrations of contaminants in water bodies [34, 214]. The increasing sensitivity of analytical techniques also enables the augmented detection of contaminants in the aquatic environment [34, 186].

Anthropogenic contamination may contain both chemical and microbial contaminants. For instance, the effluent of municipal WWTPs, despite advanced treatment steps, may contain pharmaceutical and personal care products [215], antibiotic resistant bacteria [216] and antibiotic resistance genes [217]. Also, industrial wastewaters, dependent on the type of industry, have been found to contain several chemical contaminants, such as dyes, solvents and catalysts [218]. Microbial contaminants have also been detected in industrial wastewater, for instance viruses that have been accidently released during vaccine production [44]. Chemical and microbial contaminants released into the aquatic environment can not only pose a threat to human health when water resources are used for drinking water production or recreation, but can also impact aquatic organisms. In this study, we refer to emerging contaminants for which the threat posed to human health or the aquatic environment is still unclear.

In a recent study, we showed that the current risk governance of contaminants in the aquatic environment can be improved by the more timely identification of contaminants which are of potential concern [126]. In that study, we analysed the current policy on the risk governance of emerging contaminants in the aquatic environment in the Netherlands, Germany, Switzerland and the state of Minnesota and found that timely identification enabled, among other things, appropriate risk management strategies. Furthermore, Halden [155] investigated, in retrospect, the association between the number of scientific publications about certain chemical environmental contaminants, such as dichlorodiphenyltrichloroethane (DDT) and 1,4-dioxane, and the regulatory actions subsequently taken. Halden [155] found that it generally took about 15 years from the first scientific publication about a contaminant to a peak in number of scientific publications. The peak in scientific attention was found, in many cases, to be associated with regulatory or mitigation actions. The period from the first scientific publication being released to the time at which it reaches the peak of scientific attention is referred to as the ‘period of emergence of concern’ by Halden [155]. Shortening the period of emergence of concern may accelerate the introduction of regulatory actions to control chemical contaminants in the environment and thus limit environmental effects.

Although Halden [155] looked specifically at the emergence of concern about chemical contaminants, similar trends can be found for emerging microbial contaminants. Specific pathogens have (in retrospect) been shown to be present in the environment and linked to human sources long before the disease that they cause had gained attention [157]. For the Aichi Virus this has been illustrated by Lodder et al. [158]. The Aichi virus was reported in humans for the first time in 1989. However, Lodder et al. [158] analysed environmental water samples from the Netherlands from 1987 and found that the Aichi virus had been circulating in the Dutch population well before its initial detection in humans. The fact that the Aichi virus was identified in water samples showed that the virus was already present in humans in 1987; otherwise it could not have been detected in the aquatic environment. Furthermore, the properties that cause concern among scientists and regulators about contaminants in the aquatic environment, especially when used for the production of drinking water, are similar for chemical and microbial contaminants. These properties include pathogenicity or toxicity, persistence and mobility [206, 219]. Therefore, decreasing the period of the emergence of concern about microbial contaminants is also important if timely mitigation actions are to be ensured.

Currently, we believe that the first scientific article about the presence of a contaminant in the aquatic environment is not picked up by regulators due to the large number of publications. It is not until more articles are published about the specific contaminant that the signal about the presence of the contaminant in the environment is picked up by regulators, as is shown by Halden [155]. We hypothesise that the period of emergence of concern about contaminants can be reduced by the systematic search of the universal scientific literature for articles reporting the first detection of a contaminant in the aquatic environment. As many articles about contaminants in the aquatic environment are published every day, the manual analysis of the scientific literature would be too complex, subjective and time consuming.

Text mining can be used to automate some parts of systematic literature reviews. The term refers to the automated extraction of (parts of) articles that are relevant to the researcher, or to the data mining of articles, which enables associations to be found between parts of texts [220, 221]. Text mining has been shown useful in biomedical research for several applications, such as in the identification of eligible studies and the allocation of a list of genes to inform on their role in diseases [222]. Here, eligible studies refer to articles reporting on original research that is considered relevant to the scope of the systematic literature review. Others in the field of evidence-based software engineering for systematic literature reviews have used the term “primary studies” for this purpose [223]. Furthermore, Van de Brug et al. [224] have used text mining to devise an early warning mechanism to detect potential food related risks. Sjerps et al. [225] have also used text mining to identify signals of potential emerging chemical risks to drinking water quality by combining search terms connected to chemical contaminants and the aquatic environment. However, this approach did not include microbial contaminants and was not specifically aimed at generating first reports on the presence of contaminants in the aquatic environment.

Over the past years, several software tools have been developed which integrate text mining in the systematic literature review process [226]. In this study, we assessed the applicability of two such tools, namely the StArt Tool and Adjutant. The StArt Tool automates the eligible study selection process by scoring articles based on the number of occurrences of the search terms in the title, abstract and keywords (open source and available at http://lapes.dc.ufscar.br/tools/start_tool, automates) [226]. The rationale of the StArt tool is that the highest scoring articles are most relevant to the performed search and should thus be selected as eligible studies. Adjutant, another software tool, can be used to query the PubMed® database and perform unsupervised clustering on the retrieved collection of articles [227]. Adjutant is available from https://github.com/amcrisan/Adjutant. In this study, we assessed the applicability the StArt Tool and Adjutant to identify articles that report on the detection of a contaminant in the aquatic environment for the first time.

The objective of this study is to introduce a methodology using literature mining to identify the first signal of the detection of a chemical or microbial contaminant in the aquatic environment. To keep the search as concise as possible, we focus in this study on freshwater resources. First, the development of the methodology is explained making use of the selected software tools (Section 2). Then, the application of the developed methodology to recent scientific literature is shown (Section 3). Finally, a retrospective validation of the proposed methodology is discussed using the period of emergence of concern in the Netherlands of 1) perfluorooctanoic acid (PFOA) in surface water and 2) biological industrial wastewater treatment systems as potential infection sources of Legionnaires´ disease (Section 4).

The developed methodology adds to evidence synthesis by combining signals of first detections of contaminants in the aquatic environment into manageable information. Health or environment agencies can use the methodology to inform policy makers about signals of emerging contaminants in the aquatic environment that could be relevant for public or environmental health in a national, international or river basin setting. The methodology thereby assists the proactive governance of emerging contaminants in the aquatic environment and contributes to the objective and proactive use of scientific evidence to inform policy makers.

3.2 Methodology development

A systematic literature review has three phases: planning, conducting and reporting. The planning phase includes identifying the need for a review and creating a review protocol. In the conducting phase, authors search for literature, identify and appraise eligible studies, and extract and synthesise data. In the final phase the results of the review are reported to relevant communities [223]. In this study, we have used R-based coding in the conducting phase to make the review process more efficient. A graphical representation of the development of the methodology is shown in Figure 3-1 and is described in this section. The reporting phase is not automated by the developed methodology because, in this study, the reporting phase includes the elucidation of the relevance of the identified contaminants in a national, international or river basin setting.

In this study, the first signal of the detection of a chemical or microbial contaminant in the aquatic environment refers to a scientific article. In order to find this article, we use text mining of scientific articles, from now on referred to as literature mining. Here, literature mining is the automated textual analysis of the combination of ‘title’ and ‘abstract’. This does not include the analysis of the data sets produced by the different articles [228]. The developed methodology is therefore applicable to all scientific literature, also when the full-text of the article cannot be accessed. The methodology[4] is written in R-studio, available at https://www.r-project.org/ to make it freely accessible.

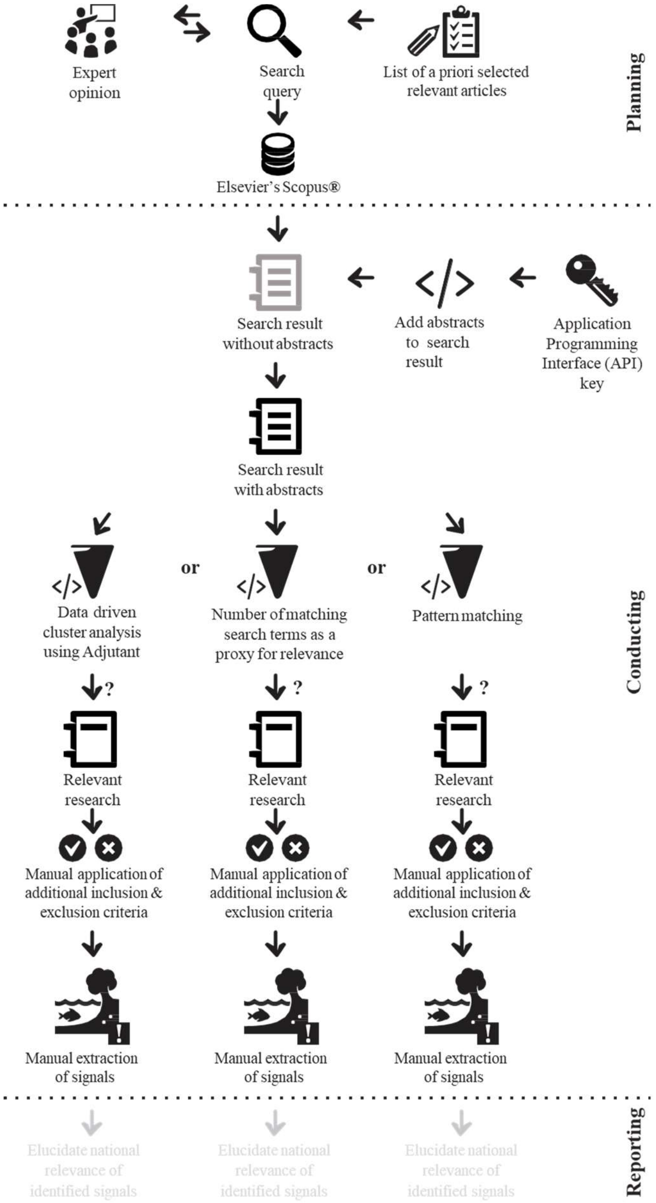

Figure 3-1 A graphical representation of the steps taken to develop the proposed methodology. Here, </> is the symbol for code written in R.

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[4] The R-based code can be found here: https://doi.org/10.6084/m9.figshare.9975722.v1

3.2.1 The planning phase

The review protocol was designed so that scientific articles that report on the first identification of chemical or microbial contaminants in the aquatic environment could be found. The search was conducted in Elsevier's Scopus®, the largest abstract and citation database of peer-reviewed literature worldwide [229]. In order to find articles reporting on the first identification of contaminants in the aquatic environment, relevant search terms and inclusion and exclusion criteria were defined.

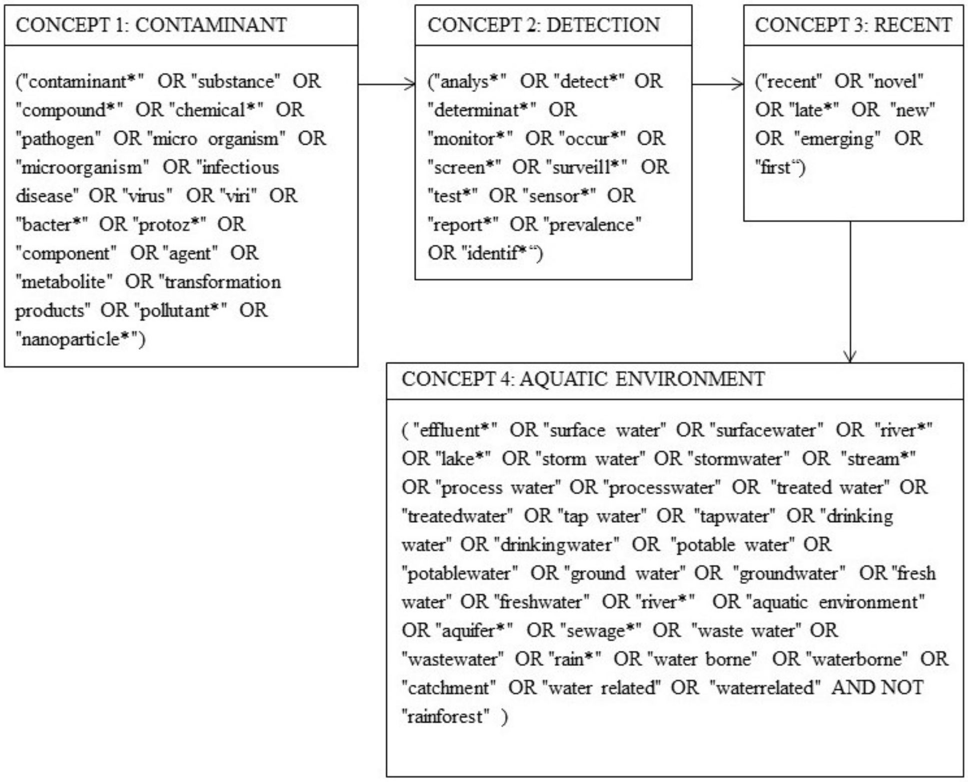

Figure 3-2 Search terms used to search Scopus® for articles reporting on the first identification of chemical or microbial contaminants in the aquatic environment. Search terms were searched for in title, keywords and abstracts. Additional information: _ = search term was used with, and without, the use of a space, * = any combination of characters, → = AND.

3.2.1.1 Search query

The search terms used in the review are shown in Figure 3-2. The search query itself was a combination of four concepts, namely *contaminant*, *detection*, *new*, and *aquatic environment*. In order to keep the search query as specific as possible, it was decided to focus on freshwater resources. Each concept included several synonyms and was searched for in the title, abstract and keywords. The search query was set up using expert opinion and a list of fourteen a priori selected articles (see Table 3-1). The fourteen articles report the identification of chemical or microbial contaminants in the aquatic environment for the first time and could thus be used to test the effectiveness of the proposed methodology. The articles were found using a simple search in Google Scholar® using the search terms “first” and “detect* OR identif*”. Furthermore, articles which the authors came across in previous research and that reported on the first identification of chemical or microbial contaminants in the aquatic environment were also included in Table 3-1.

Experts from different backgrounds, such as chemistry, microbiology, and hydrology, also provided input and feedback on a list of search terms using an iterative approach, thus ensuring that a comprehensive list of search terms was obtained. In order to keep the search query as concise as possible, it was decided that a number of specific kinds of contaminants would not be included in concept 1 (e.g. pharmaceuticals, pesticides or E. coli). However, we did add the term ‘nanoparticle’ as nanoparticles are not always referred to as compounds or contaminants and records referring to nanoparticles would otherwise be missed by the presented methodology. An overview of the search query and the inclusion and exclusion criteria used is shown in Figure 3-2.

3.2.1.2 Inclusion and exclusion criteria

In the query (shown in Figure 3-2) in Scopus we limited the search to scientific articles, reviews and articles in press written in English. Although we were looking for original research, reviews were also included as authors of original research might not have been aware that they had identified a contaminant for the first time, but a reviewer might have picked up on it. Furthermore, the search query excluded records from the following subject areas: economics, econometrics and finance, business, management and accounting, dentistry, and psychology. Finally, to develop the methodology, only articles published between 2006 and 2012 were included, as the set of articles retrieved with the search query had to contain the a priori selected articles (see Table 3-1, publication year 2006 - 2012).

Some inclusion and exclusion criteria could not be included in the search query, but were used to manually select eligible studies in the conducting phase. Although interesting, studies about new analytical techniques, new bio indicators, new toxicity results for known contaminants, new detections in the marine environment and in soil, and new removal techniques for known contaminants, were outside the scope of this study and not considered eligible studies. Studies about new detections in aquatic biota and aquatic plants were included as these are direct signals of aquatic contamination. However, first detections in terrestrial plants were not included as eligible studies. Articles about drinking water or wastewater treatment techniques were excluded as the aim of the developed methodology was to identify first detections of contaminants in the aquatic environment and not to identify new treatment techniques used to treat contaminated water. However, articles reporting the first identification of contaminants created during treatment, e.g. newly identified disinfection by-products, were included.

Table 3-1 List of 14 a priori selected articles that report on the identification of specific contaminants in the aquatic environment for the first time. The 5th column, named 'Cluster', is the result of the data driven cluster analysis using Adjutant, which is explained in Section 3.2.2.1. The 6th and 7th column, named 'Sorted on position' and 'Total search terms' show the ranking of the a priori selected articles based on presence of search terms, this approach is also explained in Section 2.2. N/A = Not Applicable (Conley et al. (27) was not found with the search query used).

Reference	**Publi-cation year**	**First detection of**	**Detection in**	**Cluster**	**Sorted on position**	**Total search terms**
Sultan and Gabryelski [230]	2006	Several contaminants, most intriguing Glycolic acid	Drinking water	Not-Clustered	11	17
Terasaki et al. [231]	2008	Five aryl hydrocarbons, including a novel chlorinated aryl ether	Surface water	Not-Clustered	241	12
Conley et al. [232]	2008	Lovastatin	Surface water	Not-Clustered	1,491	9
Radjenović et al. [233]	2008	Biodegradation product of β-blocker atenolol	Wastewater samples	Not-Clustered	41	15
Conley et al. [234]	2008	Norfluoxetine	Surface water	N/A	N/A	N/A
Xiao et al. [235]	2008	Gatifloxacin	River, influent and effluent of sewage treatment plant	Not-Clustered	2,799	8
Söderström et al. [236]	2009	Oseltamivir	Surface water	pharmaceut-concentr	1,672	9
Hamza et al. [237]	2009	Human bocavirus	Surface water (river)	infect-diseas	3,047	8
Ferrer and Thurman [238]	2010	Lamotrigine and glucuronide	Wastewater and drinking water samples	sampl-detect	3	19
Farré et al. [239]	2010	C60 and C70 fullerenes and N-Methylfulleropyrrolidine C60	Effluent wastewater treatment plant	inf-chemic-concentr	162	13
Zhao et al. [240]	2010	Three new disinfection by-products (DBPs): 2,6-dichloro-3-methyl-1,4-benzoquinone, 2,3,6-trichloro-1,4-benzoquinone, and 2,6-dibromo-1,4-benzoquinone	Drinking water	chlorin-disinfect	997	10
Kleywegt et al. [241]	2011	Roxithromycin and enrofloxacin	Drinking water resource	pharmaceut-concentr	327	12
Pereira Rde et al. [242]	2011	Identification of new ozonation disinfection by-products of 17β-estradiol	Groundwater	ozon-effect	14,570	5
Su et al. [243]	2012	Three gene cassette arrays, aac(6')-Ib-cr-aar-3-dfrA27-aadA16, aacA4-catB3-dfrA1 and aadA2-lnuF	Surface water	resist-antibiot	3,904	8

Table 3-2 Overview of the search query and the inclusion and exclusion criteria used for the method development.

Search query	Additional inclusion criteria (not included in search query)	Additional exclusion criteria (not included in search query)
(((((title-abs-key ("contaminant*" or "substance" or "compound*" or "chemical*" or "pathogen" or "micro organism" or "microorganism" or "infectious disease" or "virus" or "viri" or "bacter*" or "protoz*" or "component" or "agent" or "metabolite" or "transformation products" or "pollutant*" or "nanoparticle*")) and (title-abs-key ("analys*" or "detect*" or "determinat*" or "monitor*" or "occur*" or "screen*" or "surveill*" or "test*" or "sensor*" or "report*" or "prevalence" or "identif*")) and ((title-abs-key ("recent" or "novel" or "late*" or "new" or "emerging" or "first"))) and (title-abs-key ("effluent*" or "surface water" or "surfacewater" or "river*" or "lake*" or "storm water" or "stormwater" or "stream*" or "process water" or "processwater" or "treated water" or "treatedwater" or "tap water" or "tapwater" or "drinking water" or "drinkingwater" or "potable water" or "potablewater" or "ground water" or "groundwater" or "fresh water" or "freshwater" or "river*" or "aquatic environment" or "aquifer*" or "sewage*" or "waste water" or "wastewater" or "rain*" or "water borne" or "waterborne" or "catchment" or "water related" or "waterrelated" and not "rainforest")))))) AND (EXCLUDE (SUBJAREA , "BUSI ") OR EXCLUDE (SUBJAREA , " PSYC ") OR EXCLUDE (SUBJAREA , " ECON ") OR EXCLUDE (SUBJAREA , " DENT ") OR EXCLUDE (SUBJAREA , " CENG ")) AND (LIMIT-TO (DOCTYPE , "ar ") OR LIMIT-TO (DOCTYPE , " re ") OR LIMIT-TO (DOCTYPE , " ip ")) AND (LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2008) OR LIMIT-TO (PUBYEAR , 2009) OR LIMIT-TO (PUBYEAR , 2006) OR LIMIT-TO (PUBYEAR , 2010) OR LIMIT-TO (PUBYEAR , 2011)) AND (LIMIT-TO (LANGUAGE , "English "))	- Studies about new detections in aquatic plants and biota - Studies reporting the first identification of contaminants created during treatment, e.g. newly identified disinfection by-products	- Studies about new analytical techniques - Studies about new bio indicators - Studies about new toxicity results for known contaminants - Studies about new detections in soil - Studies about new removal techniques for known contaminants - Studies reporting first detections in plants - Articles about drinking water- or wastewater treatment techniques were excluded

3.2.2 *The conducting phase*

The search query (shown in Table 3-2) was used to search Scopus®; this generated 27,516 articles. As Scopus® does not have the functionality to export more than 2,000 records, including all bibliographic information, R-based coding was used to add abstract information to each record using the *Rscopus* package (see Figure 3-1) [244]. In order to retrieve abstract information from Scopus® by using R, an

Application Programming Interface (API) key is needed which can be requested from Elsevier, using this link https://dev.elsevier.com/.

After the code[5] was run, the list of 27,516 articles contained abstract information. It was found that only 13 of the 14 a priori selected articles were included in this dataset. Conley et al. [234] was not found by the search query[6]. This is due to the fact that the first detection of the contaminant was not mentioned in the title or abstract. We continued developing the methodology with the other thirteen articles shown in Table 3-1.

The following step in a review process would be to manually select eligible studies based on title and abstracts. However, the high number of records makes the manual selection of eligible studies unrealistic, so R was used to automate the eligible study selection process.

3.2.2.1 Eligible study selection approaches

Available software tools were used to automate the eligible study selection process in this research, namely the StArt tool [226] and Adjutant [227] (see also Figure 3-1). As the StArt tool was not R-based we implemented the rationale used in the StArt tool in R. Adjutant could be directly used in R. We also assessed whether available text mining functionalities within R could be used. An explanation of the three approaches follows below (see also Figure 3-1). Each approach has been computed into a separate R-based code[7].

1. **Data driven cluster analysis using Adjutant:** Adjutant was originally developed to cluster articles retrieved from the Pubmed database [227]. With minor adjustments to the package, Adjutant turned out to be useful for Scopus® data as well. Furthermore, the package uses 'stopwords', which are words that are considered to be so widely used in the collection of articles that they are irrelevant to the content clustering analysis. We added additional stopwords to the package based on our search query, namely: water, study, studies, studied, species, region, and stable. These words were chosen because they are widely present in the set of articles exported from Scopus.
2. **Number of search terms as a proxy for relevance:** the rationale of the StArt tool (as discussed in Section 1) was used as a guide for working out how to automatically identify eligible studies using R [223, 245]. The developers of the StArt tool advise using different values for occurrences in different parts of the text, especially lower values for occurrences in keywords. Occurrences of search terms in keywords should be rated lower because keywords are often not exported from search databases into the StArt tool. Also, as authors are obliged to choose a limited number of keywords, they might not be able to catch the research subject in this limited number [223]. We did not have any information on the keywords, as these were not in the dataset we exported from

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[5] The code can be found here: https://doi.org/10.6084/m9.figshare.9975722.v1

[6] The search string can be found here: https://static-content.springer.com/esm/art%3A10.1186%2Fs13750-019-0177-z/MediaObjects/13750_2019_177_MOESM2_ESM.docx

[7] The code can be downloaded from https://doi.org/10.6084/m9.figshare.9975722.v1.

Scopus®. Therefore, we examined whether specific terms from the search query were more frequent in the a priori selected articles than others. In that way, we were able to add more weight to those relevant terms when scoring articles. This was done using the tm and quanteda packages in R [246, 247].

3 **Pattern matching:** the abstracts of the fourteen a priori selected articles (see Table 3-1) were assessed so that we could find a common pattern which would indicate the relevance of these articles to the present study. First, the abstract and titles were split into sentences and then the pattern was used to select relevant articles using string pattern matching. The pattern checks out for a combination of different word stems (e.g. ‘new’ and ‘detect’) in one sentence. However, these do not need to occur next to each other, hence the addition of 0 - 70 characters between the word stems. This is different from the search query used in Scopus®, as Scopus® is unable to search for specific combinations of words or word stems in one sentence. Also, by using the pattern matching in R, the matching sentence can be retrieved from the specific abstract which makes analysis less time consuming.

The applicability of the three approaches to automate the eligible study selection process was analysed using the fourteen a priori selected articles. However, one of these fourteen articles was not found in any of the approaches [234]. The first approach, namely data driven cluster analysis using Adjutant (Script 2), resulted in 48 clusters. However, 12,959 records (53%) were not clustered. Figure 3-3 shows the clusters that have been constructed and Table 3-1 shows the clusters in which the a priori selected records were sorted by Adjutant. Five of the a priori selected records were not clustered. Also, the eight records that were clustered, were divided over six different clusters. Therefore, there was no clear indication as to which of the clusters contained relevant information on the first detection of contaminants in the aquatic environment. Thus, data driven cluster analysis using Adjutant was not considered a feasible approach for the automation of the eligible study selection process in this research.

The second approach to automate the eligible study selection process that was assessed was based on the classification approach used in the StArt tool [223, 245]. Figure 3-4 shows the most used search terms in 13 of the a priori selected articles (Conley et al. [234] was not found by the search query used). There is no clear indication which of the concepts (see Section 3.2.1.1 Search query) is most distinguishably present in these relevant articles. Therefore, the records were sorted based on the presence of all the search terms using the *quanteda* package, with no additional weights added to any concepts or search terms. Table 3-1 shows that not all a priori selected articles are ranked high. Therefore, the ranking of articles that was based on the frequency of search terms was found not to be applicable to automate the eligible selection process in this study.

The third approach assessed to automate the eligible selection process was pattern matching. The dataset contained 4,299 records that matched the pattern based on the a priori selected articles. This is 15.6 percent of the original number of records exported from Scopus®. All but one, namely Conley et al. [234], of the a priori selected articles were included in the 4,299 records.

Because the pattern matching approach was the only approach that clustered the a priori selected articles together, we found pattern matching to be the best approach to automate the eligible study selection in this research. Using this approach the eligible study selection process is not yet fully automated as the list of matched records still needs to be manually checked. However, the number of records that is likely to include most eligible articles and thus should be prioritised for manual checking was decreased by almost 85 percent. Therefore, pattern matching was chosen as the approach to automate (part) of the screening process.

3.2.3 Sensitivity and specificity analysis

A sensitivity and specificity analysis of the developed pattern was performed using the fraction true or false negatives and true or false positives. Here, false positives are articles that did not report the first detection of a contaminant in the aquatic environment but were extracted as eligible studies using the defined pattern defined. False negatives are articles which did not match the pattern although these articles reported on the first detection of a contaminant in the aquatic environment. Often in computational linguistics, the focus is on the proportion of true and false positives recalled by the methodology, since no information is available on the documents that were not retrieved by the methodology [248]. However, here we have information on the articles that were eliminated using the pattern. Therefore, we used the definitions of sensitivity and specificity as shown in equations 1 and 2 following the Receiver Operating Characteristics (ROC) analysis [249].

$$sensitivity = \frac{fraction\ of\ true\ positives}{fraction\ of\ true\ positives + fracti\quad of\ false\ negatives} \qquad \text{Equation 1}$$

$$specificity = \frac{fraction\ of\ true\ negatives}{fraction\ of\ true\ negatives + fraction\ of\ false\ positives} \qquad \text{Equation 2}$$

3.3 Results of applying methodology to recent literature

In this section, the results of applying the developed methodology, as explained in Section 2, to recent literature, namely articles published between 2016 and 27th of August 2018, are presented. Running the search query[8], adjusted to the new time period, resulted in 22,570 articles being found in Scopus®. A list containing these records was exported from Scopus® and the code to add abstract information (see Section 2.2) was used. Pattern matching was run to identify eligible studies, which resulted in 3,650 records (16.0 percent of the original dataset) containing 3,983 sentences that matched the pattern. These records were exported to an excel file that contained the articles' Electronic Identifier (EID), authors, title, publication year, journal, volume, page information, citations, Digital Object Identifier (DOI), link to the article in Scopus®, abstract and the sentence that matched the pattern.

Then, eligible studies were again selected by applying additional criteria to the remaining dataset of 3,650 articles. The inclusion and exclusion criteria defined in Section 2.1.2 were used. After manual analysis, 359 articles were selected as eligible

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[8] The search query can be found here: https://static-content.springer.com/esm/art%3A10.1186%2Fs13750-019-0177-z/MediaObjects/13750_2019_177_MOESM2_ESM.docx

studies[9]. The contaminants detected for the first time in these studies were categorised manually as chemical or microbial.

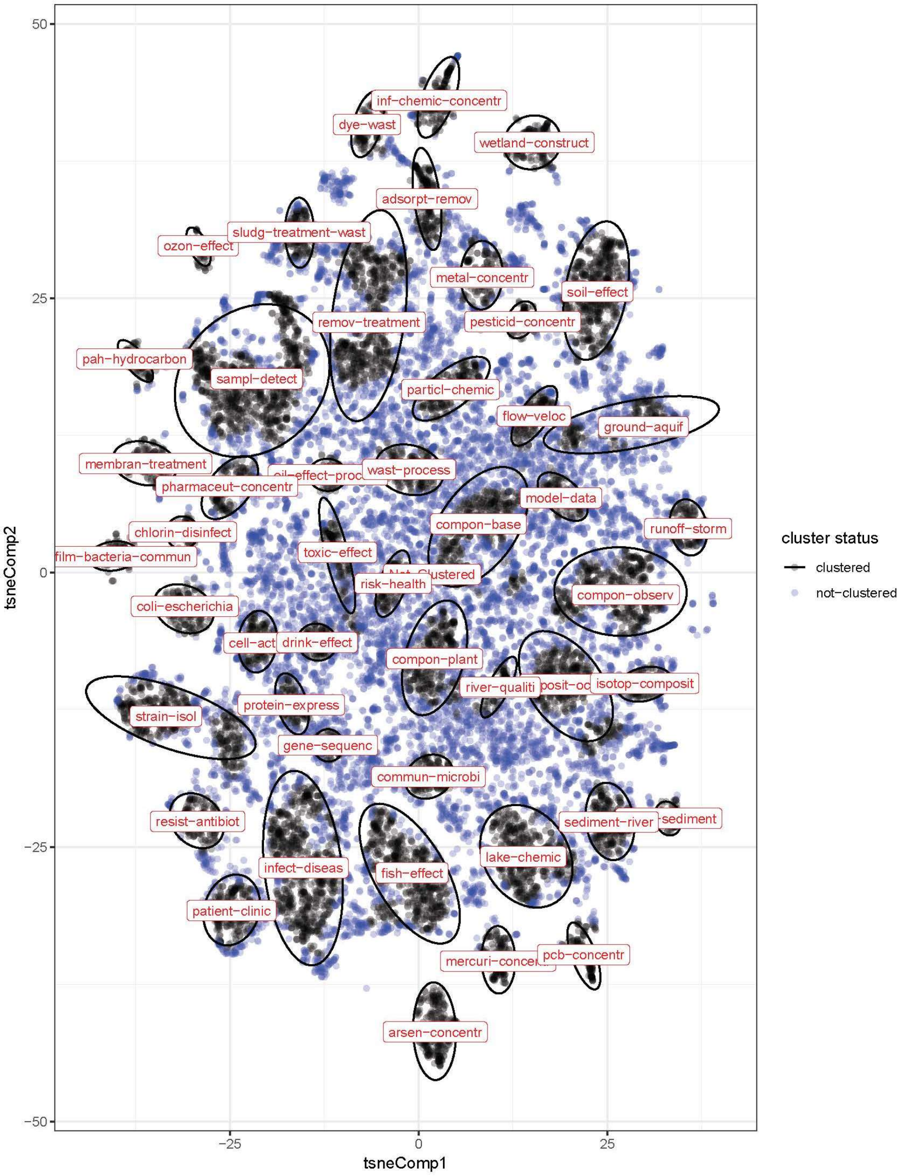

Figure 3-3 Result of the data driven cluster analysis using the Adjutant package. The names of the clusters are the two most commonly used word stems in the specific cluster.

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[9] The results of applying the developed methodology to articles published between 2016 and 27th of August 2018 can be downloaded from https://doi.org/10.6084/m9.figshare.9975728.v1.

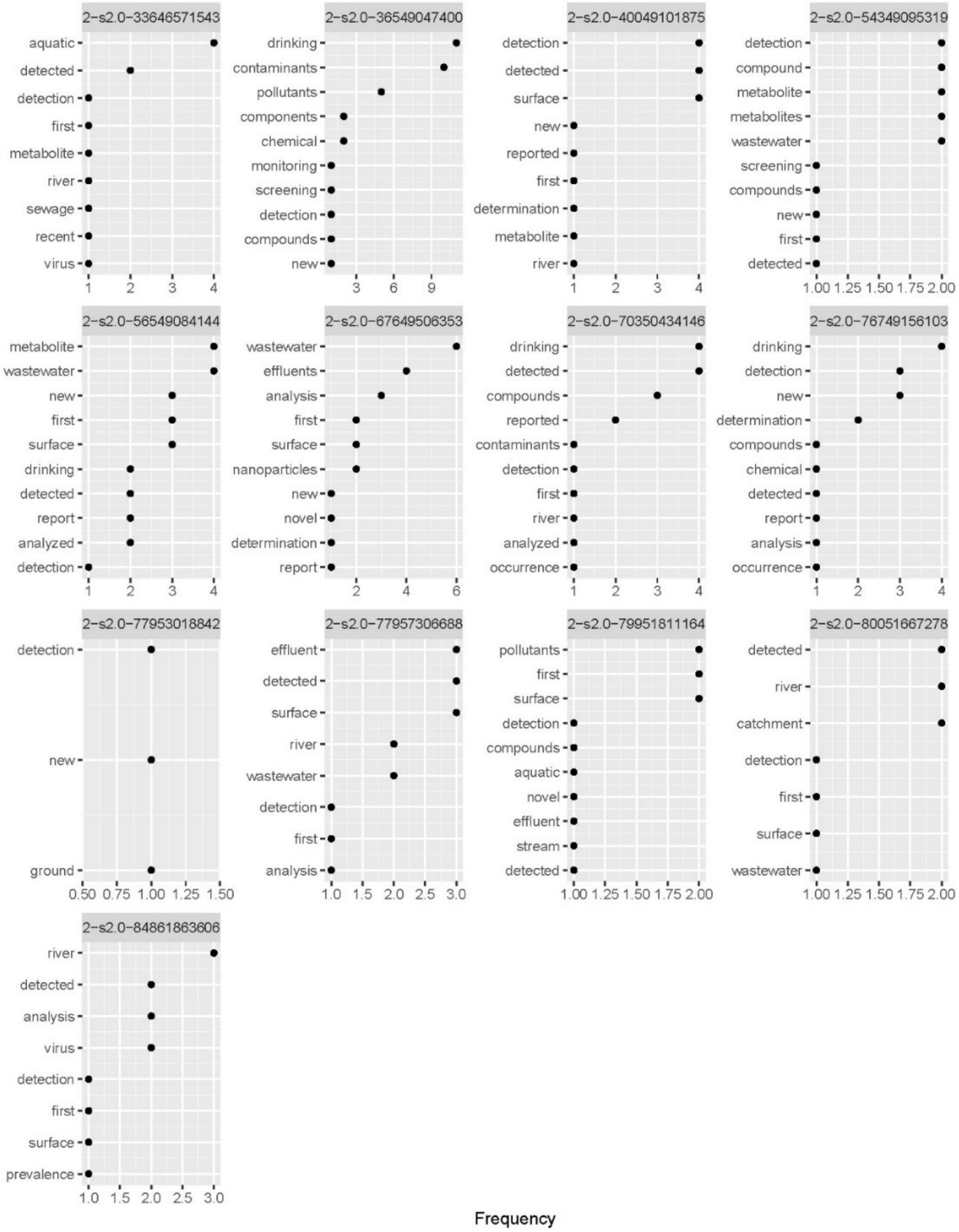

Figure 3-4 Overview of the search terms that were used most often in thirteen of the a priori selected relevant articles.

Of the 359 articles, 173 were on chemical contaminants and 186 on microbial contaminants. The next step would be to identify the relevance of the contaminants identified for the first time as potential threats to public and environmental health in national, international or river basin settings. The elucidation process is not automated by the developed methodology and therefore not within the scope of this study. However, we are planning to further develop the elucidation process in detail in future research.

3.4 Results of the sensitivity and specificity analysis

In order to find the fraction of false and true negatives, we analysed a random selection of 1,750 articles from the 23,217 articles (published between 2006 and 2012) that did not match the pattern. We found that 32 of the 1,750 articles did report on the first detection of a contaminant in the aquatic environment, resulting in a fraction of true and false negatives of 0.982 and 0.018, respectively. [10] Out of the 3,650 articles extracted as eligible studies, 359 articles were true positives resulting in a fraction of true and false positives of 0.098 and 0.902, respectively. Therefore, using equations 1 and 2, a sensitivity of 84.5% and a specificity of 52.1% were found.

3.5 Retrospective validation of the developed methodology

Could the developed methodology have contributed to the earlier identification of any of today´s emerging contaminants in the aquatic environment? To answer this question, we further analysed two examples of contaminants, one chemical and one microbial, which have caused great concern over the past years. We ran the methodology as defined above and assessed whether the use of the proposed text mining methodology would have decreased the period of emergence of concern in the Netherlands. The chemical contaminant used as an example was perfluorooctanoic acid (PFOA), which is an anthropogenic chemical belonging to the group of per- and polyfluoroalkyl substances (PFASs) [250]. The microbial contaminant example was the family of the *Legionella* bacteria.

3.5.1 Perfluorooctanoic acid (PFOA)

Since the 1940s, PFOA has been used in many industrial applications, for instance in the production of Teflon®. In 1978, it was first established that PFOA induces immunotoxicity and other adverse effects in monkeys. However, Grandjean and Clapp [251] showed that this, and other early toxicity information, was not published or was overlooked. Regulatory actions were, therefore, only initiated after the analysis of blood serum samples taken in 2000 revealed that PFOS and PFOA were detectable in all Americans [252]. In 2010, the major PFOA producing company in the United States of America stated that it had decreased its PFOA emissions by 95 percent [251].

In the Netherlands, Dupont had been using PFOA since 1970 to produce Teflon and had replaced it voluntarily in 2012 by a different perfluorinated compound. In 2015, groundwater which had been used for the production of drinking water was investigated for possible contaminants and found to be polluted by PFOA as the result of industrial wastewater discharges and subsequent infiltration into

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[10] Analysis for false negatives of random selection of 1750 articles from the 23,217 articles (published between 2006 and 2012) that did not match the pattern. The table containing the articles' Electronic Identifier (EID), authors, title, publication year, journal, volume, page information, citations, Digital Object Identifier (DOI), link to the article in Scopus®, abstract, the sentence that matched the pattern and whether the articles is considered to be a false negative or not can be found here: https://doi.org/10.6084/m9.figshare.9975734.v1.

groundwater in the period of 1970-2012 [7, 8]. This investigation caused great public concern [126].

The case of PFOA shows a long period of emergence of concern in the Netherlands, from the first articles reporting on the presence of PFOA in the environment in the early 2000s and the replacement of PFOA by another perfluorinated compound in 2012. Lau et al. [253] reviewed the literature on monitoring and toxicological findings about perfluoroalkyl acids in 2007. Based on this review, it can be concluded that Hansen et al. [254] quantitatively reported the presence of PFOA in the aquatic environment for the first time in 2002. However, we found that Moody et al. [255] had published research somewhat earlier in 2001, reporting the presence of PFOA in surface water samples. Another early paper on the presence of perfluorooctane surfactants in surface water, was the study by Boulanger et al. [256] who reported concentrations of PFOA in Great Lakes water.

The proposed methodology[11] including the pattern was run for articles published between 2001 and 2007. The methodology did not pick up the articles by both Hansen et al. [254] (published in 2002) and Moody et al. [255] (published in 2001), because they did not specifically refer in either the title or the abstract to this being the first report of PFOA in the aquatic environment. However, the study by Giesy and Kannan [257] (published in 2001) on the presence of PFCs in (aquatic) wildlife was picked up by the proposed methodology. However, these authors focused primarily on providing evidence of the global distribution of perfluorooctane sulphonic acid (PFOS) in biota not so much a first reporting. Also, the article by Boulanger et al. [256] published three years later in 2004 was picked up. Thus, using the proposed text mining methodology, attention could have been drawn to the potential presence of PFOA in the aquatic environment in the Netherlands some 8 years earlier (in 2004 instead of 2012) and proactive risk governance at a national level would have been possible.

3.5.2 Legionella

Legionella bacteria are ubiquitously present in the environment. Inhaling pathogenic *Legionella* bacteria can cause Legionnaires´ disease (LD) resulting in severe pneumonia. In 2017, the highest number of patients suffering from LD ever notified in the Netherlands was reported, namely a total of 561 cases [258], and only a minority of these were associated with exposure abroad. LD is often associated with manmade water systems, for instance, whirlpools, cooling towers and water distribution systems. However, the infection source remains unknown for most of the cases that are not part of an outbreak of Legionnaires´ disease and that have been infected in the Netherlands [258].

In 2016 and 2017, two successive clusters of a total of 14 cases of LD were reported in Boxtel, a town in the south of the Netherlands [259]. At first, no common source could be identified based on interviews and sampling. However, after continuously investigating possible sources, an industrial biological WWTP was identified as the infection source for both clusters. The growing trend in LD cases in another city in

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[11] The R-based proposed methodology can be downloaded from https://doi.org/10.6084/m9.figshare.9975722.v1.

the south of the Netherlands was also traced back to an industrial biological WWTP. These findings illustrated the importance of industrial biological WWTPs as potentially relevant sources for LD infections [258].

In 2018, Loenenbach et al. [259] reported identifying industrial biological WWTPs as potential relevant sources of Legionnaires´ disease infections for the first time in the Netherlands. However, cases of Legionnaires´ disease with biological WWTPs as infection source had already been reported in other countries before the two successive clusters in the Netherlands in 2016 and 2017 were found. Indeed, Van Heijnsbergen et al. [260] also mentioned these cases in their review of potential sources of Legionella which was published in 2015. To the best of our knowledge, Allestam et al. [261] identified the biological treatment of industrial wastewater as a possible source for *Legionella* infection for the first time in 2006.

The proposed methodology[12] was run for articles published between 2006 and 2015. The methodology did not pick up the research by Allestam et al. [261] (published in 2006), because it was not published as a scientific article, but as a book Chapter. However, a Finnish report on two cases of Legionnaires´ disease associated with biological WWTPs published in 2010 [262]was identified. Thus, if the proposed text mining methodology had been used in the Netherlands, the potential significance of biological WWTPs in Legionnaires´ disease infection could have been identified in 2010 instead of 2015. In that case, the period of concern would have been decreased by 5 years and proactive risk governance would have been possible, for example, by running a monitoring campaign to identify relevant industrial biological WWTPs in the Netherlands.

3.6 Discussion

To the best of our knowledge, this is the first attempt to develop a methodology to search the scientific literature for articles reporting the first detection of chemical and microbial contaminants in the aquatic environment. Sjerps et al. [225] used text mining in 2015 to identify potential emerging risks, comparing the manual and automated analysis of scientific literature. The authors concluded that the manual analysis was not structured, poorly reproducible and labour-intensive. The automated search using the text mining tool was fast and reproducible but generated too many hits and an unmanageable number of contaminants. Therefore, Sjerps et al. [225] suggested using automated text analysis to identify eligible studies and then performing a manual analysis of the eligible studies. Using the pattern matching approach in this study is one way of implementing this as a reproducible methodology.

In this research project, we showed the results of applying the developed methodology to literature published in the last 2.5 years (2016 until August 2018). This resulted in 3,650 records which were manually analysed using the additional predefined inclusion and exclusion criteria. Although the developed methodology minimised the manual workload as only sentences matching the pattern were analysed and not the whole abstract, this is still a time consuming step in the

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[12] The R-based proposed methodology can be downloaded from https://doi.org/10.6084/m9.figshare.9975722.v1.

analysis. Therefore, in order to keep the number of records manageable, we suggest running the methodology twice a year. Based on the number of relevant articles published between 2016 and August 2018 (2016 = 157, 2017 = 137 and until August 2018 = 74), this would result in about 70 to 80 articles per run.

The effectiveness of the methodology was tested using a priori selected articles. One of the a priori selected articles, namely Conley et al. [234], was not found by the developed methodology. This is because the first detection of norfluoxetine was not mentioned in the abstract or title, but only in the full text. Therefore, by using the developed methodology only those articles are identified, in which the authors consider the first detection of a contaminant in the aquatic environment an important aspect of their research and include this in the title or abstract. Open Access publishing would remove this limitation as the full text could then be retrieved from Scopus® instead of the abstract. The added-value of text mining full text articles instead of abstracts has been illustrated before by Westergaard et al. [263]. However, a recent estimation of Open Access publishing showed that only 28 percent of scientific articles are published Open Access [264]. Thus, the limitation of mining only title and abstracts is not expected to be eliminated any time soon.

The specificity analysis resulted in a low specificity (52.1%). This is due to the high fraction of false positives. The calculation of the low specificity is once again evidence for the need of the additional manual analysis of the identified articles, as is shown in Figure 3-1. Also, words are used in many different ways in a sentence, such as the words ‘new’ and ‘first’, which leads the pattern to extract false positives. For example, ‘new’ could be part of a region´s or city´s name, such as ‘New Zealand’ in the abstract published by Neary and Baillie [265]. The word ‘first’ is also used in many articles as a numerical transition word, for example in the abstract by Sharma and Malaviya [266]. Most false positives are unavoidable and can easily be excluded in the manual selection phase of eligible studies.

However, some of the false positives could be automatically eliminated by removing sentences in which “New” refers to a country and “first” is used in the beginning of a sentence and following by a comma. These rules were translated into additional lines of code[13] which could be run after the pattern matching code. We were able to automatically eliminate 161 sentences by using this additional line of code on the sentences shown in https://doi.org/10.6084/m9.figshare.9975728.v1.

The fraction of false negatives found was very low, namely 0.0183. However, all false negatives reported on the first detection of a microbial contaminant indicating that the pattern is more tailored to studies reporting on chemical contaminants than to studies reporting on microorganisms in the aquatic environment. This can be due to the fact that the a priori selected articles comprised only two articles reporting on the first detection of microbial contaminants in the aquatic environment [237, 243]. Therefore, we suggest an addition to the pattern[14], namely a combination of the words ‘novel’, ‘new’ or ‘undescribed’ and ‘species’, ‘first outbreak’ and ‘first description’. The extended pattern is also available at

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[13] See https://doi.org/10.6084/m9.figshare.9975722.v1.

[14] For the pattern see https://doi.org/10.6084/m9.figshare.9975722.v1.

https://doi.org/10.6084/m9.figshare.9975722.v1 and eliminates 29 out of the 32 false negatives.

The methodology was made as straightforward as possible and coded in R to make it widely applicable. However, as the methodology is R-based, some prior knowledge of programming is needed to be able to run it. Therefore, we suggest researchers use the methodology to inform policy makers. For example, researchers working in close collaboration with national or international government agencies, such as employees of health agencies. Another option is to build a user interface as has been done previously for complicated computational analysis tools such as QMRAspot [170, 267]. These tools include data, assumptions and calculations which make them more user-friendly for non-mathematicians. However, it should be noted that, in order to interpret the results of these tools, discipline related knowledge is still required.

A retrospective validation of the methodology was performed by evaluating the period of emergence of concern for two example contaminants in the Netherlands, one microbial and one chemical contaminant. Although we are aware of the fact that the period of emergence of concern related to these contaminants might be very different in other countries and that early identification of contaminants is no guarantee for regulatory actions, the retrospective validation illustrated that the methodology can be useful for the more timely identification of emerging contaminants.

Although the methodology has been developed specifically to extract articles from Scopus®, any database of peer-reviewed literature could be used with the proposed search query. In that case, the developed code could be used as is after the abstract and title information has been imported into R-studio. However, to our knowledge, no R-package exists for retrieving abstract information from databases of peer-reviewed literature except for Scopus®.

Furthermore, the search query and pattern can be easily adjusted as the codes are added as supplementary material and the additional inclusion and exclusion criteria are explicitly described. For instance, the search query and additional inclusion and exclusion criteria can be adjusted to make the methodology applicable to the search for articles identifying contaminants for the first time in soil or air. Identifying early signals of contaminants in soil might also be interesting when it comes to the quality of freshwater resources due to potential leaching. Also, by replacing all search terms in concept 1 of the search query (see Figure 3-2) by a specific contaminant group, such as “pharmaceuticals” or “personal care products”, the methodology could be used to identify a specific type of new chemicals. Finally, one might consider including studies on new toxicity results for known contaminants, and compare these to the results of national monitoring studies. In these cases, the pattern could be used as it is as long as the search terms are adapted.

When textual data were imported into the R environment, some characters were not properly encrypted and were thus replaced by random signs. Examples of characters that the R environment was unfamiliar with, even after an encryption comment was run, were Greek letters and characters in subscript or superscript. This phenomenon has caused some contaminants in the abstracts shown in https://doi.org/10.6084/m9.figshare.9975728.v1 to be named incorrectly. However, as the Scopus® link to the original research is included in https://doi.org/10.6084/m9.figshare.9975728.v1, the name of the contaminant can always be checked.

Finally, the developed methodology can be used to identify signals in any national, international or river basin setting since the search query and inclusion and exclusion criteria are not country or area specific. However, it is recognised that the elucidation of the relevance of the signals in the national, international or river basin setting is a crucial part of the proactive governance of emerging contaminants in the aquatic environment. Only when the identified signals are analysed effectively, is proactive governance possible.

3.7 Conclusions

In this study, we hypothesised that the period of emergence of concern of contaminants could be reduced by performing a systematic search for articles which reported the first detection of a contaminant in the aquatic environment. For this purpose, we developed a methodology using literature mining. The technical aspects of the developed methodology were described as well as its implementation for the screening of recent scientific literature. The hypothesis was tested by retrospectively analysing the period of the emergence of concern related to two contaminants in the Netherlands. The retrospective analysis showed that the methodology is able to extract early signals of a contaminant in the aquatic environment. However, the further elucidation of the relevance of the identified signals, here referred to as the reporting phase, is crucial in order to decrease the period of emergence of future contaminants. We therefore conclude that the developed methodology is a first step towards the proactive systematic identification of emerging contaminants in the aquatic environment.

4 EFFECTIVITY OF LITERATURE MINING FOR EARLY IDENTIFICATION OF EMERGING DRINKING WATER CONTAMINANTS

Abstract

The study[15] described in this chapter aimed to (1) assess the effectiveness of screening the scientific literature to direct sampling campaigns for early warning purposes, and (2) detect new aquatic contaminants of concern to public health in the Netherlands. By screening the scientific literature, six example contaminants (3 chemical and 3 microbial) were selected as potential aquatic contaminants of concern to the quality of Dutch drinking water. Stakeholders from the Dutch water sector and various information sources were consulted to identify the potential sources of these contaminants. Based on these potential contamination sources, two sampling sequences were set up from contamination sources (municipal and industrial wastewater treatment plants), via surface water used for the production of drinking water to treated drinking water.

The chemical contaminants, mycophenolic acid, tetrabutylphosphonium compounds and Hexafluoropropylene Oxide Trimer Acid, were detected in low concentrations and were thus not expected to pose a risk to Dutch drinking water. Colistin resistant Escherichia coli was detected for the first time in Dutch wastewater not influenced by hospital wastewater, indicating circulation of bacteria resistant to this last-resort antibiotic in the open Dutch population. Four out of six contaminants were thus detected in surface or wastewater samples, which showed that screening the scientific literature to direct sampling campaigns for both microbial and chemical contaminants is effective for early warning purposes.

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[15] This Chapter is based on Hartmann J, van Driezum I, Ohana D, Lynch G, Berendsen B, Wuijts S, van der Hoek JP, de Roda Husman AM. The effective design of sampling campaigns for emerging chemical and microbial contaminants in drinking water and its resources based on literature mining. Science of the Total Environment. 2020;742:140546.

4.1 Introduction

To provide all humans with clean drinking water by 2030 is our goal [268]. For this, we need to effectively govern and manage the quality of our drinking water resources and focus scarce resources on aquatic contaminants that pose the greatest threat to human health when water is used for drinking water production. In large parts of the world, surface water is used for the production of drinking water [39, 40]. However, surface water serves multiple functions in addition to being a drinking water resource, such as receiving industrial and municipal wastewater, being home to aquatic ecosystems and serving recreational and transportation purposes [39, 40]. These functions result in a wide variety of different chemical and microbial contaminants being present in surface water [269]. Furthermore, although contaminants (both microbial and chemical) might be absent in the water source used for drinking water production, they may be introduced during treatment (e.g. disinfection by-products) or distribution (e.g. biofilms) [41, 42]. All of these aspects contribute to the complexity of effective risk governance of drinking water and its resources [269-271].

The potential human health effect of some contaminants has been well studied (for example arsenic [56] and *Cryptosporidium* [57]. Health based targets for drinking water have been implemented for these contaminants in national and international legislation. In Europe, the European Drinking Water Directive (DWD, 98/83/EC) is in place to protect citizens from adverse health effects caused by contamination of water intended for human consumption. The requirements for the chemical and microbial quality set by the European DWD are implemented into national legislation by Member States and need to be met by drinking water companies [272]. European drinking water companies are detecting chemical and microbial contaminants in drinking water and its resources that are not listed in the European DWD [34, 185, 273]. The potential (long-term) risk posed by (mixtures of) these emerging contaminants in drinking water is often unknown [18, 69, 188, 274].

Examples of emerging chemical contaminants in drinking water and its resources that have attention over the past years are industrial chemicals such as per- and polyfluoroalkyl substances (PFAS) [275], microplastics [276], ionic liquids and new groups of disinfection by-products such as halogenated methanesulphonic acids [128]. Many of these chemicals have been in the aquatic environment for years, but have only recently been identified due to the increasing sensitivity of analytical techniques [277]. The emergence of concern about contaminants such as PFAS has shown that, by the time scientific and regulatory agreement has been reached on the risk that these chemicals pose to humans and aquatic ecosystems, they are already ubiquitously present in the environment and remediation actions are costly and time-consuming [278].

Recent examples of emerging microbial contaminants relevant to drinking water are: *Waddlia chondrophila* [71], antibiotic resistant bacteria [274] and sapoviruses [59]. Pathogens are not directly included in the current European DWD, but are governed through quality standards for faecal contamination (*E. coli* and *enterococci*) which are used to indicate the adequate disinfection performance of the drinking-water supply. However, viruses and protozoa (such as *Cryptosporidium* and *Giardia*) can be of risk to public health even in the absence of these quality standards [279]. Also, pathogens present in drinking water might remain undetected due to imperfect detection methods [280]. The revision of the European DWD will focus on risk-based monitoring based on (1) risk assessment and risk management of the catchment areas of the abstraction points, (2) risk management of water supply systems including abstraction, treatment, storage and distribution to the point of supply, and (3) risk assessment of the domestic distribution system [20]. But even with a risk-based approach, risk governance is still based on knowledge of known pathogens, including treatment efficiencies for these, which might be inaccurate for emerging pathogens [170].

To protect humans from adverse health effects from both microbial and chemical contaminants in drinking water and to prevent costly remediation actions, water authorities and drinking water companies need early warning systems. Here, early warning systems are defined as processes aimed at reducing the impact of hazards by providing timely and relevant information in a systematic way [281]. It has been shown that new hazards are reported in scientific articles long before the contaminant is globally recognised as an emerging risk for water functions [155, 158]. Scientific articles may thus be used as part of an early warning system for proactive risk governance by water authorities and drinking water companies.

In a previous study, the authors developed a methodology to identify the first scientific article that reported the presence of a specific contaminant in the aquatic environment [156]. The semi-automated methodology uses literature mining to enable the simultaneous analysis of a large number of scientific publications and is freely accessible. Using retrospective validation (period 2001-2015), the developed methodology was found to be effective in picking up early signals of aquatic contaminants of concern [156]. However, this was a theoretical exercise and the practical effectiveness of the methodology still needs to be proven. The methodology was therefore applied to studies published between 1 January 2016 and 27 August 2018. This resulted in a list of 359 articles which reported one or more chemical (173 articles) and microbial (186 articles) contaminants for the first time[16].

In this study, the results from this literature screening were used to direct a sampling campaign for chemical and microbial contaminants in the Netherlands. The integrated analysis of both emerging chemical and microbial contaminants in the aquatic environment is an innovative feature of this study and is considered valuable as chemical and microbial contaminates often arise from similar sources of contamination (e.g. municipal and industrial wastewater). The objective of this study was twofold, namely (1) to validate the practical effectiveness of screening the scientific literature for early warning purposes, and (2) to detect new aquatic contaminants of concern to public health in the Netherlands. First, the list of contaminants reported in the 359 articles was assessed to select both aquatic chemical and microbial hazards not yet recognised as such in the Netherlands. Then, possible sources of these contaminants in the Netherlands were identified, and based on these sources a monitoring campaign was set up to target the contaminants in municipal and industrial wastewater, drinking water resources, and/or drinking water. Monitoring results as well as information sources and

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[16] See Appendix A of https://doi.org/10.1016/j.scitotenv.2020.140546 for the detailed list of articles.

stakeholders consulted are described, to conclude with suggestions for successfully developing a sampling campaign based on literature mining.

4.2 Materials and methods

4.2.1 Drinking water production in the Netherlands

In the Netherlands, 58% of the drinking water is produced from groundwater, 35% from surface water, 6% from riverbank filtration and 1% from natural dune water [30]. The main surface water resources for the production of drinking water are the rivers Rhine and Meuse and the lake IJsselmeer [30]. Dutch drinking water is of very high quality due to good asset management, the use of preventive risk assessment and risk management from source to tap, and the application of a multi-barrier approach in drinking water treatment [169, 170, 177]. Despite the high quality of drinking water, emerging contaminants in drinking water and its resources, such as microplastics and PFAS, have led to considerable regulatory challenges and media attention in the Netherlands [61, 126, 178].

4.2.2 Contaminant selection

The result of applying the literature mining methodology developed by Hartmann et al. [156] is a list of 359 articles[17] that report the detection of one or more contaminants for the first time in the aquatic environment. For details on the text mining methodology, see [156].

To validate the practical effectiveness of screening the scientific literature for early warning purposes, three chemical and three microbial contaminants were selected from the list[17] of contaminants. These contaminants were selected as examples of potential new aquatic contaminants of concern to Dutch drinking water. Selecting six and not more contaminants was done for practical reasons. As this study integrates the chemical and microbial assessment of water samples, the word ‘contaminant’ is used to indicate both chemical and microbial water constituents. All six contaminants met the following hazard and exposure related criteria, namely:

- The contaminant is an unknown water constituent in surface water in the Netherlands or is a known water constituent but the relevance to drinking water quality is unknown;
- The contaminant could potentially be present in Dutch surface water resources used for drinking water production based on the presence of potential sources of pollution (e.g. industrial use of the contaminant, presence of the contaminant in human wastewater);
- The contaminant has a potential to be toxic or pathogenic, or the toxicity and pathogenicity of the contaminant are unknown;
- An analytical methodology is available for the analysis of the contaminant in water samples.

The three chemical contaminants selected were mycophenolic acid (MPA, Chemical Abstracts Service (CAS) number 24280-93-1), tetrabutylphosphonium compounds (Bu_4P^+, hereafter referred to as TBP, CAS number 2304-30-5) and Hexafluoropropylene Oxide Trimer Acid (HFPO-TA, CAS number 13252-14-7). The

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[17] See Appendix A of https://doi.org/10.1016/j.scitotenv.2020.140546 for the detailed list of articles.

three microbial contaminants selected were mobilised colistin resistance-1 positive *Escherichia coli* (MCR-1 *E. coli*), a novel variant of *Vibrio cholerae* O1 El Tor ctxB and *Legionella longbeachae*. We consciously opted to investigate 6 constituents as the sampling campaign itself was not the aim of the paper. The aim was to test the effectiveness of designing sampling campaigns based on literature mining, and for this purpose 6 constituents were sufficient. The manner in which the six contaminants fit within the selection criteria for potential new aquatic contaminants of concern to Dutch drinking water is discussed in detail in the following sections and in brief in Table 4-1.

Table 4-1 Fulfilment of the selection criteria for potential new aquatic contaminants of concern to Dutch drinking water by MPA, TBP, HFPO-TA, MCR-1 E. coli, Vibrio cholerae O1 El Tor ctxB and Legionella longbeachae.

Contaminant	Signal reported by	Study detected contaminant in	Potential relevance to drinking water production in the Netherlands
MPA	Franquet-Griell et al. [282]	River Llobregat in Spain	Pharmaceutical estimated to be discharged in high amounts to surface water due to high daily dose (2 g), minor metabolic impact and limited removal in wastewater treatment plants. No environmental concentrations available for the Netherlands.
TBP	Brand et al. [68]	River Elbe in Germany	Industrial chemical used as phase-transfer catalyst in the synthesis of organic compounds. Potential industrial source present in the Netherlands. Observed cytotoxic potential in human cells. Presence in the (aquatic) environment in the Netherlands unknown.
HFPO-TA	Pan et al. [283]	Xiaoqing River in China and the common carp (*Cyprinus carpio*)	Industrial chemical (PFAS) used by fluorochemical industry. Potential industrial source present (fluorochemical company) in the Netherlands. Potential hepatotoxic effects. Limited environmental concentrations available for the Netherlands [284].
MCR-1 *E. coli*	Jin et al. [285]	Hospital wastewater in Bejing, China	Colistin is considered a last-resort antibiotic. Dissemination of resistance to last resort antibiotics poses a major public health risk. Unknown whether MCR-1 *E. coli* is present in wastewater to the aquatic environment in the Netherlands.
Vibrio cholerae* O1 El Tor with mutation in *ctxB	Bhattacharya et al. [286]	Faecal specimen from various Cholera outbreaks in India	*Vibrio* detected in salt and brackish water in the Netherlands, freshwater less frequently. Vibrio species are known to be effectively removed by drinking water treatment in the Netherlands. However, the genetic mutation found by Bhattacharya et al. (2016) of *V. cholerae* O1 El in *ctxB* (gene sequence that encodes cholera toxin B) could be transferred via Horizontal Gene Transfer (HGT) to other bacteria, thereby posing a threat to public health.
Legionella longbeachae	[287]	Manmade water system (cooling tower) in New Zealand	Increase in endemic cases of Legionellosis in the Netherlands. Infection source remains often unknown. Whether infection with *L. longbeachae* via manmade water systems could be a source of infection is unknown.

4.2.2.1 Mycophenolic acid (MPA)

MPA was identified by Franquet-Griell et al. [282] as a potential emerging risk to drinking water quality in Spain. MPA is prescribed in the Netherlands predominantly as an immunosuppressant. At the time of this study, MPA had not been considered a contaminant of concern for the aquatic environment in the Netherlands. Neither the number of users (14,182 in 2018), nor the total number of Defined Daily Dosages (DDDs) prescribed per year (2,924,500 in 2018) were very high compared to other commonly-used pharmaceuticals (e.g. Naproxen was used by 674,260 people in 2018 with a total of 34,543,200 DDDs prescribed) [288].

However, as 1 DDD of MPA is 2 grams according to the World Health Organization [289], it can be estimated that 5,849 kilogram of MPA was consumed in the Netherlands in 2018. After ingestion, 60 percent of the drug is excreted via urine as mycophenolic acid glucuronide and 3 percent remains unchanged [282]. I The glucuronide metabolite is deconjugated and the parent compound is formed again in wastewater treatment plants (WWTPs) [282]. Consequently, an estimated 3,685 kg MPA was discharged via effluents of WWTPs to surface water in the Netherlands in 2018. The estimated load of MPA is high (mainly due to the expected limited removal in WWTPs) compared to the widely-used Naproxen (864 kg, estimated removal in Dutch WWTPs is 95%) and similar to Irbesartan (3,221 kg, no expected removal in Dutch WWTPs) [290]. MPA was thus considered a potential contaminant of concern to drinking water quality in the Netherlands.

4.2.2.2 Tetrabutylphosphonium compounds (Bu_4P^+, TBP)

Brand et al. [68] detected TBP for the first time in the River Elbe in Germany. TBP compounds are used as phase-transfer catalysts in the synthesis of organic compounds. Two different tetrabutylphosphonium compounds were registered by companies located in the Netherlands as part of the regulation (EC) No 1907/2006 of the European Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). These registrations suggest the potential emission of TBP to the environment in the Netherlands. Furthermore, Brand et al. [68] showed that TBP is persistent in the environment and observed cytotoxic potential in human cells of $Bu_4P^+Cl^-$. Therefore, the analysis of the potential presence of TBP in surface waters in the Netherlands was considered valuable.

4.2.2.3 Hexafluoropropylene Oxide Trimer Acid (HFPO-TA)

Per- and polyfluoroalkyl substances (PFAS) are an increasing cause of concern due to their persistence in the environment and their potential to cause adverse effects in humans. PFAS have been widely used since the 1950s in many industrial applications such as in the production of polytetrafluoroethylene and paints [5, 291]. After the phase out of PFOA, a widely used PFAS, alternative PFAS have been developed. Hexafluoropropylene Oxide Trimer Acid (HFPO-TA), one of the alternatives, was recently detected for the first time in the aquatic environment by Pan et al. [283]. HFPO-TA was detected in concentrations up to 68.5 μg/L in the Xiaoqing River in China as a result of wastewater discharges from a fluoropolymer manufacturing plant. Sheng et al. [292] showed that HFPO-TA has a higher bioaccumulation potential than PFOA and is more hepatotoxic. Little is known about the annual production and environmental occurrence of HFPO-TA in Europe's surface waters.

HFPO-TA is not registered under REACH by any company located in the Netherlands, indicating that if HFPO-TA is used or produced in the Netherlands it is below 1,000 kg per year. This indicates low emission potential to the aquatic environment. Pan et al. [284] detected trace levels of HFPO-TA in water samples taken from the Dutch and German part of the River Rhine as well as in water samples from other European countries, such as Sweden and the United Kingdom, indicating potential emission of HFPO-TA in Europe.

The presence of another PFOA alternative, Hexafluoropropylene Oxide Dimer Acid (HFPO-DA), in surface and drinking water in the Netherlands has caused considerable public and regulatory concern over the past years. Since July 2019, HFPO-DA has been categorised as a Substance of Very High Concern by the European Chemicals Agency (ECHA) following a Dutch proposition [62].

Pan et al. [284] sampled locations on the River Waal (a Dutch branch of the River Rhine) upstream of a fluorochemical production plant in the Netherlands. Whether the concentrations of HFPO-TA found by [284] were the result of wastewater discharged by the fluorochemical production plant in the Netherlands has not yet been investigated. Due to the concern about HFPO-DA and the limited knowledge about HFPO-TA, it was considered valuable to analyse the potential presence of HFPO-TA in surface water and wastewater of the fluorochemical production plant in the Netherlands.

4.2.2.4 Mobilised colistin resistance-1 positive Escherichia coli (MCR-1 E.coli)

Jin et al. [285] reported the presence of mobilised colistin resistance-1 positive Escherichia coli (MCR-1 *E.coli*) in hospital wastewater for the first time in China. They detected MCR-1 *E.coli* in both the influent and effluent of the wastewater treatment plant, thereby indicating the introduction of MCR-1 *E.coli* into the aquatic environment via hospital wastewater. MCR-1 *E.coli* has also been detected in isolates obtained from hospitalised patients and in retail chicken meat in the Netherlands [293, 294]. Dissemination of resistance to colistin is considered a serious threat to public health as it is used to treat human infections caused by multidrug-resistant and carbapenem-resistant bacteria that cannot be treated by conventionally used antibiotics [295]. No information is available on the dissemination of MCR-1 *E.coli* to the aquatic environment through wastewater in the Netherlands.

Drinking water treatment is effective in removing bacteria and resistance does not limit the removal efficiency [170, 274]. However, antibiotic resistant genes (ARG) have been shown to persist drinking water treatment [296]. Zhang et al. [297] detected an increase in antibiotic resistance in drinking water due to the detachment of biofilm. ARG could be transferred to pathogens via Horizonal Gene Transfer (HGT), thereby posing a threat to public health. Therefore, the potential presence of MCR-1 *E.coli* in the aquatic environment in the Netherlands is relevant from a drinking water perspective.

4.2.2.5 Vibrio cholerae O1 E1 Tor with mutation in cholera toxin B subunit gene (ctxB)

Vibrio bacteria are found abundantly in the aquatic environment, especially in the marine environment, and play an important role in maintaining the health of the aquatic ecosystem [298, 299]. Of the 100 *Vibrio* species known to humans, 11 are known pathogens [299]. Infection with *V. cholerae* O1/O139 can cause cholera, a severe diarrheal disease, which is responsible for an estimated 95,000 deaths worldwide per year [300]. Bhattacharya et al. [286] were the first to report a new variant of *Vibrio cholerae* O1 E1 Tor in South India with a mutation in the cholera toxin B subunit gene (*ctxB)*.

In the Netherlands, *Vibrio* infections caused by swimming in contaminated waters have been reported [301]. Furthermore, the presence of *V. alginolyticus*, *V. parahaemolyticus*, *V. cholerae non O1/O139* and *V. fluvialis* in coastal waters has been shown but, to date, has rarely been detected in freshwater [302]. *Vibrio* species are known to be effectively removed by drinking water treatment in the Netherlands. However, the potential presence of the newly identified *Vibrio cholerae* O1 E1 variant in surface water was initiated as *ctxB* could be transferred to other pathogens by HGT which might be less effectively removed by drinking water treatment.

4.2.2.6 Legionella Longbeachae

Thornley et al. [287]first reported the transmission of *Legionella longbeachae* (aerobic Gram-negative bacteria) from cooling towers citing it as a potential cause for Legionnaires' disease (LD). In general, the watering of contaminated compost or soil is expected to be the major source of infection for *L. longbeachae* [303, 304]. The Thornley et al. [287] study highlights the relevance of waterborne transmission in investigations to find the source of *L. longbeachae* infection.

Since 2012, an increase in endemic LD cases has been observed in the Netherlands which might be related to an increase in in the number of warm, humid and showery weather days [258, 305]. For most of the *Legionella* infections, the infection source remains unknown. Recently, the infection risk posed by Dutch wastewater treatment plants was investigated, but whether cases of LD caused by *L. longbeachae* in the Netherlands could be related to WWTPs is currently unknown[306]. Therefore, an investigation into the potential presence of *L. longbeachae* in wastewater in the Netherlands was considered relevant to protect public health.

4.2.3 Development of the sampling campaign: consulted stakeholders and information sources

In order to develop the sampling campaign, different stakeholders from the Dutch water sector as well as several information sources were consulted. Two questions were taken into consideration: (1) what could be the potential source of the contaminant and (2) which drinking water production location would be potentially impacted by this source of pollution.

First, a vast array of stakeholders, including Dutch drinking water companies and their laboratories, the association of River water companies for both the River Rhine and Meuse (RIWA) as well as the national water authority (Rijkswaterstaat), were asked whether the selected chemical contaminants had ever been detected in surface water in the past. Both target and non-target screening data (when available) were checked. None of the contaminants had been detected in the available monitoring data. Also, no next generation sequencing data were available for the microbial contaminants from the labs. Therefore, no indication for potential sources or drinking water production sites at risk could be abstracted from this information.

Based on the literature information, it was concluded that human wastewater could be a potential source of MPA and MCR-1 *E.coli* [282, 285]. This could also be the case for *L. longbeachae*, as indicated by Thornley et al. [287]. As surface waters receive discharges from municipal WWTPs and *Vibrio* species are their natural inhabitants, surface waters used for the production of drinking water were considered for this study.

Based on the information from the REACH registrations for TBP, a company was contacted that could potentially produce or use TBP. The company has two locations in the Netherlands. One in the city of Bergen op Zoom, which is the location mentioned in the REACH registration, and one on an industrial site in the southern part of the Netherlands where an industrial WWTP collects and treats wastewater from 150 chemical companies. The effluent from this industrial WWTP is discharged into a branch of the River Meuse which is an important drinking water resource in the Netherlands. The potential emission of TBP by this location of the company could thus potentially influence the production of drinking water. The company appreciated the early signal and investigated whether any of the products used on site, including chemical cleaning products, contained TBP. To the best of their knowledge, TBP was not used on their site (personal communication May 2019). It was decided to investigate the wastewater from the chemical industry site to confirm the absence of TBP.

The fluorochemical manufacturer near the city of Dordrecht was considered a potential industrial source of HFPO-TA (also referred to in a recent study by Brandsma et al. [61]). At the time of this study, because of the national and international concern about HFPO-DA, the Dutch national water authority (Rijkswaterstaat) was already closely monitoring the wastewater from the fluorochemical manufacturer for the presence of HFPO-DA. Through Rijkswaterstaat, sites that would have been otherwise restricted could be sampled. The company appreciated the early signal, and declared that it was not aware of any use of HFPO-TA at their company. Whether HFPO-TA was formed as a by-product during the process was unknown and triggered the investigation of their wastewater. The wastewater of this company is directly and indirectly (via a municipal WWTP) discharged into the River Beneden Merwede, a river which influences the River Noord that is used for the production of drinking water downstream.

4.2.4 Sample collection

Based on the potential sources of contamination, receiving surface waters and possibly influenced drinking water production sites, two different sampling campaigns were initiated in the Netherlands. The first campaign was located around the city of Dordrecht and the second one in the southern part of the Netherlands. In both campaigns samples were collected from industrial wastewater, municipal wastewater, surface water and drinking water.

Samples for Campaign 1 were collected from May until October 2019. In October 2019 all samples for Campaign 2 were collected. The sampling locations are shown in Table 4-2. Sampling locations are based on previous research by drinking water companies and water authorities. Detailed information is provided in Table 4-2 on the number of samples in which a contaminant was analysed at the particular location.

If possible, composite samples were collected at the municipal WWTPs. However, for practical reasons (e.g. samples needed for quality monitoring by the WWTP and the time of collection), composite sampling was not done at all locations. Where it was not possible, grab samples were collected. Wastewater samples were taken at a WWTPs receiving hospital and municipal wastewater (C1L25 an C1L26), a WWTP that did not treat hospital wastewater (C2L5 - C2L8) and at an industrial WWTP that collects and treats wastewater from 150 chemical companies and their sanitary installations (C2L9 and C2L10). Runoff from the industrial site (C1L18 – C1L22) was sampled at designated collection locations were concentrated rainwater was discharged. Drinking water samples were collected before water entered the distribution network. Surface water samples taken during Campaign 1 were collected at multiple locations in the river by boat with the help of Rijkswaterstaat. During Campaign 2 no boat was available, these samples were thus collected from shore. The samples used for the analysis of HFPO-TA, MPA and TBP were stored at 4°C until the time of analysis. The samples used for the analysis of *V. cholerae*, MCR-1 *E. coli* and *L. longbeachae* were analysed within 24 hours.

4.2.5 Sample analysis

The analyses of MPA, TBP, *V. cholerae,* MCR-1 *E. coli* and *Legionella longbeachae* were performed at the Dutch National Institute for Public Health and the Environment (RIVM) and the analysis of HFPO-TA was carried out by Wageningen Food Safety Research.

4.2.5.1 Mycophenolic acid (MPA)

Before sample preparation, isotopically labelled MPA was added to all samples and quality control samples. Blank matrix samples were used for quality control and were prepared following the same procedure as the water samples. 15 mL of the samples was concentrated in duplicate using *Solid Phase Extraction* (SPE) and run through a Waters OASIS HLB 6 cc/200 mg column. The column was washed with 40% methanol and water. MPA was eluted from the column by 4 mL methanol and the eluate was evaporated at 45°C. Finally, the residue was dissolved in 300µl methanol.

The analysis of MPA was carried out using liquid chromatography coupled to tandem-mass spectrometry (LC-MS/MS) in positive heated ESI mode. 10 µL was injected on a Waters Acquity UPLC HSS C18 column of 150 × 2.1 mm, 1.8 µm particles. MPA was eluted using a 14 minutes gradient: mobile phase A, 10 mM ammonium formate; mobile phase B, acetonitrile.

The mass spectrometer (QTrap 6500, AB Sciex) was operated at 400 °C with an ion spray voltage of 5,500 V and a decluttering potential of 26 V. The curtain gas was 40 psi, the ion source nebuliser gas was 90 psi and the ion source heater gas 50 psi. MPA was identified using the transition of m/z 321 > 207 for quantification, and m/z 321 > 159 for qualification. For quantification of the deuterated MPA the transition of m/z 324 > 210 was used, following Franquet-Griell et al. [282]. The Limit of Detection (LOD) was 0.01 ng/L and Limit of Quantification (LOQ) was 0.04 ng/L.

4.2.5.2 Tetrabutylphosphonium compounds (Bu_4P^+, TBP)

For the analysis of TBP, samples were not concentrated by SPE, but were only centrifuged. Isotopically labelled TBP was added to the samples before analysis, which was carried out using the same gradient conditions and column on the LC-

MS/MS system as was the case for the MPA analysis (*Section 2.5.1.2*). The mass spectrometer (QTrap 6500, AB Sciex) was operated at 500 °C, with an ion spray of 5,500 V and a decluttering potential of 66 V. The curtain gas was 40 psi, the ion source nebuliser gas was 90 psi and the ion source heater gas 50 psi. TBP was identified using the transition of m/z 259 > 76 for quantification and the transitions of m/z 259 > 61 and m/z 259 > 90 for qualification. The LOD and LOQ were 0.01 ng/L and 0.04 ng/L respectively.

4.2.5.3 Hexafluoropropylene Oxide Trimer Acid (HFPO-TA)

HFPO-TA was analysed using a Wageningen Food Safety Research in-house method. Before sample preparation, isotopically labelled HFPO-DA was added to all samples and quality control samples. A blank matrix and a blank chemical sample were used for quality control and were prepared following the same procedure as the water samples. 200 mL of the samples was concentrated by using weak anion exchange solid phase extraction (WAX-SPE). The samples were run through activated WAX columns (Strata-X, Phenomenex). HFPO-TA was eluted from the column by alkaline acetonitrile after washing with sodium acetate buffer and methanol. The eluate was evaporated at 40 °C under nitrogen. The residue was dissolved in 300 µl acetonitrile and diluted with 2 mM ammonium acetate in water to 1 mL.

The analysis of HFPO-TA was carried out using liquid chromatography coupled to tandem-mass spectrometry (LC-MS/MS). 20 µL of the extract was injected on an Acquity UPLC BEH C18 analytical column of 50 x 2.1 mm, 1.7 µm particles. An isolator column was used to prevent any interference by substances from the mobile phase. HFPO-TA was eluted using a 12.5 minutes gradient: mobile phase A, 2 mM ammonium acetate buffer in water; mobile phase B, acetonitrile.

The mass spectrometer (Q-Trap 5500, Sciex) was equipped with an electrospray interface in the negative ion mode. HFPO-TA was detected based on the ion transition m/z 495 > 185 and 185 > 119, the latter originating from an in-source fragment of HFPO-TA. The LOD was 1 ng/L unless a sample proved to be highly contaminated with other PFAS (e.g. PFOA or HFPO-DA). In that case no concentration step was carried out to prevent contamination of the laboratory equipment, yielding an LOD of 300 ng/L. Quantification of all samples was performed with a linear 7 point calibration curve with concentrations ranging from 5 ng/L up to 125 ng/L. To check for an adequate performance of the instrumentation, isotopically labelled PFOA was added just before injection into the LC-system.

Table 4-2 Overview of samples collected during Campaign 1 (Location codes = C1L1 - C1L28) and Campaign 2 (Location codes = C2L1 - C2L13). Explanation of abbreviations and symbols used: - = not applicable, GS = grab sample, CS = composite sample, WWTP = wastewater treatment, HFPO-TA = Hexafluoropropylene Oxid Trimer Acid, MPA = mycophenolic acid, TBP = tetrabutylphosphonium compounds, V. cholerae = Vibrio cholerae O1 E1 Tor with mutation in cholera toxin B subunit gene (ctxB), MCR-1 E. coli = Mobilised colistin resistance-1 positive Escherichia coli (MCR-1 E.coli),* = Time-proportional composite sample over 24 hours, ** = Flow-proportional composite sample (40 mL sample per 180 m^3 water)

Location code	**Type of water**	**Type of sample**	**Shore side**	**Number of samples for specific contaminant analysis collected at particular locations**					
				HFPO-TA	***MPA***	***TBP***	***V. cholerae***	***MCR-1 E.coli***	***L. longbeachae***
C1L1	Surface water	GS	Middle	4	-	-	-	-	-
C1L2	Surface water	GS	Right	4	-	-	-	-	-
C1L3	Surface water	GS	Middle	4	-	-	-	-	-
C1L4	Surface water	GS	Left	4	-	-	-	-	-
C1L5	Surface water	GS	Middle	2	6	6	1	-	-
C1L6	Surface water	GS	Right	5	3	3	1	-	-
C1L7	Surface water	GS	Right	5	-	-	-	-	-
C1L8	Surface water	GS	Middle	5	-	-	-	-	-
C1L9	Surface water	GS	Left	5	1	1	-	-	-
C1L10	Surface water	GS	Right	5	2	2	1	-	-
C1L11	Surface water	GS	Middle	5	-	-	-	-	-
C1L12	Surface water	GS	Right	5	-	-	-	-	-
C1L13	Cooling water used in industrial processes	GS	-	2	3	3	-	-	-
C1L14	Wastewater fluorochemical company	GS	-	3	3	3	-	-	-
C1L15	Wastewater fluorochemical company	GS	-	3	-	-	-	-	-

C1L16	Wastewater fluorochemical company	GS	-	3	2	2	-	-	-
C1L17	Wastewater fluorochemical company	GS	-	3	3	2	-	-	-
C1L18	Runoff from industrial site	GS	-	2	-	-	-	-	-
C1L19	Runoff from industrial site	GS	-	2	-	-	-	-	-
C1L20	Runoff from industrial site and process water	GS	-	3	1	1	-	-	-
C1L21	Runoff from industrial site	GS	-	2	-	-	-	-	-
C1L22	Runoff from industrial site	GS	-	2	-	-	-	-	-
C1L23	Wastewater fluorochemical company	CS*	-	-	2	2	-	-	-
C1L24	Wastewater fluorochemical company	GS	-	-	1	1	-	-	-
C1L25	Influent municipal WWTP	GS	-	1	3	3	-	1	
C1L26	Effluent municipal WWTP	GS	-	5	2	2	-	-	-
C1L27	Intake water	GS	-	1	4	4	-	-	-
C1L28	Drinking water	GS	-	1	4	4	-	-	-
C2L1	Surface water	GS	Left	-	2	2	-	-	-
C2L2	Surface water	GS	Right	-	3	3	1	-	-
C2L3	Surface water	GS	Right	-	3	3	1	-	-
C2L4	Surface water	GS	Right	-	3	3	1	-	-
C2L5	Influent municipal WWTP	GS	-	-	1	1	-	1	1
C2L6	Influent municipal WWTP	CS**	-	-	2	2	-		
C2L7	Effluent municipal WWTP	GS	-	-	1	1	-	-	1
C2L8	Effluent municipal WWTP	CS**	-	-	2	2	-	-	-
C2L9	Influent industrial WWTP	GS	-	-	3	3	-	1	1

C2L10	Effluent industrial WWTP	GS	-	-	3	3	-	-	1
C2L11	Intake water	GS	-	-	2	2	-	-	-
C2L12	Drinking water	GS	-	-	2	2	-	-	-

Figure 4-1 Map of the Netherlands giving an overview of the sampling sites. A more detailed view of both sampling campaigns is also shown.

4.2.5.4 *Mobilised colistin resistance-1 positive Escherichia coli (MCR-1 E.coli)*

Three wastewater samples were analysed within 6 hours of sample collection for the presence of MCR-1 *E.coli*. The protocol published by Biomérieux [307] for the screening of Colistin-resistant *Enterobacteriaceae* was used.

Each sample was tested in two dilutions after filtration using a 0.45 µm Millipore® filter. The two dilutions were prepared with 1 mL or 10 mL of the sample and 9 mL or 10 mL of Brain Heart Infusion broth (BHI), respectively. After incubation for 4 hours at 37 °C, 50 µL of each of the dilutions and 10 and 100 µL of the filtered samples were transferred to CHROMID® Colistin R disks containing 10 µg colistin each. This resulted in 12 disks that were incubated for 18 to 24 hours at 44 °C (a deviation from the protocol by Biomérieux [307] which calls for incubation at 37 °C). NCTC 13864 CR-*E. coli* and ATCC 25922 *E. coli* were used as positive and negative controls, respectively.

After incubation, pink coloured colonies were transferred to Tryptone Soy Agar (TSA) plates (Oxoid®). Polymerase chain reaction (PCR) was used for confirmation following the multiplex PCR methodology published by Rebelo et al. [308].

4.2.5.5 *Vibrio cholerae O1 E1 Tor with mutation in cholera toxin B subunit gene (ctxB)*

The methodology used for the identification of *Vibrio cholerae* in water is based on ISO 21872-1:2017 [309]. On day 1, 1 mL, 10 mL and 100 mL of the samples were filtered over a 0.45 µm Millipore® cellulose nitrate filter. The filters were incubated at 37 ºC overnight in 50 mL Alkaline Peptone Water (APW, Biotrading®). The next day, 10 µL from the subsurface layer of each APW suspension were transferred to thiosulfate citrate bile-salts sucrose (TCBS) agar plates and again incubated overnight at 37ºC [310]. *Vibrio cholerae* are known to appear as translucent, flat, yellow or green colonies on TCBS agar [310]. Therefore, on day 3, five yellow and five green colonies were transferred to TSA plates (Oxoid®) and incubated overnight at 37 ºC. The next day, all isolates were identified using API20E Biochemical Tests and confirmed using APIWEB™ by Biomerieux. In order to investigate the strains of the isolates identified as *V. cholerae* by APIWEB™, PCR was used.

The *V. cholerae* identified colonies were diluted in 500 µL 0.85% NACL in a 1.5 mL clean Eppendorf Tube®. The tubes were put in a water bath for 4 to 6 minutes at 95 ºC and then centrifuged at 10,000 g for one minute. Two PCR tests were carried out for confirmation, one for *V. cholerae* O:1 Ogawa and one for *V. cholerae* non O1. In both cases, 0.85% NACL was used as negative control.

Table 4-3 shows primers and probes used. The PCR mix consisted of 12.5 µL of master mix, 0.4 µL each of forward and reverse primer, 0.2 µL of probe, 6.5 µL water and 5 µL of DNA. The realtime PCR programme used for *V. cholerae* identification was one cycle of three minutes at 95 ºC for initial denaturation and polymerase activation and 45 cycles each of 15 seconds at 95 ºC for denaturation and 60 seconds at 60 ºC for annealing.

Table 4-3 Primers and probes used to identify Vibrio cholerae using PCR [308].

Ctx	**Forward**	**TTTGTTAGGCACGATGATGGAT**
Ctx	Reverse	ACAGACAATATAGTTTGACCACTAAG
Ctx	Probe	TGTTTCCACCTCAATTAGTTTGAGAAGTCCC
Tox R	Forward	GTGCCTTCATCAGCCACTGTAG
Tox R	Reverse	AGCAGTCGATTCCCCAAGTTTG
Tox R	Probe	CACCGCAGCCAGCCAATGTCGT

4.2.5.6 Legionella Longbeachae

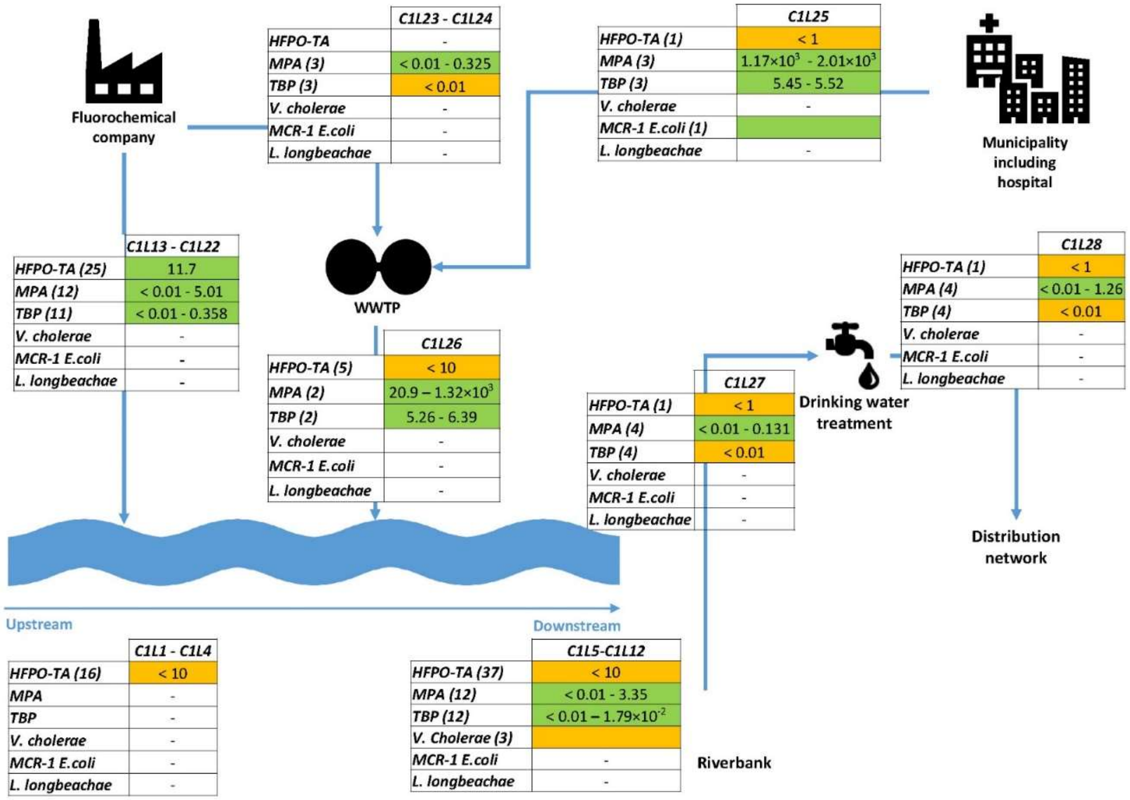
Four wastewater samples, two influent and two effluent samples, were analysed for the presence of *L. longbeachae* using NEN-EN-ISO 11731:2017 [311]. For practical reasons, the analysis was only possible for samples taken during Campaign 2. The methodology used for analysis of *Legionella* deviated from NEN-EN-ISO 11731:2017 in two aspects. Firstly, all samples were tested with and without acid and with and without heat treatment. This is in line with other published methodologies for the detection of *Legionella* bacteria in environmental samples [312]. Secondly, all samples were transferred to three different media to maximise the probability of culturing *Legionella* bacteria, namely buffered charcoal yeast (BCYE) agar (Oxoid®) with, and without, added antibiotics and BCYE supplemented with glycine (3 g/L), vancomycin (1 mg/L), polymyxin B (50,000 UI/L) and anisomycin (MWY, Oxoid®). The Oxoid® *Legionella* Latex test was used to serogroup isolated colonies suspected to be *Legionella* bacteria.

4.3 Results

In total, 166 samples were analysed. MPA was detected in 41 out of 67 samples, TBP was found in 48 out of 66 samples, HFPO-TA in 1 out of 86 samples and MCR-1 *E. coli* was found in all three tested samples. *V. cholerae* was identified in 2 out of 6 samples. However, the novel variant of *V. cholerae* O1 E1 Tor and *L. longbeachae* were not detected in the analysed samples. The results are shown in Figure 4-2 and Figure 4-3 for sampling Campaigns 1 and 2, respectively, and are discussed in detail below. For the statistical analysis of MPA, TBP and HFPO-TA concentrations, the numerical value of the LOD was used for non-detects.

4.3.1 Mycophenolic Acid (MPA) detected in 41/67 samples

The highest MPA concentrations were found in influent samples of WWTPs, with a maximum of 1.46×10^3 ± 369 ng/L found in the influent of the WWTP sampled during Campaign 1 (7.899×10^2 – 2.01×10^3ng/L in all analysed influent samples). In order to compare the MPA concentrations to other pharmaceuticals in wastewater in the Netherlands, the Watson Database was consulted [313]. Figure 4-4 shows the average detected concentrations of MPA and twelve other prescription drugs that have been detected in influent and effluent of Dutch WWTPs in 1990 – 2019. These are all pharmaceuticals with expected high loads to the aquatic environment based on the DDD and prescription data [288]. The average influent concentration of MPA found in this study is in the same order of magnitude as Sotalol (treats and prevents abnormal heart rhythms) and Hydrochlorothiazide (high blood pressure medication). The MPA concentration found in the effluent is comparable to pharmaceuticals such as Naproxen and Ibuprofen (both nonsteroidal anti-inflammatory drugs).



	C1L23 - C1L24
HFPO-TA	-
MPA (3)	< 0.01 - 0.325
TBP (3)	< 0.01
V. cholerae	-
MCR-1 E.coli	-
L. longbeachae	-

	C1L25
HFPO-TA (1)	< 1
MPA (3)	1.17×10^3 - 2.01×10^3
TBP (3)	5.45 - 5.52
V. cholerae	-
MCR-1 E.coli (1)	🟩
L. longbeachae	-

	C1L13 - C1L22
HFPO-TA (25)	11.7
MPA (12)	< 0.01 - 5.01
TBP (11)	< 0.01 - 0.358
V. cholerae	-
MCR-1 E.coli	-
L. longbeachae	-

	C1L28
HFPO-TA (1)	< 1
MPA (4)	< 0.01 - 1.26
TBP (4)	< 0.01
V. cholerae	-
MCR-1 E.coli	-
L. longbeachae	-

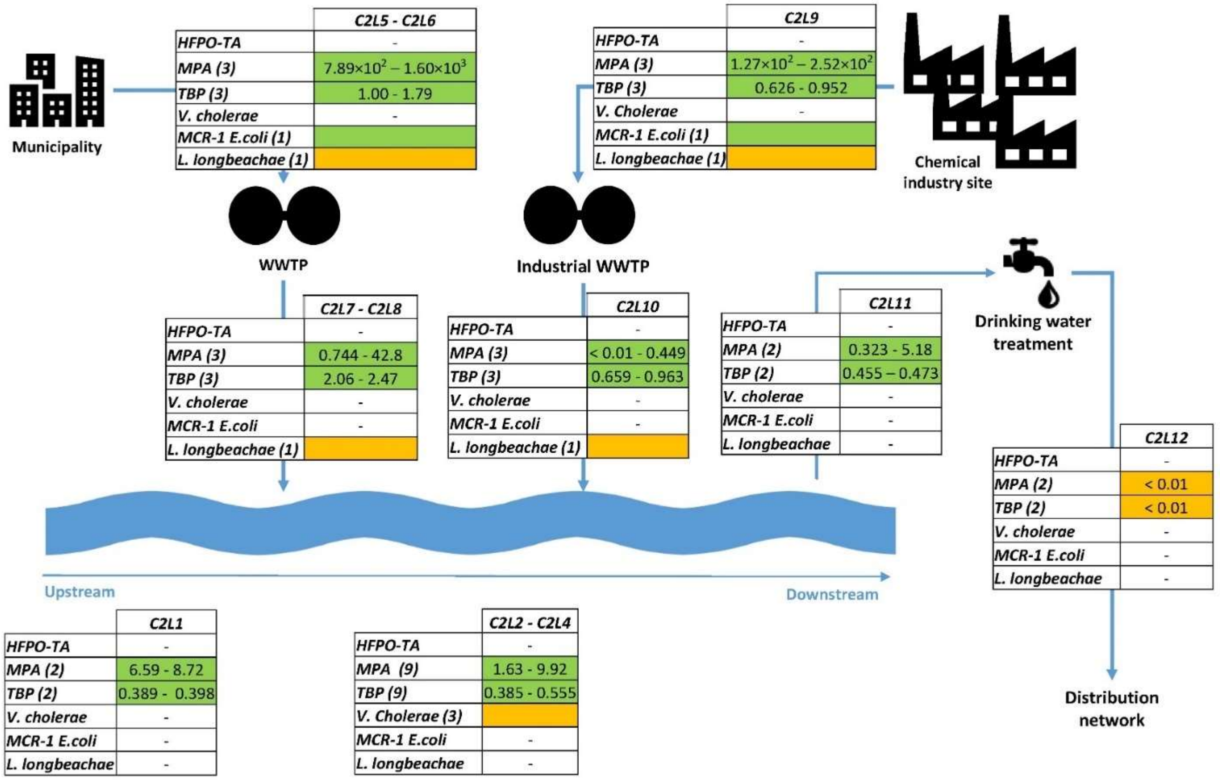
	C1L26
HFPO-TA (5)	< 10
MPA (2)	20.9 – 1.32×10^3
TBP (2)	5.26 - 6.39
V. cholerae	-
MCR-1 E.coli	-
L. longbeachae	-

	C1L27
HFPO-TA (1)	< 1
MPA (4)	< 0.01 - 0.131
TBP (4)	< 0.01
V. cholerae	-
MCR-1 E.coli	-
L. longbeachae	-

	C1L1 - C1L4
HFPO-TA (16)	< 10
MPA	-
TBP	-
V. cholerae	-
MCR-1 E.coli	-
L. longbeachae	-

	C1L5-C1L12
HFPO-TA (37)	< 10
MPA (12)	< 0.01 - 3.35
TBP (12)	< 0.01 – 1.79×10^{-2}
V. Cholerae (3)	🟧
MCR-1 E.coli	-
L. longbeachae	-

Figure 4-2 Results of HFPO-TA, MPA, TBP, V. cholerae, MCR-1 E. coli and Legionella longbeachae analyses in surface water, wastewater and drinking water samples collected during Campaign 1. Green = detected, orange = not detected, - = not analysed. For chemical contaminants the detected concentration is shown in ng/L (minimum - maximum). Detection limits are, depending on the sample 1 or 10 ng/L for HFPO-TA and 0.01 ng/L for both MPA and TBP. In case of V. cholerae, MCR-1 E. coli and L. longbeachae, the concentration in the samples could not be determined based on the performed analyses. For details on sampling locations see Figure 1. The number between brackets behind each contaminant is the number of samples the contaminant is analysed in at the specific location(s).



	C2L5 - C2L6
HFPO-TA	-
MPA (3)	$7.89\times10^{2} – 1.60\times10^{3}$
TBP (3)	1.00 - 1.79
V. cholerae	-
MCR-1 E.coli (1)	🟩
L. longbeachae (1)	🟧

	C2L9
HFPO-TA	-
MPA (3)	$1.27\times10^{2} – 2.52\times10^{2}$
TBP (3)	0.626 - 0.952
V. Cholerae	-
MCR-1 E.coli (1)	🟩
L. longbeachae (1)	🟧

	C2L7 - C2L8
HFPO-TA	-
MPA (3)	0.744 - 42.8
TBP (3)	2.06 - 2.47
V. cholerae	-
MCR-1 E.coli	-
L. longbeachae (1)	🟧

	C2L10
HFPO-TA	-
MPA (3)	< 0.01 - 0.449
TBP (3)	0.659 - 0.963
V. cholerae	-
MCR-1 E.coli	-
L. longbeachae (1)	🟧

	C2L11
HFPO-TA	-
MPA (2)	0.323 - 5.18
TBP (2)	0.455 – 0.473
V. cholerae	-
MCR-1 E.coli	-
L. longbeachae	-

	C2L12
HFPO-TA	-
MPA (2)	< 0.01
TBP (2)	< 0.01
V. cholerae	-
MCR-1 E.coli	-
L. longbeachae	-

	C2L1
HFPO-TA	-
MPA (2)	6.59 - 8.72
TBP (2)	0.389 - 0.398
V. cholerae	-
MCR-1 E.coli	-
L. longbeachae	-

	C2L2 - C2L4
HFPO-TA	-
MPA (9)	1.63 - 9.92
TBP (9)	0.385 - 0.555
V. Cholerae (3)	🟧
MCR-1 E.coli	-
L. longbeachae	-

Figure 4-3 Results of HFPO-TA, MPA, TBP, V. cholerae, MCR-1 E. coli and Legionella longbeachae analyses in surface water, wastewater and drinking water samples collected during Campaign 2. Green = detected, orange = not detected, - = not analysed. For chemical contaminants the detected concentration is shown in ng/L (minimum - maximum). Detection limits are, depending on the sample 1 or 10 ng/L for HFPO-TA and 0.01 ng/L for both MPA and TBP. In case of V. cholerae, MCR-1 E. coli and L. longbeachae, the concentration in the samples could not be determined based on the performed analyses. For details on sample locations see Figure 1. The number between brackets behind each contaminant is the number of samples the contaminant is analysed in at the specific location(s).

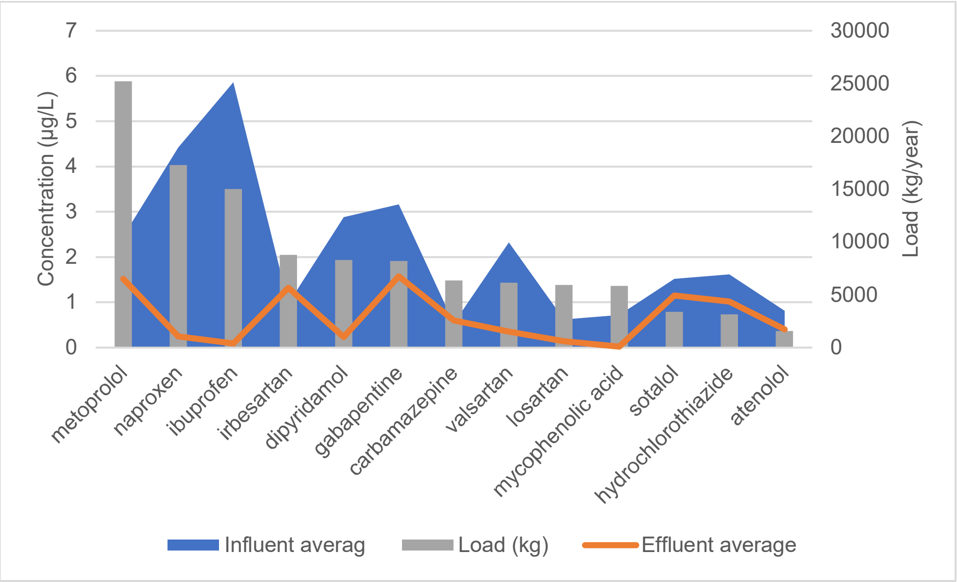


Figure 4-4 Average detected concentrations of pharmaceuticals in influent and effluent of Dutch WWTPs in 1990 – 2019. The presented concentrations for mycophenolic acid are based on this study, whereas the concentrations shown for the other 12 pharmaceuticals are based on the Dutch Watson Database. The loads are calculated using number of DDDs prescribed in the Netherlands in 2018 multiplied by the DDD [288].

4.3.2 Tetrabutylphosphonium compounds (Bu_4P^+, TBP) detected in 48/66 samples

TBP was detected in industrial and municipal wastewater and in surface water. The maximum concentration was detected in WWTP influent and was 5.47 ng/L. The average of all tested WWTP influent samples was 3.47 ng/L (standard deviation = 2.01 ng/L) . In surface water, the concentrations detected ranged from 0.10 to 0.56 ng/L (average = 0.28 ng/L, standard deviation = 0.18 ng/L).

4.3.3 Hexafluoropropylene Oxide Trimer Acid (HFPO-TA) detected in 1/86 samples

In total, 86 samples were analysed for the presence of HFPO-TA. In all but one sample, HFPO-TA was not detected above the limit of detection. HFPO-TA was detected at 11.7 ng/L in one sample taken from a collection point of runoff from an industrial site which is discharged directly into the River Beneden Merwede. The source of HFPO-TA in this water could not be determined.

4.3.4 Mobilised colistin resistance-1 positive Escherichia coli (MCR-1 E.coli) isolated from 3/3 samples

Table 4-4 Number of colonies suspected to be MCR-1 E. coli in different volumes tested of wastewater samples taken at locations C1L25, C2L9 and C2L6, - = no suspected colonies were isolated.Table 4-4 shows the number of colonies suspected to be MCR-1 *E. coli* on the CHROMID® Colistin R disks. Of these colonies, 35 colonies were isolated and transferred to TSA plates for confirmation (15 of C1L25, 10 of C2L9 and 10 of C2L6). The results of the multiplex PCR are shown in Appendix

C of https://doi.org/10.1016/j.scitotenv.2020.140546. MCR-1 *E. coli* colonies were confirmed in all three wastewater samples.

Table 4-4 Number of colonies suspected to be MCR-1 E. coli in different volumes tested of wastewater samples taken at locations C1L25, C2L9 and C2L6, - = no suspected colonies were isolated.

Type of sample tested	Location code		
	C1L25	*C2L9*	*C2L6*
1×10^{-2}	54	8	268
1×10^{-1}	-	36	> 200
1 mL dilution	-	-	1
10 mL dilution	5	3	21

4.3.5 Vibrio cholerae O1 E1 Tor with mutation in cholera toxin B subunit gene (ctxB) isolated from 0/6 samples

After 3 days, green and yellow colonies were found on all TCBS agar plates. APIWEB™ confirmed the presence of *Vibrio cholerae* in surface water sample locations C1L10 (all tested volumes) and C1L6 (only in 100 mL). Table 4-5 shows all confirmed *Vibrio* species found in the studied samples.

PCR confirmation tests showed that the detected *Vibrio cholerae* species were non-O1/O139. Therefore, the detected *V. cholerae* species did not belong to the novel strain identified by Bhattacharya et al. [286].

Table 4-5 Bacterial species isolated from surface water samples in the Netherlands. All species shown are Vibrio species, except for those indicated by *.

Volume tested (mL)	Location code					
	C1L5	*C1L6*	*C1L10*	*C2L2*	*C2L3*	*C2L4*
100	-	*cholerae*	*cholerae*	*plesiomonas **	-	*alginolyticus*
10	-	-	*cholerae*	-	-	-
1	*fluvialis*	-	*cholerae*	-	*aeromonas **	*alginolyticus*

4.3.6 Legionella longbeachae isolated from 0/4 samples

Table 4-6 shows the results of *Legionella*. After 10 days, colonies suspected to be *Legionella* were found on 2 out of 184 plates. The first presumptive colony was found on BCYE agar prepared with the sample from location C2L6. The second presumptive colony was cultured on MYC agar with a sample from location C2L10. The two colonies were then subcultured on BCYE agar and serogrouped using the Oxoid® Legionella Latex test. The Oxoid® Legionella Latex test was not able to unambiguously confirm the isolates as *Legionella* bacteria.

Table 4-6 Results of Legionella analysis in four wastewater samples, both untreated (C2L6 and C2L9) and treated (C2L8 and C2L10)

Location code	**Type of sample**	**Nr. of colonies tested**	**Nr. of colonies suspected**			**Nr. of colonies confirmed**
			day 3	*day 7*	*day 10*	
C2L6	Influent municipal WWTP	16	0	0	1	0
C2L8	Effluent municipal WWTP	13	0	0	0	0
C2L9	Influent industrial WWTP	9	0	0	0	0
C2L10	Effluent industrial WWTP	9	0	0	1	0

4.4 Discussion

This study aimed to validate the practical effectiveness of screening scientific literature for early warning purposes. Four out of six analysed contaminants were detected in Dutch surface and wastewater samples, namely mycophenolic acid, tetrabutyl phosphonium compounds, HFPO-TA and colistin resistant *E. coli*, which showed that directing sampling campaigns based on literature mining is effective in finding unknown aquatic contaminants. The second objective was to detect new aquatic contaminants of concern to public health in the Netherlands.

The highest MPA level in drinking water found in this study was 1.26 ng/L. When a daily intake of 2L of water per person is assumed, this results in a maximum daily intake of 2.52 ng/day. This is well below the acceptable daily exposure of 75 µg per day [314].

Straub et al. [314] provide an overview of measured environmental concentrations of MPA in surface waters in Europe and found a median measured concentration of 2 ng/L and a maximum measured concentration of 656 ng/L. The overall mean of all the studies was 22 ng/L. These data are restricted to studies conducted in Switzerland, Poland and Spain. Based on available toxicological data, a no-observed-effect concentration (NOEC) was derived of 132 ng/L (Straub et al. [314]. This study detected MPA levels in surface water between 0.24 and 8.72 ng/L, which were well below the NOEC. Therefore, based on this study, no risk to drinking water safety or the aquatic environment from MPA exposure in the Netherlands is expected.

The highest concentration of TBP was 5.47 ng/L and was detected in treated wastewater from the WWTP sampled in Campaign 1. This is comparable to the lowest concentrations detected in surface water by Brand et al. [68]. The maximum concentration of TBP detected in surface water in this study was 0.49 ng/L. Brand et al. [68] found concentrations of up to 4700 ng/L. Based on these results, TBP is not expected to pose a risk to the production of safe drinking water in the Netherlands.

HFPO-TA was detected at 11.7 ng/L in one industrial wastewater sample, but was not detected in any of the surface water samples. Pan et al. [284] reported trace levels of HFPO-TA upstream of the perfluorochemical company. However, these were based on a very low limit of detection (0.1 ng/L) and do not indicate any use of HFPO-TA by the fluorochemical company in the Netherlands. Also, no HFPO-TA was found in municipal wastewater. As HFPO-TA was not detected in any of the surface water samples (C1L1 – C1L12), or drinking water sample (C1L28) above 1 ng/L, no other significant sources for HFPO-TA to enter the aquatic environment are expected. Based on these findings, HFPO-TA is not expected to pose a risk to the production of drinking water in the Netherlands.

Due to unforeseen circumstances, HFPO-TA was only analysed in one sample at locations C1L25 (= influent WWTP from municipality), C1L27 (= intake water for drinking water production) and C1L28 (= drinking water). However, the fact that HFPO-TA was not detected > 10 ng/L in 37 surface water samples taken from eight different locations around the intake point for drinking water production, supports the result of HFPO-TA not being detected > 1 ng/L in riverbank filtrated water and finished drinking water (C1L27 and C1L28). Also, since HFPO-TA was not detected > 10 ng/L in five different WWTP effluent samples (C1L26), it could be concluded that the WWTP is not discharging HFPO-TA to the Beneden Merwede River. Colistin resistant bacteria were detected in all three untreated wastewater samples. To our knowledge this is the first study to report the presence of MCR-1 *E. coli* in Dutch wastewater. Jin et al. [285] detected MCR-1 *E. coli* specifically in hospital wastewater. Here, MCR-1 *E. coli* was also detected in wastewater not influenced by hospital wastewater as well as industrial wastewater.

The presence of MCR-1 *E. coli* was confirmed by multiplex PCR. The positive control used in the PCR did not show a band at MCR-1 *E. coli*. This is probably due to the fact that the concentration used was too low. Colonies cultured from all three tested samples showed very clear bands at the MCR-1 location. Therefore, the presence of MCR-1 *E.coli* in these samples was considered conclusively shown despite the failing positive control.

The number of wastewater samples analysed for the presence of MCR-1 *E. coli* was limited (N = 3). Also, only untreated wastewater samples were tested for the presence of MCR-1 *E. coli* as no information was available on the level of MCR-1 *E. coli* present in wastewater in the Netherlands. In order to determine the magnitude of the prevalence of MCR-1 in the Dutch population, further quantification of MCR-1 *E. coli* samples, surface water and drinking water is needed.

The novel variant of *V. cholerae* O1 E1 Tor first reported by Bhattacharya et al. [286] was not detected in the analysed samples. *V. cholerae non-O1/O139* was isolated from samples taken at locations C1L6 and C1L10. The salinity at these locations in July 2019 was estimated to be between 0.006 - 0.009% [315]. *Vibrio* species are rarely detected in freshwater. Schets et al. [302] detected *V. cholerae non-O1/O139* at a location in the North-Western part of the Netherlands at the Lake Ijsselmeer, near Enkhuizen, with similar salinity ranges (0.007 to 0.015%).

L. longbeachae was not isolated from the collected industrial and municipal wastewater samples (both treated and untreated). However, for practical reasons, only a limited number of wastewater samples was analysed. Caicedo et al. [316] reviewed the available literature on *Legionella* species in industrial and municipal wastewater and pointed out several disadvantages of the, although broadly applied, culture method. Reported disadvantages that might have influenced the results in this study are: (1) sample pre-treatment which can temper the cultivability of

Legionella and (2) the optimisation of the method for *L. pneumophila* SG1 which might make it less suitable for *L. longbeachae*. A suggestion for future research would be to develop the optimal culturing conditions (nutrient composition and amount and culture temperature) for *Legionella longbeachae* in wastewater. Then the analysis of more Dutch industrial and municipal wastewater samples for presence of *Legionella longbeachae* would be valuable.

4.5 Recommendations and conclusions

In Hartmann et al. [156], we suggested health and environmental agencies, water authorities or drinking water companies to run the literature mining methodology twice a year in order to keep the number of records manageable. This would enable drinking water companies and water authorities to use the resulting list of contaminants[18] when designing risk-based monitoring campaigns [169]. A few suggestions can be made for effectively directing a sampling campaign based on early signals of new aquatic contaminants in scientific literature. First, several information sources are available to find out which contaminants reported in the scientific literature could be of potential concern in a specific river basin or drinking water production chain. These information sources include: REACH registrations, patents and discharge permits. Also, the paper reporting the contaminant for the first time might already give an indication of the circumstances in which the contaminant might be of concern (e.g. Thornley et al. [287]).

As information on potential sources of chemicals, in particular, is often scattered, the involvement of key stakeholders such as drinking water companies, water authorities and industry is crucial. Drinking water companies and water authorities can be contacted to find out whether (non-target) monitoring data is available or whether data needs to be collected. Also, the early inclusion of industry as a potential source of contamination would be useful to investigate whether they are aware of (the level of) potential emission of the contaminant. Including as many stakeholders as possible increases the impact of the signalling process as more stakeholders will have knowledge about the contaminant.

In this study, by screening scientific literature, six example contaminants were selected from screening the scientific literature as potential contaminants of concern to drinking water in the Netherlands. The chemical contaminants, mycophenolic acid, tetrabutylphosphonium compounds and HFPO-TA, were detected in low concentrations in wastewater and surface water and were thus not expected to pose a risk to Dutch drinking water. Colistin resistant *Escherichia coli* was detected for the first time in Dutch wastewater not influenced by hospital wastewater indicating the circulation of bacteria resistant to this last-resort antibiotic in the general Dutch population. Four out of six contaminants were thus detected in surface or wastewater samples, which showed that screening the scientific literature to direct sampling campaigns for both microbial and chemical contaminants is effective for early warning purposes.

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[18] See Appendix A of https://doi.org/10.1016/j.scitotenv.2020.140546 for the detailed list of articles.

5 MODEL DEVELOPMENT FOR EVIDENCE-BASED PRIORITISATION OF POLICY ACTION ON EMERGING CHEMICAL AND MICROBIAL DRINKING WATER RISKS

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[19] 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.

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[19] This chapter is based on Hartmann J, Chacon-Hurtado JC, Verbruggen E, Schijven J, Rorije E, Wuijts S, de Roda Husman AM, van der Hoek JP, Scholten L. Model development for evidence-based prioritisation of policy action on emerging chemical and microbial drinking water risks. Journal of Environmental Management. 2021;295:112902.

5.1 Introduction

5.1.1 *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) [159]. 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 [22, 161, 317, 318].

While the global burden of disease caused by inadequate drinking water is declining, new challenges from previously unknown aquatic contaminants are increasing as a result of social, technological, demographic and climatological developments [34, 138, 184, 319]. Examples of such emerging aquatic contaminants include ionic liquids [128], per- and polyfluorinated alkyl substances (PFASs) [58] and antimicrobial resistant genes [274]. Hence, understanding and preventing the negative impact of contaminants in drinking water (resources) continues to be a global challenge.

5.1.2 *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 [18, 320]. This process is known as risk-informed [321] or evidence-based [322] decision making and is characterised by experts providing decision makers with an evaluation based on available facts and values [323]. Here, *values* are defined as "characteristics in virtue of which something is considered valuable" [324]. 'Epistemic values' are generally agreed upon by experts in the same field [323-325]. 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) [159]) or the acceptable infection risk caused by pathogens in drinking water (e.g. below 1 per 10,000 persons per year in the Netherlands [326]). 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 [321].

As emerging contaminants were identified only recently, evidence about their hazard and exposure potential is often scarce and experts frequently disagree on its evaluation [322, 327]. Disagreements might be caused by inconclusive evidence or differences in non-epistemic values and expertise [322, 328-331]. As decision making on the risks of contaminants in drinking water should be justifiable to the public, transparent risk-informed decision making is needed [332]. 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 [324, 333].

5.1.3 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 [334];
2. enable the identification of actions that are effective for several types of contaminants [50] and
3. prevent actions where elimination of risk posed by one contaminant is traded off against higher risk posed by another [41].

Integrated approaches are rarely published [52-54] because of differences in risk evaluations [159] and data scarcity [335, 336]. 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 [159]. So far, initiatives to achieve integrated risk evaluations for microbial and chemical contaminants in drinking water used the Disability Adjusted Life Years (DALY) approach [336, 337], 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.

5.1.4 The potential of value-focused thinking to structure contaminant assessment

The concept of value-focused thinking [338] has proven to be effective in structuring complex interdisciplinary decision problems, such as river quality assessments [339], water supply [340] or endangered species recovery [328] planning, and prioritisation of emerging infectious diseases [341]. 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) [332, 338] (see also Figure 5-1).

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 [340]. MCA methods support the decision process with mathematical analysis [340, 342, 343], thereby providing a basis for discussion and enabling the quantification of uncertainties within the decision problem [344]. 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 [339, 341, 345-347] and are thus used in this study for the integration of microbial and chemical risk evaluation.

5.1.5 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.

5.2 Definitions and concepts

5.2.1 Terminology in value-focused thinking

Figure 5-1 shows the outline of the assessment hierarchy developed in this study. Table 5-1 provides an overview of the terminology used for different components of the hierarchy.

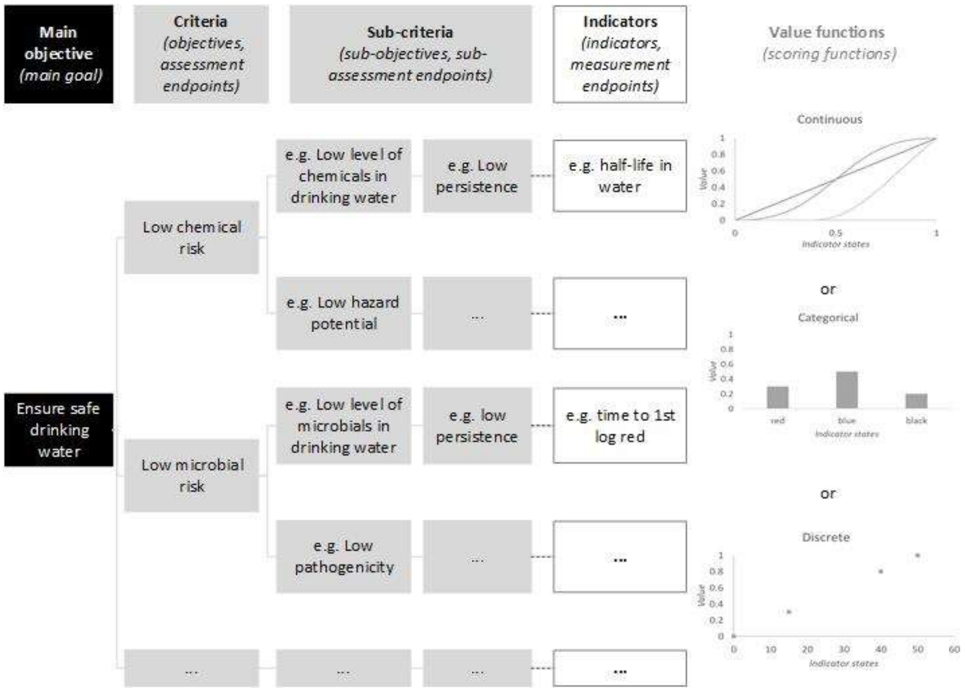

Figure 5-1 Example of an assessment hierarchy for the overall objective of ensuring safe drinking water. Each column represents one of the different types of components introduced in Table 5-1.

5.2.2 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"* [342]. 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 5-1). 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.

Table 5-1 Terminology used in this study regarding different components of the objectives hierarchy in Figure 5-1 (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 *objectives* is often used instead [342, 348, 349].
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 [350] or time to first log reduction [351] 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 [348].	Linear, discrete or categorical (see Figure 5-1).	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 Figure 5-1.
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 [345].	Rank alternatives from highest to lowest expected risk to drinking water quality based on the defined criteria and indicators.	

5.3 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 [342, 352]. Actors were risk assessors, drinking water experts and members of responsible authorities. Figure 5-2 provides an overview of the applied methodology.

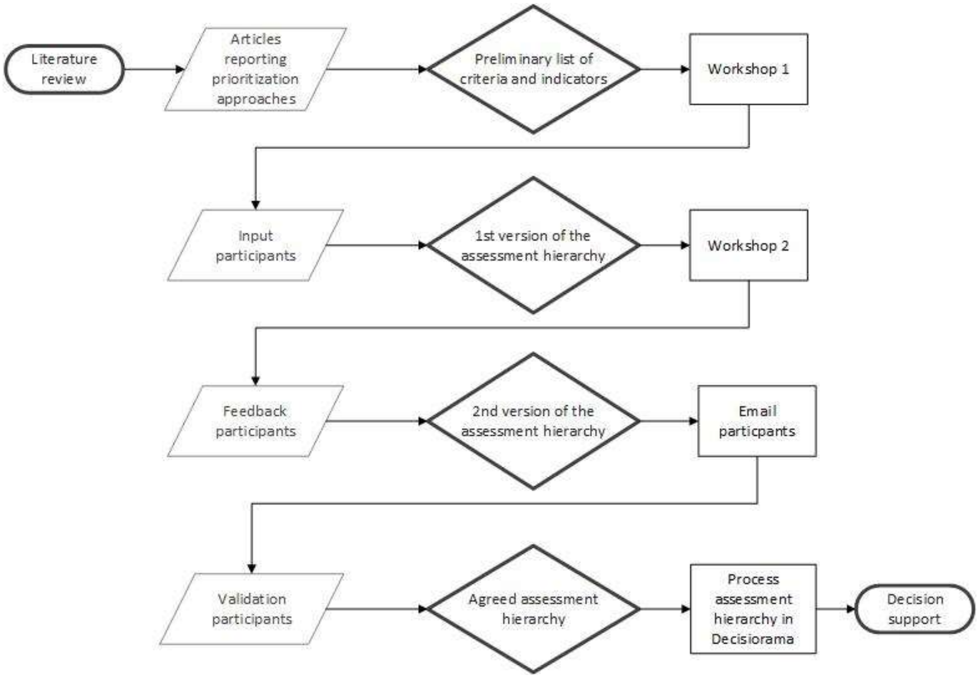

Figure 5-2 Overview of the development process of the decision support tool which was developed in Python using the Decisi-o-rama library (see also Section 5.3.3 and Chacon-Hurtado and Scholten [353]).

5.3.1 Preliminary list of criteria and indicators from the literature review

A meta-synthesis[20] was performed to compose a preliminary list of criteria and indicators. A meta-synthesis brings together qualitative data from different studies [354]. 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 retrieved[21] from Scopus® on the 5th of June 2019. Criteria and

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[20] A meta-synthesis is also known as a meta-ethnography or a meta-synthetic literature review

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

indicators used by these studies were synthesised into criteria and indicators for the integrated prioritisation of emerging chemical and microbial drinking water risks.

5.3.2 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 Table A-2 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.

5.3.2.1 Details first workshop: review and supplement preliminary list of criteria and indicators

Stakeholders were asked to individually brainstorm about criteria that should be considered in the assessment of the risk a newly identified chemical or pathogen might pose to drinking water. For this first part of the workshop, the results from the literature review were not shared to prevent stakeholders from being biased into a certain line of thinking [355]. After the individual consultation, self-selected criteria were discussed in groups of six participants and added to one of three criteria categories: (1) hazard related criteria, (2) exposure related criteria, and (3) other (e.g. the economic impact of taking mitigation actions).

Then, the criteria suggested by the stakeholders were compared to the preliminary list of criteria from the literature. To make sure all stakeholders were heard, the consultation session was concluded by asking the experts to give written feedback on the preliminary list of criteria and indicators extracted from the literature. All suggestions were documented and reviewed by the authors, and if feasible, added to the resulting 1st version of the assessment hierarchy.

5.3.2.2 Details second workshop: review 1st version of assessment hierarchy and investigate usefulness of the decision aid

The aim 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. To this end, after plenary presentations of SW and JH, participants were asked to rank four pathogens and four chemicals based on the potential risk they might pose to drinking water production in the Netherlands, on a scale from 1 (highest risk) to 8 (lowest risk). Tied ranks were allowed. The included contaminants were: prazosine, perfluorooctanoic acid, 3-(4-tert-Butylphenyl)propanal, minocycline, mcr-1-positive *E. coli*, *Legionella longbeachae*, *Norovirus GII. 17* and *Cryptosporidium parvum*. These contaminants were chosen because they were identified as potential aquatic contaminants of concern by Hartmann et al. [156]. The familiarity of the participants with the contaminants varied. Also, the selection covers different health and environmentally relevant characteristics. The participants received hand-outs with maximum and minimum indicator levels for each contaminant, see tables below.

Individual rankings were discussed in small groups (5-7 participants), with one facilitator to guide the process and document the arguments. Each group attempted to arrive at an agreed ranking. Participants returned to the plenary room and the facilitators presented the agreed group rankings (if the group managed to agree) and discussion points that came up. Then, JH presented the ranking result of the model based on the 1st version of the assessment hierarchy. All participants were invited to comment on the usefulness of the decision aid and how to improve it. Suggestions given and related actions were documented and included in the final version of the model. Suggestions were divided into three categories, namely suggestions related to (1) missing or incorrect criteria, (2) incorrect indicator levels or (3) other remarks related to the assessment hierarchy. 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.

5.3.3 Decision support tool to compute the risk scores

Using Decisi-o-rama [353] 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 [353].

5.4 Results

5.4.1 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 5-2 and 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.

Table 5-2 Preliminary criteria and indicators for the assessment of the hazard and exposure potential of emerging chemical or microbial contaminants. This list was used during Workshop 1.

Preliminary criteria	**Preliminary criterion number**	**Preliminary indicators**	**Preliminary Indicator levels**	**Criterion and indicator based on**
Acute potency	1	How much of the contaminant is needed to cause the most severe health effect after acute (< 24 hours) exposure? (Based on e.g. LD50 or ID50 in mice/rats)	• High potency • Moderate potency • Low potency • Unknown	[52, 54, 350, 356-360]
Chronic potency	2	How much of the contaminant does it take to cause a health problem after chronic (> 24 hours) exposure? (Based on e.g. LD50 or ID50 in mice/rats)	• High potency • Moderate potency • Low potency • Unknown	[52, 54, 350, 356-360]
Severity of health effects after short-term exposure	3	What is the most severe health effect after short-term exposure to contaminated drinking water (<24 hours)?	• Immunotoxic effects • Neurotoxic effects • Liver and kidney effects (observed in single-dose studies or early in repeated-dose studies) • Endocrine effects • Developmental effects • Intestinal inflammation (with symptoms such as diarrhoea and fever) • Lung inflammation • Death • Antibiotics less effective • Unknown	[54, 350, 360-362]

Severity of health effects after long-term exposure	4	What is the most severe health effect after chronic exposure (> 24 hours)?	• Carcinogenicity • Mutagenicity • Impairment of fertility • Developmental effects • Immunotoxic effects • Endocrine effects • Intestinal inflammation (with symptoms, such as diarrhoea and fever) • Lung inflammation • Death • 5CMR (based on structural similarity) • Antibiotics less effective • Unknown	[54, 350, 360-362]
Host sensitivity	5	Does the contaminant pose an increased risk to sensitive populations?	Yes, only in immunocompromised individuals, (young) children or elderly	[360]
Source presence in the Netherlands – point source	6	Is the contaminant in the river due to sources that are treated by a wastewater treatment plant?	• Yes, it is a common source in the Netherlands • Yes, but the source is not that common in the Netherlands • No, the source is currently not present in the Netherlands • Unknown	[356, 363]
Removal in Wastewater Treatment Plant – point source	7	What is the expected removal rate or percentage in the wastewater treatment plant? This can be industrial or from the municipal wastewater treatment plant or a combination of both.	• High removal rate (e.g. for chemicals >90% and for microorganisms >99.99%) • Medium removal rate • Low removal rate • Unknown	NA
Source presence in the Netherlands – diffuse sources	8	Is the contaminant in the river due to sources that are not treated by a wastewater treatment plant?	• Yes, it is a common source in the Netherlands • Yes, but the source is not that common in the Netherlands	[356, 363]

			• No, the source is currently not present in the Netherlands • Unknown	
Persistence/survival in surface water	9	What is the expected persistence/survival of the contaminant in surface water?	• High persistence/survival • Medium persistence/survival • Low persistence/survival • Unknown	[207, 350, 356]
Potential to occur in drinking water after treatment	10	<u>Chemicals:</u> combination of mobility and volatility <u>Microorganisms:</u> ability to survive/grow in drinking water in distribution system	• Yes, very likely to occur in drinking water after treatment (very mobile, low volatility, pathogens that survive drinking water treatment and grow in drinking water) • Yes, likely to occur in drinking water after treatment (mobile, volatile, pathogens that survive drinking water treatment, but do not grow in drinking water) • No, not likely to occur in drinking water after treatment • Unknown	[69, 357, 364]

The literature search yielded 167 articles, 22 of which reported approaches to prioritise chemical and/or microbial aquatic contaminants for a safe drinking water supply [41, 52-54, 69, 207, 350, 356, 358-370]. One grey literature study by the international organisation of companies using the River Meuse for the production of drinking water (RIWA Meuse) [357] was added to the results retrieved from Scopus, because the River Meuse is an important drinking water resource in the Netherlands and its authors participated in this study.

Only one study ranked microbial aquatic contaminants [360], three studies ranked chemical and microbial aquatic contaminants [52-54] and the remaining publications ranked only chemical aquatic contaminants.

5.4.1.1 Construction of preliminary list of criteria and indicators

The sub-criteria and indicators used to assess the hazard potential of a contaminant were very different for chemical (e.g. No Observed Adverse Effect Levels (NOAELs) [358, 359]) and microbial (e.g. the severity of the disease [360]) contaminants.

Therefore, two sub-criteria of Rosen and Roberson [54] were used to synthesize sub-criteria suitable for the assessment of the hazard potential of both chemical and microbial contaminants (see Table 5-2). These sub-criteria were *severity* (i.e. how bad is the health effect) and *potency* (i.e. how much of the contaminant is needed to induce the health effect). Also, a criterion was added to assess whether the contaminant poses an increased risk to sensitive people, following Hoffman et al. [360].

To assess the exposure potential of a contaminant via drinking water, half of the reviewed studies used the frequency of detection of the contaminant in drinking water [41, 52, 53, 69, 360-362, 365-367, 369]. For emerging contaminants, this is not a suitable sub-criterion as monitoring data will rarely be available. Therefore, the preliminary list of sub-criteria and indicators to assess the exposure potential of a contaminant was based on a combination of the (estimated) emission to the aquatic environment and the expected behaviour in drinking water treatment plants following [69, 350, 356, 357, 359, 364, 370] (see Table 5-2). Also, a sub-criterion for the removal rate in wastewater treatment plants was added to estimate potential emission to the aquatic environment as accurate as possible.

5.4.1.2 Participant suggestions for revision of preliminary list of criteria and indicators

Table 5-3 provides an overview of the changes and additions made to the preliminary criteria and indicators 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. Actor's suggestions and the preliminary list of criteria and indicators in Table 5-2 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 5-3 Revision of the preliminary criteria and indicators shown in Table 5-2 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 [162].	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).	Hazard	Plenary discussion
Criteria/indicators were not revised, can be used as information sources to score alternatives.	Add criterion on authorisation dossier available at ECHA, EFSA, EMA.	Exposure	Individual suggestion (1/25)
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.	Hazard	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 chronical 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 5-4 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 5-4 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 (Figure 5-3). The 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.

Table 5-4 Participant's suggestions provided during Workshop 2 to improve the first version of the assessment hierarchy (Figure 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.	The distinction between health effects after acute or chronic	Missing or incorrect criteria

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.	exposure to the contaminant should be included in the model.	
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 in the drinking water treatment plant.	Missing or incorrect criteria
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.	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

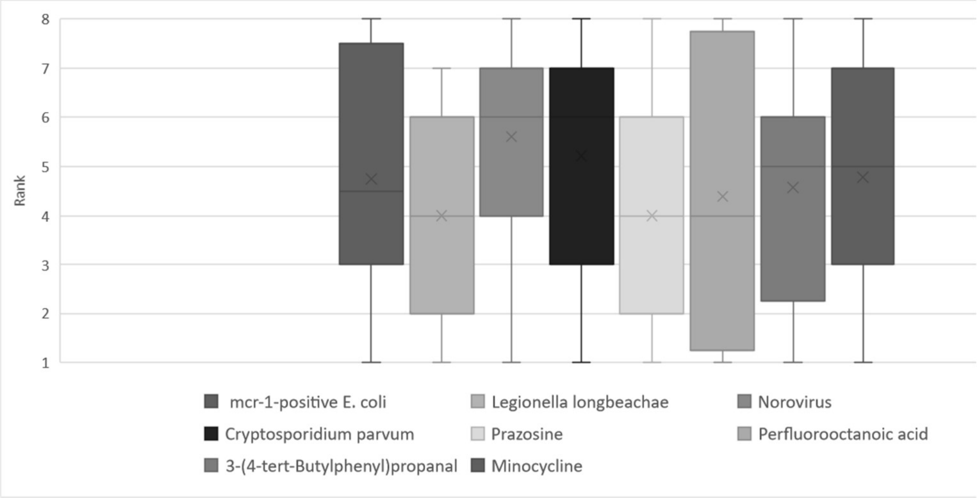

Figure 5-3 Results of the individual exercise performed by participants (N=27) of Workshop 2. Participants were asked to rank four pathogens and four chemicals based on the potential risk they might pose to drinking water production in the Netherlands (1 = low risk, 8 = high risk). The mean rank is indicated with a cross.

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 (Figure 5-4).

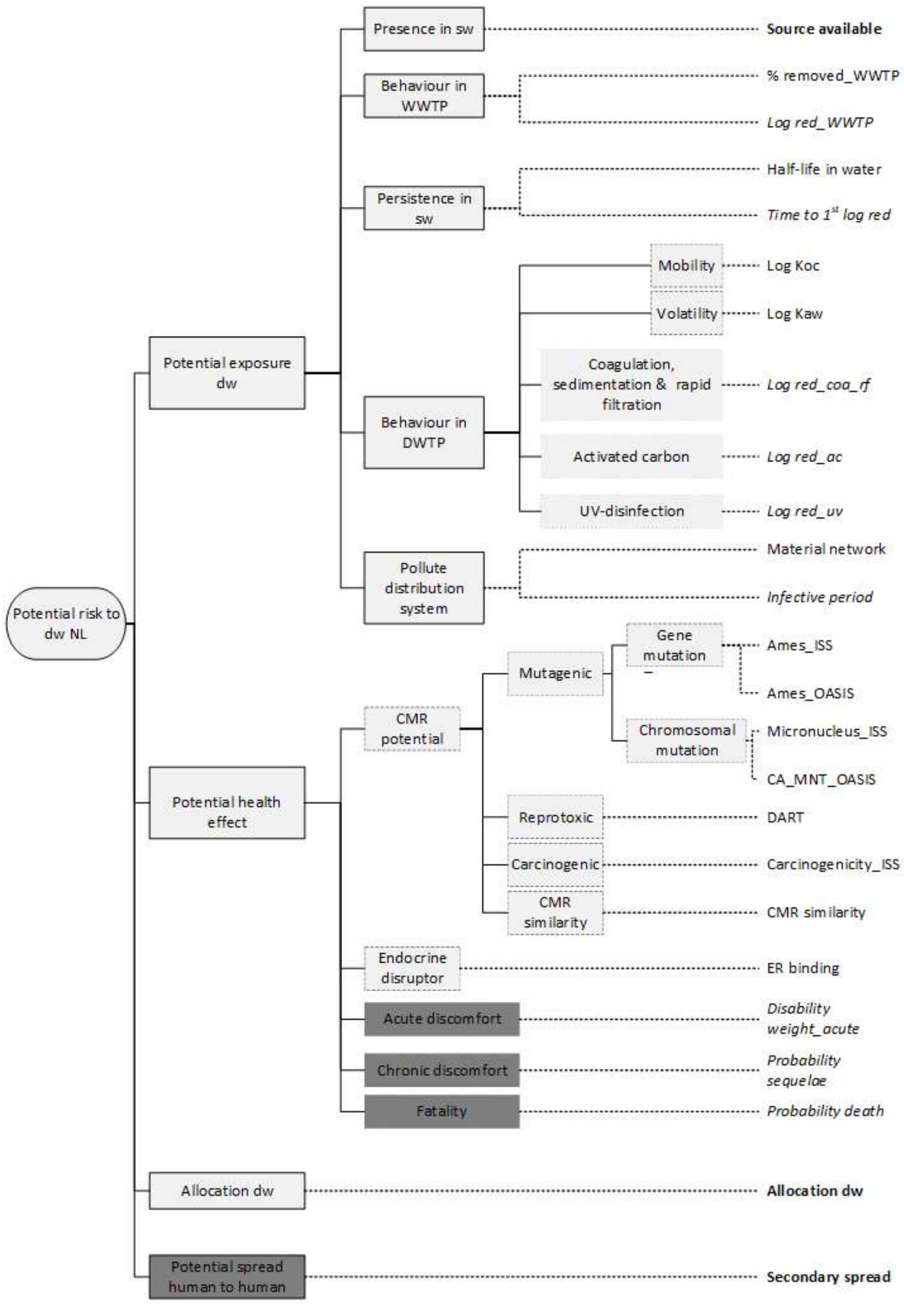

Figure 5-4 Agreed assessment hierarchy to evaluate the potential drinking water risk posed by emerging chemical or microbial aquatic contaminants. Boxes reflect four levels of criteria with associated indicators connected via the dotted lines. The indicators in italics were suggested for microbial contaminants, 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 Table 5-5. The criteria that 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.

5.4.2 Final assessment hierarchy

Figure 5-4 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 and in the Appendices, 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.

5.4.2.1 Information sources used to define indicator levels

The basis for indicator level definition is shown for each indicator Table 5-5. 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 [169], 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 [375]. For drinking water treatment steps - coagulation, sedimentation, rapid sand filtration, disinfection with UV light (40 mJ/cm^2) 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 5-6). This information was used to define indicator levels for log red_coa_rf, log red_ac and log red_uv.

Table 5-5 Overview of indicators used in the final assessment hierarchy shown in Figure 5-4 and information sources used to define indicator levels.

Indicator	Indicator explanation	Indicator range			Basis for indicator level definition
		min	*max*	*Additional information on indicator range*	
Source available	Likelihood of emission to the aquatic environment in the Netherlands.	0	3	*For chemicals:* 0 = not likely 1 = Somewhat likely (registered under REACH in Austria, Belgium, Liechtenstein, France, Germany or Luxembourg) 2 = Very likely (registered under REACH in the Netherlands, pesticides and medicines used in the Netherlands) 3 = Definitely (detected in Dutch drinking water resource or drinking water) *For micro-organisms:* 0 = Not likely (source not present in Netherlands) 1 = Somewhat likely 2 = Very likely	*For chemicals:* - Publicly accessible data of the mandatory registration dossiers within European legislation No 1907/2006 on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) were suggested. - Plant protection chemicals: https://toelatingen.ctgb.nl/en/authorisations - Human medicines: • https://www.gipdatabank.nl/ *For microbials:* Expert judgement

				3 = Definitely (detected in Dutch drinking water resource or drinking water)	
% removed_WWTP	Indicates the fraction of a chemical removed by conventional wastewater treatment plant.	0	100%	Continuous	STPWIN^{TM} of the EPI (Estimation Programs Interface) Suite™ 4.1
Log red_WWTP	Indicates the fraction of a microbial reduced by conventional wastewater treatment plant.	0	19	Continuous	Based on information for similar contaminants in Oakley and Mihelcic [371]
half-life in water	Indicates persistence of a chemical in water.	0	200,000	Continuous	BIOWIN^{TM} of the EPI (Estimation Programs Interface) Suite™ 4.1
Time to 1st log red	Indicates persistence of a microbial in water, which is the amount of days until 90% of the initial concentration of the microbial is reduced in surface water under different light conditions and temperature between 5 and 25 degrees.	0	100	Continuous	Based on information for similar contaminants in Murphy [372]
Log K_{oc}	Indicates the removal potential of chemicals by drinking water treatment plant based on their affinity to water.	0	45	Continuous	KOCWIN^{TM} of the EPI (Estimation Programs Interface) Suite™ 4.1 (using both the Molecular Connectivity Index (MCI) and a log Kow-based method)
Log K_{aw}	Indicates the removal potential of chemicals	-60	60	Continuous	KOWWIN^{TM} and KOAWIN^{TM} of the EPI (Estimation Programs Interface) Suite™ 4.1 (Kow/Koa)

	by drinking water treatment plant based on their affinity to air.				
Log red_coa_rf	Log reduction by coagulation and rapid filtration.	0	19	Continuous	See Table 5-6, can be replaced by similar information for other countries
Log red_ac	Log reduction by activated carbon.	0	19	Continuous	See Table 5-6, can be replaced by similar information for other countries
Log red_uv	Log reduction by UV disinfection	0	19	Continuous	See Table 5-6, can be replaced by similar information for other countries
Material network	Indicator for the potential leakage of a chemical into drinking water in distribution network.	0	1	0 = No 1 = Yes	If chemical is included in the Positive list for Organic Materials in Contact with Drinking Water, then Material network = 1 [373]
Infective period	Indicates those contaminants that have the potential to pollute drinking water in the distribution network and in buildings. Detection period in days in for infective stage in water supply at 20 °C.	0	365 days (or may multiply)	Continuous	Table 7.1 of WHO [159]
Ames_ISS	In vitro mutagenicity (Ames test) alerts by ISS.	0	1	0 = No alert found 1 = Alert found	QSAR Toolbox 4.3.1
Ames_OASIS	In vitro mutagenicity (Ames test) alerts by Oasis.	0	1	0 = No alert found 1 = Alert found	QSAR Toolbox 4.3.1
Micronucleus _ISS	In vivo mutagenicity (Micronucleus) alerts by ISS.	0	1	0 = No alert found 1 = Alert found	QSAR Toolbox 4.3.1
CA_MNT_OASIS	The scope of this profiler is to investigate the presence of alerts	0	1	0 = No alert found 1 = Alert found	QSAR Toolbox 4.3.1

	within the target molecules responsible for interaction with DNA related to Chromosomal aberration and Micronucleus tests.				
DART	Developmental And Reproductive Toxicity (DART) alert.	0	1	0 = Not known precedent reproductive and developmental toxic potential 1 = Known precedent reproductive and developmental toxic potential	QSAR Toolbox 4.3.1
Carcinogenicity_ISS*	Carcinogenicity (genotox and nongenotox) alerts by ISS.	0	1	0 = No alert found 1 = Alert found nongenotoxic 2 = Alert found genotoxic 3 = Alert found both genotoxic and nongenotoxic	QSAR Toolbox 4.3.1
CMR similarity	Indication of the structural similarity of the contaminant to a contaminant that has been classified as carcinogenic, mutagenic and reprotoxic.	0	1	0 = not similar 1 = indication for structural similarity	Wassenaar et al. [374] https://rvszoeksysteem.rivm.nl/ZzsSimilarityTool
ER binding	Estrogen receptor (ER) binding is a molecular initiating event much like protein binding. Here	1	5	5. Very strong binders: Chemicals with MW between 200 and 500 Da and two rings with	QSAR Toolbox 4.3.1

	we indicate whether the molecule has a potential to be an estrogen receptor binder.			a hydroxyl group connected to each of them. 4. Strong binders: Chemicals with at least one 5-or 6-members carbon ring with an unhindered hydroxyl or amino group and MW between 200 and 500 Da; 3. Moderate binders: Chemicals with at least one 5- or 6-members carbon ring with an unhindered hydroxyl or amino group and MW between 170 and 200 Da; 2. Weak binders: Chemicals with at least one 5-or 6-members carbon ring with an unhindered hydroxyl or amino group and MW less than 170 Da; 1. Non binder	
Disability weight_acute	Represents the magnitude of health loss associated with exposure to the contaminant in	0	1		Literature on similar pathogens

	drinking water. Most and least severe health outcomes are included.				
Probability sequelae	Probability of infection resulting in sequelae.	0	1	Continuous	Literature on similar pathogens
Probability death	Probability of infection resulting in death.	0	1	Continuous	Literature on similar pathogens
Allocation_dw	Percentage allocation to drinking water of total exposure.	0	100%	Continuous	Expert knowledge
Secondary spread	The impact of a contaminant on public health is partly determined on the potential of the contaminant to cause disease via secondary spread.	0	1	0 = No 1 = Yes, one could take protective actions to protect oneself from exposure.	Literature on similar pathogens

Table 5-6 Overview of parameters of the beta distribution that describes the fraction of indicator organisms that are able to pass a drinking water treatment step [375]. 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. [375]*	*Hijnen et al. [376]*	*Hijnen et al. [376]*	*Hijnen et al. [376]*
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. [377]*	*Hijnen et al. [377]*	*Hijnen et al. [377]*

5.4.3 Decision support: risk scores for eight emerging contaminants

The assessment hierarchy introduced in Section 4.5 was operationalised using Decisi-o-rama [353, 378]. Table 5-7 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):

$$V(x) = \mathrm{V}(x_1, \ldots, x_n) = \sum_{i=1}^{n} w_i v_i(x_i)\,, \text{where } \sum_{i=1}^{n} w_i = 1 \qquad \textit{Equation 1}$$

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 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. 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*. 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 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.

Table 5-7 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	y = 0.0526x	Assumed linear value function
half-life in water	$\frac{1}{1 + 10\wedge((\mathrm{LOG}(60) - \mathrm{LOG}(x))/(\mathrm{LOG}(60) - \mathrm{LOG}(40)) * \mathrm{LOG}(2))}$	Rorije et al. [379], 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 K_{oc}	$\frac{1}{1+10^\wedge((2-x)/(2-3)*LOG(2))}$	Rorije et al. [379], but here centred around Log K_{oc} = 2 for very mobile contaminants and Log K_{oc} = 3 for mobile contaminants.
Log Kaw	$\frac{1}{(1+10^\wedge(\frac{-2.7-x}{-2.7-(-1.4)}*LOG(2)))}$	Rorije et al. [379], but here centred around Log Kaw = -2.7 for very poorly volatile compounds and Log Kaw = -1.4 for poorly volatile compounds.
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	Dichotomous indicator
Infective period	x 0 7 28 365 y 0 0.33333 0.66667 1	WHO [159]
ER binding	Y = 0.25x-0.25	Approach of Langhans et al. [339] for discrete variables

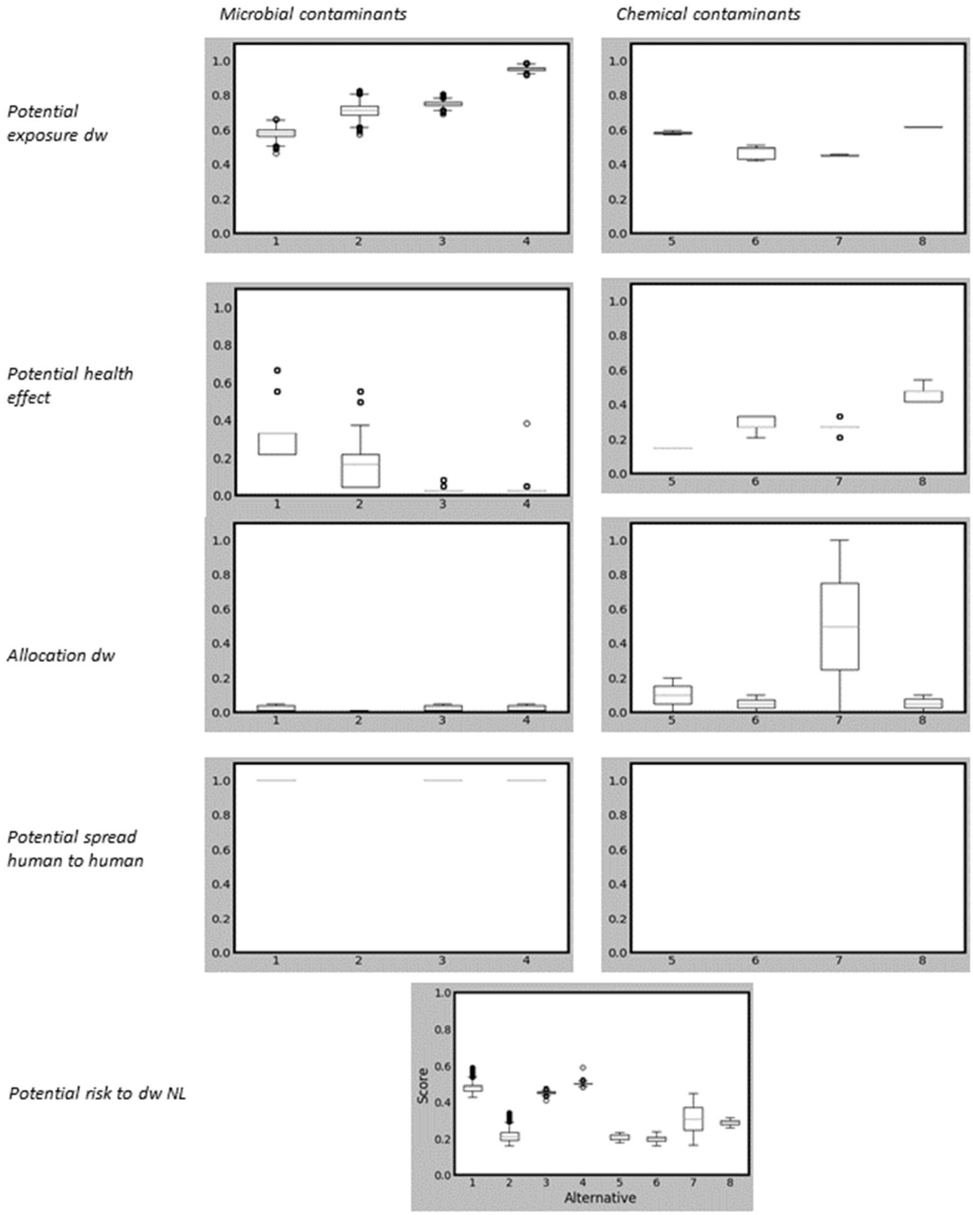

Figure 5-5 Calculated risk scores for MCR-1 E. coli (=1), Legionella longbeachae (=2), Norovirus GII. 17 (=3), Cryptosporidium parvum (=4), prazosine (=5), perfluorooctanoic acid (=6), 3-(4-tert-Butylphenyl) propanal (=7) and minocycline (=8) and scores for the four highest level criteria using the developed 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.

5.5 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 5.1.3), (2) elucidation of uncertainties in evidence-based decision making of emerging drinking water risks (see Section 5.1.2) , and (3) clarification of the values used by risk assessors when evaluating emerging drinking water risks (see Section 5.1.2). Was the developed decision support tool able to fulfil the identified needs and what are areas for improvement of the model?

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

Figure 5-5 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 microbial risks to drinking water integrated the assessment of emerging chemical and microbial risks and uncertainty awareness in a multi-actor approach (see Section 5.4.1). Existing prioritisation approaches are limited, especially when it comes to assessing emerging microbial drinking water risks [52-54, 360]. This study illustrates a first attempt at an uncertainty aware semi-quantitative approach suitable for the prioritisation of emerging microbial drinking water contaminants [53, 54]. 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 [322, 328-331].

In terms of emerging chemical drinking water contaminants risks, Clarke et al. [370] also developed a model which enables the computation of risk scores with uncertain indicator levels. However, this model (Clarke et al. [370]) is not suitable for the assessment of both microbial 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 [41, 52, 350, 356, 380]. 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 [381]. Neumann and Schliebner [381] 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 [379], which gives the model more distinctive power than the Neumann and Schliebner [381] approach. Another difference between Neumann and Schliebner [381] and the present study is that Neumann and Schliebner [381] included the Cramer Classes of the threshold of toxicological concern approach [164] 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.

5.5.2 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 [344].

5.5.2.1 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 [126]. 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 [353] .

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. [382].

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 potential of contaminants in drinking water (ignoring the relevance of drinking water as an exposure route and the potential of secondary spread) (see Figure 5-6)[22] and one based on all criteria.

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[22] To construct Figure 5-6, 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]*

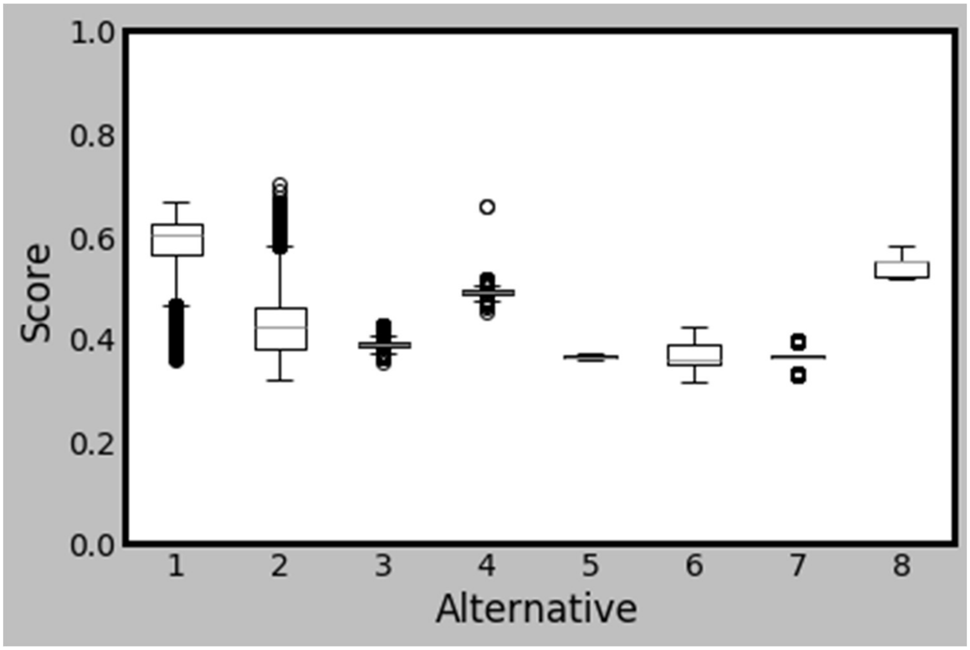

Figure 5-6 The calculated risk scores for MCR-1 E. coli (=1), Legionella longbeachae (=2), Norovirus GII. 17 (=3), Cryptosporidium parvum (=4), prazosine (=5), perfluorooctanoic acid (=6), 3-(4-tert-Butylphenyl) propanal (=7) and minocycline (=8) based on only the hazard and exposure potential of the 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.

5.5.2.2 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 Table 5-5 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 [140].

5.5.2.3 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. 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 overestimated exposure potential of the microbial contaminants (see Figure 5-5, especially for *Cryptosporidium parvum* [383]). A recent study by Wood et al. [384] illustrated the challenges faced with similar preference elicitation.

5.6 Conclusions

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 [156] or, in the case of chemical contaminants, from registration databases (such as the registration, evaluation, authorization 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.

6 EFFECTIVE COMMUNICATION ON EMERGING CHEMICAL AND MICROBIAL DRINKING WATER RISKS

Abstract

The perceived safety of tap water is an important condition for consumers to drink it. Therefore, addressing consumers' concerns should be included in the roadmap towards the UN SDG 6 on safe drinking water for all. This chapter[23] studies consumers' information needs regarding emerging contaminants in drinking water using a mental model approach for the development of targeted risk communication. As most consumers expect safe drinking water, free of contamination, communication on emerging contaminants may increase concerns. Here, we showed that communication strategies better tailored to consumers' information needs result in smaller increases in risk perception compared with existing strategies.

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[23] This Chapter is based on Claassen L, Hartmann J, Wuijts S. How to Address Consumers' Concerns and Information Needs about Emerging Chemical and Microbial Contaminants in Drinking Water; The Case of GenX in The Netherlands. International Journal of Environmental Research and Public Health. 2021;18(20):10615.

6.1 Introduction

Safe tap water is crucial in maintaining public health as it is used for drinking water purposes, personal hygiene and food preparation [22, 317]. According to the World Health Organization (WHO), tap water is considered safe when *it does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages* [55]. In addition to this physical aspect of safe drinking water, the safety of tap water as perceived by consumers is also crucial because consumers who perceive tap water as unsafe will search for alternatives to drink, e.g. bottled water or sodas, which is undesirable from a sustainability and health perspective [124, 171, 172]. For this reason, addressing consumers' concerns should be included in the roadmap towards the United Nations Sustainable Development Goal number 6 on safe drinking water for all [385]. Initiatives such as the Right2Water-initiative demonstrate that consumers also acknowledge the importance of safe drinking water [270]. Protecting both the physical and perceived safety of tap water throughout the world is thus vital in safeguarding public health. This paper aims to contribute to this protective role by developing targeted risk communication regarding contaminants in tap water, based on consumers' information needs.

Given that the focus here is on the exposure to tap water through drinking, tap water will be referred to as drinking water. In Europe, approximately 40 per cent of drinking water from the tap is produced from groundwater and 60 per cent from surface water [386]. Both groundwater [37, 387] and surface water [388] are susceptible to chemical and microbial contamination from various anthropogenic activities, such as agriculture [389, 390] and wastewater discharges from municipalities and industry [39, 128, 391].

In addition to well-known drinking water contaminants, several (often unregulated) emerging chemical compounds have been detected in drinking water and its resources over the past decades, posing a new, or increased, threat to public health [67-69, 126, 128, 188, 392]. These chemicals are referred to as *emerging contaminants, emerging pollutants* or *contaminants of emerging concern* [73]. Recent examples are perfluoroalkyl and polyfluoroalkyl substances (PFAS) [393], 1,4-dioxane [67] and quaternary phosphonium compounds [68]. In addition to emerging chemical contaminants, emerging contaminants of a microbial nature have also been identified in drinking water in recent years [59, 71].

The issue of emerging chemical and microbial contaminants in drinking water resources is expected to increase due to (1) demographic developments (e.g. increased consumption of pharmaceuticals by a growing and ageing population [138, 139]), (2) societal changes (e.g. growing industrial activities [141], (3) technological improvements (e.g. the increasing sensitivity of analytical techniques [128, 129]), (4) regulatory changes (e.g. use of even more hazardous alternatives as a result of phasing out of specific contaminants, referred to as *regrettable substitution* [70]), and (5) climate change (e.g. discharges of untreated wastewater due to sewage overflows during heavy rain events [394, 395]). Given these developments, providing consumers with safe tap water now and in the future remains a challenge.

Following the definition in the WHO Guidelines for Drinking-Water Quality, safe drinking water is not necessarily free of contaminants. Still, it must be free of levels of contaminants that pose a significant threat to humans [55]. This is based on the notion that a contaminant may have hazardous properties, but the risk it poses to human health depends on the level of exposure. To this end, so-called health-based guideline values (HBGV) in drinking water are calculated, representing the concentration in drinking water that does not adversely affect human health even over a lifetime consumption of that drinking water.

Risk assessment of chemicals in drinking water differs for threshold and non-threshold chemicals [159]. For threshold chemicals, it is assumed that a level of exposure exists below which no adverse health effects occur. This level is typically based on a no observed effect level found in animal toxicity testing, which is then extrapolated to humans using Uncertainty Factors (UF) [159, 161, 162]. Uncertainty factors can range from 10 to 10,000 based on the reliability and relatability to humans of the available data. The obtained value is multiplied by the average weight of a human and the relative importance of the exposure to the chemical via drinking water compared to other routes (e.g. air or food) [11]. Finally, the estimated daily intake of drinking water is taken into consideration (e.g. 2 L) [159, 161, 162]. For genotoxic carcinogens, so called non-threshold chemicals, it is believed that exposure to one additional molecule can cause cancer by inducing DNA mutations [160]. Therefore, acceptable levels in drinking water are based on the concentration leading to a theoretical acceptable excess lifetime cancer risk (e.g. 1 excess case of cancer per 100,000 people according to the WHO [159]).

When it comes to emerging contaminants, toxicity data might be unreliable or insufficient and other risk assessment approaches need to be used to define HBGVs, such as the Threshold of Toxicological Concern (TTC) approach [11, 18, 164, 165]. The TTC is a level of daily intake that poses no significant risk to human health. This is based on the notion that contaminants with similar structures have similar toxic properties. This maximum level of daily intake per person per day can be combined with the daily intake of drinking water to calculate a HBGV. The use of the TTC approach and related approaches to derive HBGVs has been explained in depth elsewhere [11, 164, 166, 200]. HBGVs may differ between countries in case of risk assessment based on contaminant specific toxicity data (e.g. use of different standard body weights or different exposure allocations to drinking water) as well as when using the TTC approach (use of different threshold values for different classes in the TTC approach) [126, 167, 168]. The uncertainty associated with the risk assessment of emerging drinking water contaminants, as well as the international differences in what is considered safe drinking water, can be a challenge in risk communication [126].

With respect to the quality of their drinking water, consumers rely on science to identify and monitor hazards, determine health risks and inform them about potential health threats and on policymakers to regulate these threats, by enforcing strict safety levels. Frequently, consumers are confronted with information stating that a hazardous chemical or microbial contaminant has been detected in their drinking water but that this presence does not constitute a risk to public health because the doses do not exceed the safety levels. While experts may be familiar with such statements, public understanding of these risk statements generally does not correspond with the scientific interpretation [173, 174].

First, for consumers, the difference between ‘hazard’ and ‘risk’ is not always clear; they tend to consider all hazards as risks. This is partly due to the use of ‘risk’ instead of ‘hazard’ in risk communication [396]. Often, there is also a mismatch between the intended (scientific) meaning and consumers’ interpretation of terminology describing the hazardous qualities of a contaminant [174, 397, 398]. For example ‘possibly carcinogenic’ is often understood by the public as ‘likely to cause cancer’ [174]. A second potential mismatch is that references to safe exposure levels in risk information are mostly provided in scientific terms such as ‘acceptable daily intake’ without translating these into familiar language and meaningful amounts for consumers. Third, although many consumers can distinguish the conceptual difference between hazard and risk [174, 396, 399], Dutch citizens generally think their tap water is very safe [29] and thus free of contaminants. The mere presence of pathogens or chemicals with toxicological properties may violate that belief. Moreover, consumers may doubt that there is such a thing as a safe amount of a contaminant that can cause serious harm in higher doses. Fourth, to interpret the unfamiliar information, non-experts rely on beliefs associated with known hazards, based on perceived similarity of characteristics [173]. These associations are strengthened by personal experience with and knowledge of the known hazard, and information provided by media. For example, people tend to associate the effects of phthalates on unborn children with the effect of the drug Softenon (thalidomide) [173].

The aforementioned communication mismatches can create misunderstandings, which may result in unintended and undesirable consumer behaviour, such as avoiding drinking water from the tap [124], particularly when hazardous contaminants have been detected in their drinking water. For a more effective risk communication strategy that bridges the gap between experts using complex scientific and technical knowledge and terminology, and consumers who often base their risk judgments on prior beliefs, lay interpretations of terminology and proximity of the risk are required.

A better understanding of consumers’ mental models underlying their beliefs and behavioural decisions is a good starting point for developing risk communication materials [400]. The differences between consumers’ mental models and experts’ representations of the risk assessment process should provide clear insights into the consumers’ information needs. When consumers receive information that fits their mental models and adequately addresses their information needs, this improves their understanding of the risk assessment and management processes so that they are able to make informed and independent judgments about the hazards that they face and about the adequacy of mitigation policies [400].

An often used medium to clarify data and explain concepts in science communication is the use of visual illustrations or embellished infographics. Such infographics can summarise, reduce and simplify information, highlight the most important aspects and convey the complexity of interrelated processes, such as the risk assessment process. There is some evidence that well-designed visual materials offer an effective means of communicating risk numbers [401]. However, evidence for the effectiveness of infographics to explain concepts and processes is scarce [9, 402, 403]. Some studies show that infographics illustrating concepts are easier to comprehend and remember than text alone [402, 403]. Fandel et al. [9] and Guo et al. [403] also point to various aspects of infographic design that can have a considerable impact on comprehension, such as the use of ambiguous or irrelevant illustrations that are not or not clearly linked to the corresponding text. Moreover, comprehension of an infographic often varies widely within a population, revealing that many people have great difficulty in understanding the meaning.

In the present study, we tested the effectiveness of textual and visual risk communication materials on emerging contaminants, both chemical and microbial, in drinking water. Based on mental models research, we redrafted an existing web text on the presence and health risk of the chemical GenX, a recently identified PFAS [61], in drinking water and developed an accompanying infographic explaining the general risk assessment process. GenX substances are used in the production of fluoro-polymers. Fluoro-polymers have many applications, such as in coatings. In June 2019, the European Chemicals Agency unanimously decided that GenX substances are substances of very high concern based on their mutagenic, carcinogenic, reproductive toxic and bioaccumulative properties, as well as their persistence in the environment. Specific information on GenX presence in drinking water in the Netherlands as well as the Dutch health-based guideline value is included in the Appendices for Chapter 6. We performed an experiment to assess the effects of alternative risk information on judgments and decision making.

6.2 Materials and Methods

6.2.1 Development of Materials

To identify relevant consumer information needs and to construct effective communication strategies about risks from emerging chemical and microbial contaminants in drinking water, we followed the mental models approach to risk communication [400]. The approach used in this study is depicted in Figure 6-1.

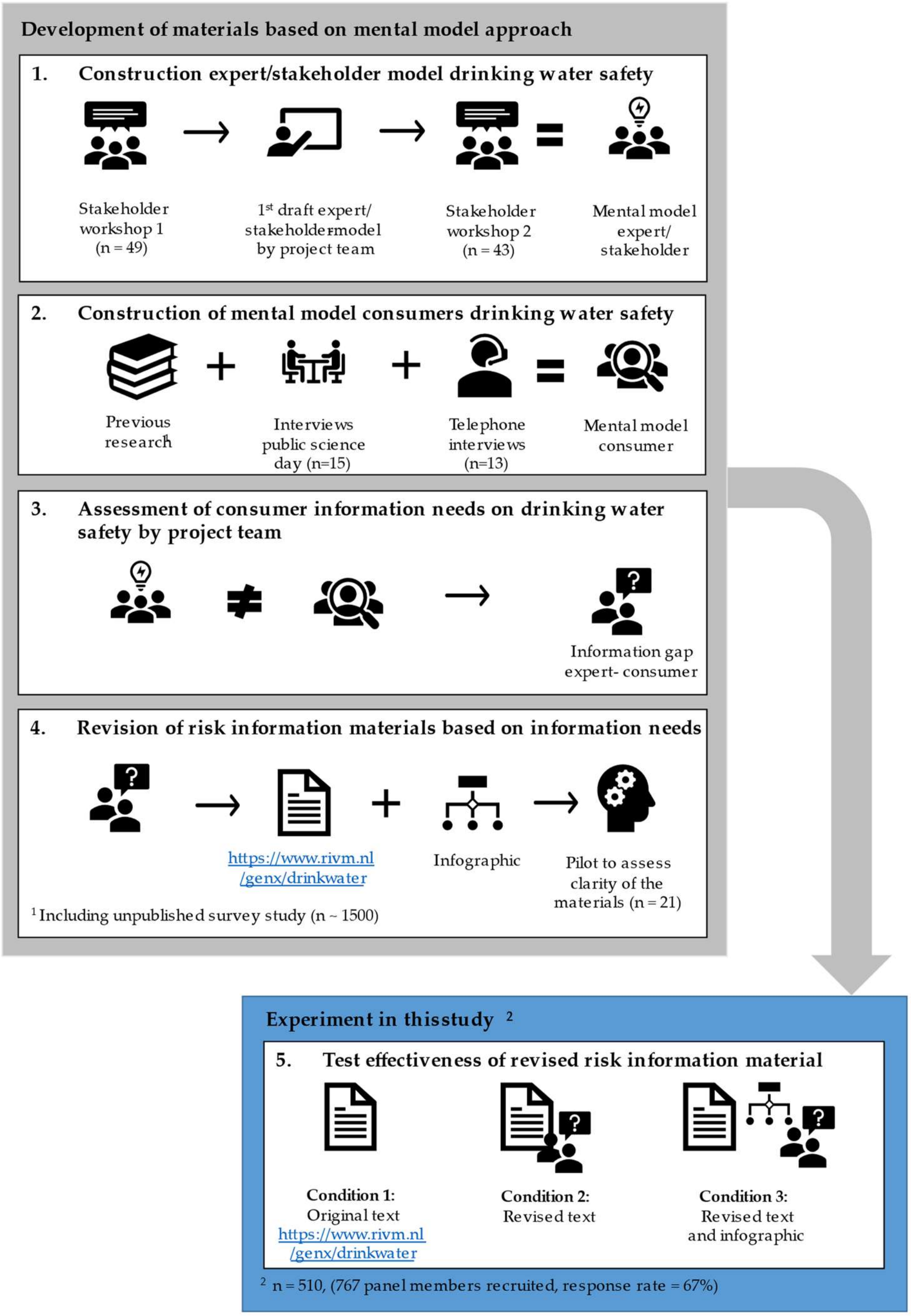


Figure 6-1 Overview of the methodology applied in this study.

First, to construct an expert/stakeholder mental model, the project team, consisting of scientists selected for their expertise on chemical and microbial drinking water quality, risk assessment and risk communication, mapped relevant professional stakeholders from Dutch drinking water companies, industry and responsible authorities (hereafter referred to as 'stakeholders'). These stakeholders were invited to participate in two workshops on November 9th, 2017 and November 6th, 2018, organised by the project team.

The aim of the workshops was to describe stakeholders' perspectives on safe drinking water. These perspectives were used as an indication of what consumers need to know about safe drinking water. In Workshop 1, stakeholders' perspectives were gathered using key questions on (1) the quality and safety of Dutch drinking water (including threats, treatment, pollution sources and risk factors), (2) stakeholders' concerns regarding drinking water safety in the Netherlands, (3) potential mitigation actions and (4) risk communication strategies. The project team used the information gathered in Workshop 1 and complemented it with the scientific perspective on drinking water safety to construct a comprehensive mental model. Stakeholders reviewed the expert/stakeholder model during Workshop 2.

Subsequently, a mental model of consumers' perspectives was constructed to define what consumers already know about drinking water safety and what their information needs are. The consumers' mental model was based on (1) previous research [29, 404, 405], (2) short interviews (n=15) on perceptions of drinking water quality in a convenient sample (visitors of a public science day) and (3) more in-depth telephone interviews (n =13) with members from a consumer panel of a Dutch internet research agency (Flycatcher Internet Research, ISO 26362). This research agency has its own panel consisting of more than 10,000 members representative of the Dutch population (in composition of age/gender/education and distribution over different parts of the country) and is in possession of a quality label for market, opinion and social research (ISO 20252) and is certified according to the environmental standard (ISO 14001). The telephone interviews focused on what people perceived as important threats to the quality of drinking water, what they knew about water management and safety limits and their information needs concerning drinking water quality.

The expert/stakeholders' mental model was compared with the consumers' mental model to identify relevant knowledge gaps, common lay beliefs and questions regarding drinking water safety. We found that consumers generally acknowledge industrial wastewater discharges and runoff from agricultural land as significant threats to drinking water safety; some consumers also specifically mentioned the presence of GenX in drinking water. However, others thought that safe drinking water is entirely free from contaminants. Most consumers did not know how the safety of drinking water is monitored. Finally, the meaning of a safety limit (HBGV) was not clearly understood (See also Table 6-1).

Table 6-1 Results from the comparison of the developed expert/stakeholders' mental model and consumers' mental model

Lay knowledge and knowledge gaps	Lay beliefs	Lay questions
Industry and agriculture are recognised as polluters, but transport (e.g. shipping) is not.	Increased tap water hardness is unhealthy.	*What contamination is found in drinking water? **
Some knowledge about chemical threats to drinking water safety (e.g. GenX, plastic), but microbiological hazards are mostly unknown.	*Drinking water treatment processes remove all contaminants. **	*What are the sources of chemical contamination? **
Knowledge about drinking water resources is very limited.	*If water is not free of contamination, it will make you sick. **	***How are risks assessed, and what is the basis for safety levels? *****
*Responsibilities and tasks concerning drinking water safety of local, regional and national authorities and drinking water companies are unclear. **		*What kind and level of industrial emissions are permitted? **
		*What does it mean when a contaminant is present in drinking water 'under the (safety) limit'? **

* The knowledge gaps, lay beliefs and questions in Italics were addressed in the revision of the web text (https://www.rivm.nl/genx/drinkwater).
** A supporting infographic was designed (following recommendations of Fandel et al. [9]) to answer the question in bold.

Several of the knowledge gaps, lay beliefs and questions (see italics in Table 6-1) identified were then addressed in the revision of a published text from the website of the Dutch National Institute for Public Health and the Environment (RIVM) (https://www.rivm.nl/genx/drinkwater (last accessed on 4 October 2021), in Dutch). The chosen text addresses the recent public and scientific attention for the presence and health risk of GenX, a recently identified PFAS [61], in drinking water, and informed consumers about the risk assessment. A general supporting infographic was designed (following recommendations of Fandel et al. [9]) to clarify the risk assessment process for chemical and microbial contaminants in drinking water (addressing the question in bold in Table 6-1).

A pilot test was then conducted among 21 members from the Flycatcher Internet Research panel, who commented on the clarity of the materials and survey items (see measurements in Paragraph 6.2.4 and Figure 6-1), before the actual survey was conducted. Based on the responses from the pilot test, several adjustments in formatting and wording were made.

The final version of the original text, the revised web text and the infographic (all three are available in Dutch and English) were then tested in an online experiment among 510 participants (materials are included in the Appendices for Chapter 6) as indicated by Figure 6-1.

6.2.2 The Online Experiment

An online survey was used for data collection. In May 2020, participants were invited by e-mail to participate in a survey on drinking water safety by clicking on a unique hyperlink in the invitation. The survey consisted of three consecutive parts. The first part contained questions concerning drinking water safety, trust in information and regulation (see pre-text measurement described in Section 2.4.1). In the second part, participants first received basic information about the presence of GenX in drinking water and were then randomly allocated across the three information conditions (all texts are included in the Appendices (in Dutch and English)):

- Condition 1: Existing website text on GenX
- Condition 2: Alternative website text on GenX
- Condition 3: Alternative website text on GenX and risk assessment infographic.

In the third section, participants were presented with questions about how they evaluated the information, concerns about hazards after reading the text, acceptance of risk management and drinking water use (see Section 6.2.4.2).

6.2.3 Participants

We invited participants through Flycatcher Internet Research. The members in their panel can state their voluntary and active participation in online research through a double-active opt-in procedure. By participating in a study, members can earn points that can be exchanged for gift cards. A total of 510 members participated in the survey study (response rate 67%), of whom 259 were residents of the South Western (S-W) provinces and 251 of other parts of the Netherlands. The S-W provinces of The Netherlands are relevant here, as GenX was found in the drinking water from this region [61]. Both samples were representative of the Dutch general population in 2019 with respect to age, gender and education level.

6.2.4 Measurements

Pre-Text Measurement Variables

Participants of the survey were asked to rate the *quality of Dutch drinking water* ('The drinking water from my tap is…') on four 5-point bipolar semantic differential scales, each representing a specific quality adjective ('tasty' – 'not tasty', 'unsafe' – 'safe', 'healthy' – 'unhealthy', and 'bad' – 'good'). The internal consistency of this scale (with negative scales reverse coded) was satisfactory (α=.77).

Next, to assess their *knowledge about drinking water safety*, participants were asked to state to what extent (on a scale from 1= 'definitely false' to 5 = 'definitely true') they thought the following five statements, formulated in line with expert opinions, were true: 'Drinking water companies check the drinking water for harmful substances on a daily basis', 'There are harmful substances in the drinking water', 'You can ingest a little bit of a harmful substance every day without ever getting ill', 'Researchers can determine the amount of a harmful substance for which drinking water is safe', 'If the drinking water is safe, anyone can drink it daily'. In addition to these knowledge questions, one specific lay belief which is not in line with expert opinions was assessed: 'Drinking water is only safe if it contains no harmful substances'. The response to this last statement was reversely coded, following which a knowledge sum score over the six items was calculated.

Subsequently, participants were asked to what extent (on a scale from 1 = 'not at all' to 5 = 'a lot') they had *concerns* about the four following potential contaminants in their drinking water: carcinogenic substances, endocrine disruptors, bacteria and other microorganisms and calcium. These items are analysed separately.

In addition, we assessed *trust in risk management* by asking to what extent (on a scale from 1 = 'not at all', to 5 = 'a lot') respondents trusted the information of the Dutch National Institute for Public Health and the Environment (RIVM), the information of drinking water companies, and laws and regulation concerning drinking water. These three items formed an internally consistent scale (α=.86).

Post-Text Measurement Variables
After participants went through the provided information, we asked them to indicate (on 5-point bipolar semantic differential scales) whether they thought the information was 'difficult' – 'easy to understand', 'complete' – 'incomplete' (reverse coded), 'not trustworthy' – 'trustworthy', 'new' – 'known', 'clear' – 'vague' (reverse coded), and 'inconsistent' – 'consistent'. They were also asked to clarify their responses (open question). Except for newness of information, the responses formed an internally consistent *evaluation of information* scale (α = 0.82).

Next, we reassessed their concerns about contaminants in drinking water (carcinogenic substances, endocrine disruptors, bacteria and other microorganisms and calcium) using the pre-text measurement variables.

In addition, we asked participants questions about their *perceptions of GenX risk* (on 5-point rating scales; 1= 'certainly not', 5 = 'certainly'): 'I ingest GenX via drinking water', 'You can develop cancer due to the amount of GenX in the drinking water', 'I think the information is reassuring' (reverse coded), 'I think my drinking water is safe to drink' (reverse coded), 'I can get ill due to the amount of GenX in my drinking water', 'I think the risk of GenX in drinking water is high', 'I worry about the harmful effects for children' (internal consistency α = 0.85).

Acceptance of norms and regulation was assessed by asking respondents whether they thought (on 5-point rating scales; (1= 'certainly not', 5 = 'certainly')): 'The norms for GenX in drinking water are strict enough', 'A small amount of GenX in drinking water is acceptable', 'As long as the amount of GenX in drinking water stays within the safe norm, it is all right', 'The risk of GenX in drinking water is too high' (reverse coded) (internal consistency α = 0.89).

And finally, we assessed participants' self-reported *restricted water use* with four items (on 5-point rating scales; 1= 'certainly not', 5 = 'certainly'): 'I drink it without limitations' (reverse coded), 'I prefer bottled water', 'I only drink the water after boiling (e.g. for tea)', 'I filter the water before I drink it'. A sum score was calculated, ranging from 4 (not restricted) to 20 (very restricted).

6.2.5 Statistical Analyses

After checking for socio-demographic differences between information conditions and regions, using χ2 tests for gender and education level and analyses of variances (ANOVAs) for age, we performed t-tests to assess the regional differences in pre-text measurement variables. Next, we calculated Pearson's correlations between measurement variables and performed ANOVAs to test for informational effects of the alternative text, with and without an infographic, on the post-text measurement variables with region and condition as fixed factors.

6.3 Results

6.3.1 Sample

Of the 767 panel members recruited, 510 participated in the study (response rate 67%) (see Figure 6-1). Most participants completed the survey within 10 minutes (95% CI (7.6-9.8 minutes)). The demographic characteristics of the participants are presented in Table 6-2. There were no significant differences in demographic characteristics between the two regions.

Table 6-2 Demographic characteristics of the study sample

Category	**Range**	**N *(%)***	**N *(SD)***
Gender			
Male		271 *(53)*	
Female		239 *(47)*	
Age	18 - 89		51 *(17)*
Education level			
High		149 *(29)*	
Medium		209 *(41)*	
Low		152 *(30)*	
Drinking water regions			
Southwestern region *		259 *(52)*	
Other regions		252 *(48)*	

* In the Southwestern provinces of the Netherlands, GenX was found in the drinking water.

Table 6-3 presents the pre-text evaluations of the study sample. No differences were found between regions with respect to the evaluation of the quality of drinking water, knowledge about drinking water safety and concerns. However, there was a small but significant difference in trust in risk management; in the S-W region respondents demonstrated less trust compared with the other regions (t(508) = -2,202, p= 0.028).

Table 6-3 Pre-text evaluations

Pre-text measurements	**Means (SD)**	
	SW-region	*Other*
Quality of drinking water (range: 1-5)	4.5 (0.6)	4.6 (0.6)
Knowledge about safety (range: 6-30)	21.8 (2.9)	21.9 (2.5)
Concerns about contaminants in drinking water: (range: 1-5) Carcinogenic substances * Endocrine disruptors Microorganisms Calcium	1.7 (0.9) 2.0 (1.0) 2.0 (0.9) 2.2 (1.0)	1.7 (0.8) 1.9 (0.9) 2.0 (0.8) 2.2 (1.0)
Trust in risk management (range: 1-5)	3.9 (0.8)	4.1 (0.7) **

* These concerns are strongly correlated with concerns about endocrine disruptors (r = 0.70) and microorganisms (r = 0.59) and moderately correlated with concerns about calcium (r = 0.30).
** significant difference between regions: $p < 0.05$).

6.3.2 Associations between measures

Pearson's correlations between variables are presented in Table 6-4. There was a relatively strong positive association between the pre-text measurement variables trust in risk management and the evaluation of the quality of drinking water. Both variables were also positively correlated with the evaluation of information and acceptance of norms and negatively associated with post-text concerns and perceptions of GenX risks and restricted water use. All associations between knowledge about safety and the other pre-text and post-text measurement variables were either non-significant or low (r < 25). Table 6-4 also shows relatively strong associations between the post-text measures. As expected, lower concerns and perceptions of GenX corresponded with greater acceptance of norms and fewer self-reported restrictions in water use. Notably, more positive evaluations of information corresponded with lower concerns and perceptions of GenX and more acceptance of fewer restrictions in water use.

*6.3.3 E*ffects of web text and infographic

Table 6-5 shows the results of an interaction effect of both condition and region on the evaluation of information. There was no significant difference between the conditions with and without the infographic. The open comments in response to the infographic varied strongly: it was perceived as complicated and difficult to understand by some, whereas others felt it clarified the process.

Table 6-4 Associations between outcome measures

	Knowledge	Trust	Evaluation of information	Newness of information	Concerns	Perceptions of GenX risk	Acceptance of norms	Restricted water use
Pre-text measures								
Quality of drinking water	.089*	.479**	.347**	-.035	-.287**	-.410**	.322**	-.444**
Knowledge about safety		.132**	.242**	.089*	-.017	-.136**	.135**	-.206**
Trust in risk management			.375**	-.053	-.332**	-.445**	.388**	-.437**
Post-text measures								
Evaluation of information				.104*	-.307**	-.440**	.380**	-.260**
Newness of information					-.135**	-.060	.028	.002
Concerns about GenX						.694**	-.602**	.373**
Perceptions of GenX risk							-.731**	.505**
Acceptance of norms								-.391**

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Table 6-5 Post-text outcomes per condition and region

Post-text measurements *	**Existing web text Means (SD)**		**Alternative web text Means (SD)**		**Alt. text + infographic Means (SD)**	
	SW-region n = 82	*Other n = 86*	*SW-region n = 97*	*Other n = 73*	*SW-region n = 80*	*Other n = 92*
Evaluation of information	3.8 (0.7)	3.9 (0.7)	4.1 (0.7)	3.9 (0.7)	4.0 (0.7)	3.7 (0.7)
Newness of information	2.5 (1.3)	2.4 (1.2)	2.6 (1.3)	2.4 (1.3)	2.8 (1.3)	2.4 (1.3)
Post-text concerns:						
Carcinogenic substances	2.3 (1.0)	2.5 (1.0)	2.2 (1.0)	2.3 (0.9)	2.3 (1.0)	2.1 (0.9)
Endocrine disruptors	2.4 (1.0)	2.3 (1.0)	2.2 (1.0)	2.3 (1.0)	2.3 (1.0)	2.2 (1.0)
Microorganisms	2.3 (1.0)	2.1 (0.9)	2.0 (0.8)	2.3 (0.9)	2.2 (0.9)	2.1 (0.8)
Calcium	2.2 (0.9)	2.0 (1.0)	2.1 (0.8)	2.1 (1.0)	2.1 (1.0)	2.1 (1.0)
Perceptions of GenX risk	2.8 (0.7)	2.7 (0.6)	2.6 (0.7)	2.5 (0.7)	2.7 (0.8)	2.5 (0.7)
Acceptance of norms	3.2 (0.9)	3.4 (0.8)	3.3 (0.9)	3.4 (0.8)	3.3 (0.9)	3.5 (0.8)
Restricted water use	8.3 (3.4)	7.1 (3.0)	7.4 (3.0)	7.3 (2.8)	7.9 (3.1)	7.2 (2.9)

For post-text concerns, we found effects within subjects. After going through the provided information, participants' concerns increased with respect to carcinogenic substances ($F(1,504) = 268.904$, $p < 0.001$), endocrine disruptors ($F(1,504) = 86.309$, $p < 0.001$), and microorganisms ($F(1,504) = 20.449$, $p < 0.001$) in drinking water, while concerns with respect to calcium in drinking water decreased ($F(1, 504) = 8.686$, $p = 0.003$). There was a between-subjects interaction effect of pre-text concerns and condition on post-text concerns: participants in the conditions with the alternative text showed smaller increases in concerns about carcinogenic substances ($F(2,504)= 8.359$, $p < 0.001$) and endocrine disruptors ($F(2,504) = 3.589$, $p = 0.028$) compared with participants in the condition with the existing web text (but not for microorganisms and calcium). This interaction effect was independent of the region. There was no significant difference between alternative conditions with and without the infographic.

Perception of GenX risks was higher in the S-W region compared with the other regions ($F(1,504) = 5.119$, $p = 0.024$) and lower in the conditions with the alternative text compared with the existing web text ($F(2,504) = 3.971$, $p = 0.019$). There was no significant difference between the alternative conditions with and without the infographic.

In the S-W region, acceptance of norms was lower ($F1,504) = 5.368$, $p = 0.021$) and restricted water use was higher compared with the other regions ($F(1,504) = 5.914$, $p = 0.015$). There was no significant effect of conditions on acceptance of norms and drinking water use.

6.4 Discussion

In this study, mental models-based risk information on microbiological and chemical hazards in drinking water such as GenX was developed and an experiment was carried out to assess the effects of providing this information on judgments and decision making by consumers. To this end, the expert/stakeholders' mental model was compared with the consumers' mental model to identify their concerns and information needs (e.g. the meaning of a safety limit (HBGV)).

The results show that in the context of this study, risk communication materials that are developed with the information needs from consumers in mind, are appreciated more and result in smaller increases in risk perception compared with existing materials. In this section, we will reflect on these results, their relevance in the international context and the strengths and limitations of the methodology applied and explore some avenues for future research.

6.4.1 Reflection on results

In the experiment, participants were assigned to one of three alternative information packages: the original text from the website on GenX, a modified text that aimed to meet information needs previously identified among consumers, or the modified text complemented with an infographic on the process of risk assessment for emerging chemical and microbiological contaminants in drinking water. The results showed that the modified text was better understood and appreciated in the region with higher GenX emission, indicating that the modifications addressed consumers' information needs better. Moreover, the modified text prompted less apprehension about GenX risk compared with the existing website text. As these factors were also associated with greater acceptance of GenX norms and regulation, and fewer self-reported restrictions in water use, the modified mental models-based information material delivered promising outcomes. Using a mental models approach to ensure that risk communication materials take consumers' information needs into account has also been found effective in improving risk comprehension and in changing attitudes and behaviour towards risk in other studies (see review Boase et al. [406]). In a Mexican study, for example, a comic book explaining carbon monoxide (CO) poisoning risks to residents reduced misunderstanding about CO risk and increased the willingness to use CO alarms [407].

The use of the infographic explaining the risk assessment process did not result in improved understanding and appreciation of the modified text. Nor did it affect risk apprehensions, although it should be noted that it did not have adverse effects either. There are many factors that may explain the lack of effect. Meta-analyses of studies using illustrations to improve understanding showed that although graphics accompanying texts can facilitate readers' comprehension [403], many features can hamper comprehension. Graphs, which require more investment from the reader, often yield less robust effects. In particular, the density and variety of visuals, the intricacy of individual visual representations, the spatial and semantic integration of text and visuals demand cognitive effort from readers. In our study, the infographic was indeed perceived as rather complex by some, possibly because the infographic offered a lot of information to digest or did not clarify the link with the provided text on GenX satisfactorily, since the infographic focused on drinking water and emerging contaminants *in general* and was not tailored to GenX.

We were specifically interested in the responses of participants in the S-W region. The S-W region harbours a few large chemical industries, and over the past few years, reports have been published on the presence of PFAS in the drinking water in this region. The first reports were about possibly contaminated groundwater, which had been used for the production of drinking water. The groundwater was found to be polluted by PFOA due to industrial wastewater discharges and subsequent infiltration into groundwater in the period of 1970-2012 [7, 8, 126]. Then, in 2017, GenX, which has been used as an alternative for PFOA by the chemical industry since 2012, was also detected in the drinking water in this region [61, 408]. These results require risk communication specifically targeted to consumers in this region, for whom it is most relevant [409]. It may not be surprising that the participants in this region were more vigilant with respect to drinking water safety. They demonstrated less trust in risk management, were less satisfied with GenX norms and regulations and also reported more restrictions in water use compared with the other regions. However, they were also more susceptible to this targeted communication material. As noted above, they evaluated the modified information more positively compared with the existing text.

Before reading the information, participants in both regions were more concerned about the water's hardness than about chemical and microbial contaminants. It is likely that they were previously unaware of the presence of hazardous contaminants in their drinking water. The provision of information on the presence of GenX resulted in increases in concerns about not only carcinogenic substances but also about endocrine disruptors and microbiological contaminants (interestingly, however, concerns about the hardness decreased). These increases in concerns may trigger unintended and undesirable consumer behaviour, such as avoiding drinking water from the tap. Nevertheless, keeping consumers in the dark about the presence of contaminants is not a viable option. The real challenge is to adequately inform people about the presence of contaminants to enable them to make informed decisions that they face and about the adequacy of norms [400].

6.4.2 International context

In a previous study by Hartmann et al. [126], several risk communication strategies used in Minnesota (USA), Germany, Switzerland and the Netherlands on another PFAS (perfluorooctanoic acid) in drinking water were analysed. Hartmann et al. [126] concluded that timely communication resulted in lower concern among the public. However, in all studied countries, mostly one-way technical communication strategies [193] were used to inform, assure and possibly change the behaviour of consumers, by conveying scientifically determined risk [126]. With the present study in mind, we suggest that taking concerns and questions of consumers on GenX in drinking water into account could have resulted in more adequate risk communication in the cases studied by Hartmann et al. [126]. Given that the cases studied by Hartmann et al. [126] also consider a PFAS in drinking water, similar information needs are expected to the ones identified in this study (see Table 6-1). For instance: ‘What does it mean when a contaminant is present in drinking water under the (safety) limit?’. Such an approach may offer valuable input for developing risk communication materials. This is particularly relevant in light of the expected increase in risk communication about drinking water as new information on the toxic potential of PFAS is published. This recent information is likely to affect national drinking water safety limits for PFAS.

In addition to improving the future international risk communication on PFAS in drinking water, the identified information needs as shown in Table 6-1 can also be used to guide communication strategies for other emerging drinking water contaminants. Examples include communication on pharmaceuticals in drinking water [185] and the role of drinking water in the dissemination of antibiotic resistance [274].

6.4.3 Strengths and limitations

A specific strength of this study is the interdisciplinary and participatory approach, providing different sources of information to develop the materials. By addressing both chemical and microbiological risks and involving natural and social scientists, professional stakeholders and members of the general public, we aimed to tackle professional, disciplinary and institutional boundaries. Although this process towards mutual understanding is rather challenging, it provides the opportunity to learn and benefit from one another’s knowledge and is likely to result in broadly beneficial and more socially robust risk communication.

The effectiveness of information materials is often evaluated by assessing the impact on knowledge [406]. However, choices made by consumers are often based on other factors too, irrespective of knowledge. This is also likely for knowledge about drinking water safety, as in our study we did not find a clear link between knowledge, concerns about contaminants, acceptance of norms and regulation and restrictions in water use. For this reason, this study aimed to identify the gaps between expert and lay views on risks related to emerging contaminants in drinking water and, specifically, to explore test information materials that were tailored to the information needs and that tested the effects on evaluation of information, concerns and acceptance rather than on consumers' knowledge.

The difference in content and length of the risk messages can be considered a limitation in this study. In particular, the condition with the infographic differed considerably from the other two conditions. It not only presented a different type of information but also required more reading time and engagement from the respondents. This has likely affected the results. An alternative and perhaps a more insightful approach would have been to test the infographic in comparison with other existing illustrations of the risk assessment process.

A second consideration is the participants' representativeness. Online panels are susceptible to sampling bias. Although the invited panel of participants was a stratified random sample drawn in terms of the distribution of gender, age, education level and geographical regions in the Netherlands according to Statistics Netherlands (2018), we cannot exclude that sampling bias may still have occurred.

Finally, it should be noted that we carried out this experiment in the European context, in one country, the Netherlands. In the Netherlands, the trust in the quality and safety of drinking water is generally very high as compared with other (European) countries [29]. When using the results in other countries, the context in those countries should be accounted for. However, in view of the implementation of the revised European Drinking Water Directive ((EU) 2020/2184) and the important role given to information and risk communication, this study offers insights into possibilities to develop more effective risk communication strategies.

6.4.4 Avenues for future research

The experiment in this study was carried out to gain insight in the information needs and communication strategies regarding emerging chemical and microbiological drinking water contaminants, and focused specifically on the emerging chemical contaminant GenX. Chemical contaminants in drinking water primarily impose a health risk after prolonged exposure. In addition, emerging microbiological contaminants may cause acute health effects, as illustrated by a recent outbreak of gastrointestinal illness in Finland due to sapoviruses in drinking water [59]. Thus, information needs and communication strategies could be different, but it is yet unknown whether these risks are perceived differently by consumers. A similar experiment could be carried out for an emerging microbiological contaminant such as SARS-CoV-2, which, although this was not clear at first, now does not appear to be waterborne [140, 410].

Furthermore, drinking water is not the only exposure route for emerging contaminants. Food may be another exposure route, and so is air, but it is unknown how consumers weigh these different exposure routes and what information needs they have on this topic. Information needs regarding emerging chemical and microbiological contaminants can also vary for different groups (e.g. the chronically ill, parents of young children, the elderly), which is an interesting avenue for future research as well.

6.5 Conclusions

Emerging chemical and microbial contaminants in drinking water resources are expected to become more of an issue in the near future. It is currently not technically viable to remove all contaminants, yet most consumers expect safe drinking water, free of contamination. This provides a new challenge for effective risk communication, i.e. how to adequately inform consumers about the presence of contaminants in drinking water while achieving or maintaining trust in drinking water safety among different consumer groups. In this study, we demonstrated that a mental models-based communication strategy, specifically tailored to consumers' information needs, resulted in smaller increases in risk perception compared with existing strategies. The presented results can be used by drinking water companies as well as public health institutes to develop (web) texts on emerging contaminants in drinking water that do not hamper perceived drinking water safety among consumers.

7 GENERAL DISCUSSION

7.1 Introduction

Perfluoroalkyl and polyfluoroalkyl substances (PFAS) [393], sapoviruses [59], pharmaceuticals [185] and colistin resistant bacteria [285] are just a few examples of aquatic contaminants for which public and scientific concern has emerged over the past couple of years. The level of concern caused by these contaminants, and whether this was related to drinking water safety, was dependent on a diverse set of aspects including their mobility and persistence in the environment, the severity and duration of the health effects, and the possibility for protective measures. As this dissertation was finalised during the COVID-19 pandemic, SARS-CoV-2 cannot be left unmentioned in this context. While SARS-CoV-2 did not pose a risk to drinking water safety [411], the COVID-19 pandemic has once more shown the importance of picking up and acting on signals that point towards new contaminants of concern and the imperative role that science has in this process [412]. The importance of the early assessment of emerging risks is also relevant in the context of drinking water safety. This is shown by the recent concern about persistent, mobile and toxic contaminants [413] as well as by drinking water related outbreaks caused by emerging waterborne pathogens [59]. The challenge is how can we pick up signals of unknown contaminants and how do we prioritise the human health impact that these contaminants have when evidence on exposure and hazard potential is limited. Once identified and assessed, the challenge of effective risk communication in a climate of uncertainty needs to be dealt with as well [414]. In this dissertation, an integrated approach was developed to tackle these challenges, focussing on one specific exposure route: drinking water.

Section 7.2 presents the answers to the research questions formulated in Section 1.8. Answers are based on the results and conclusions of the studies presented in Chapters 2 to 6. The contribution of this dissertation to the overall research aim – to improve the risk governance of emerging chemical and microbial drinking water contaminants - and its relevance for other research done in the field, is discussed in Section 7.3. Section 7.4 suggests valuable avenues for future research. The relevance of this dissertation for drinking water suppliers, policy makers and researchers is discussed in Section 7.5. Finally, in Section 7.6, a number of conclusions relevant to the effective risk governance of emerging chemical and microbial drinking water contaminants are presented.

7.2 Research questions answered

In Section 1.8, the following research questions were formulated:

I. *What are the weaknesses in the current risk governance approaches for the identification of, and manner of dealing with, unregulated compounds in drinking water and its resources?*
II. *How do we develop a method for the early identification of potential emerging chemical and microbial risks in drinking water (resources)?*
III. *Is the developed methodology effective for the early identification of emerging chemical and microbial drinking water contaminants?*
IV. *How do we prioritise microbial and chemical contaminants based on the risk they present to drinking water quality?*
V. *How do we effectively communicate about emerging chemical and microbial drinking water risks to the public?*

In the following subsections and in Figure 7-1, each research question is answered using the studies presented in Chapters 2 to 6.

7.2.1 Delayed identification of risks from exposure to chemical and microbial drinking water contaminants

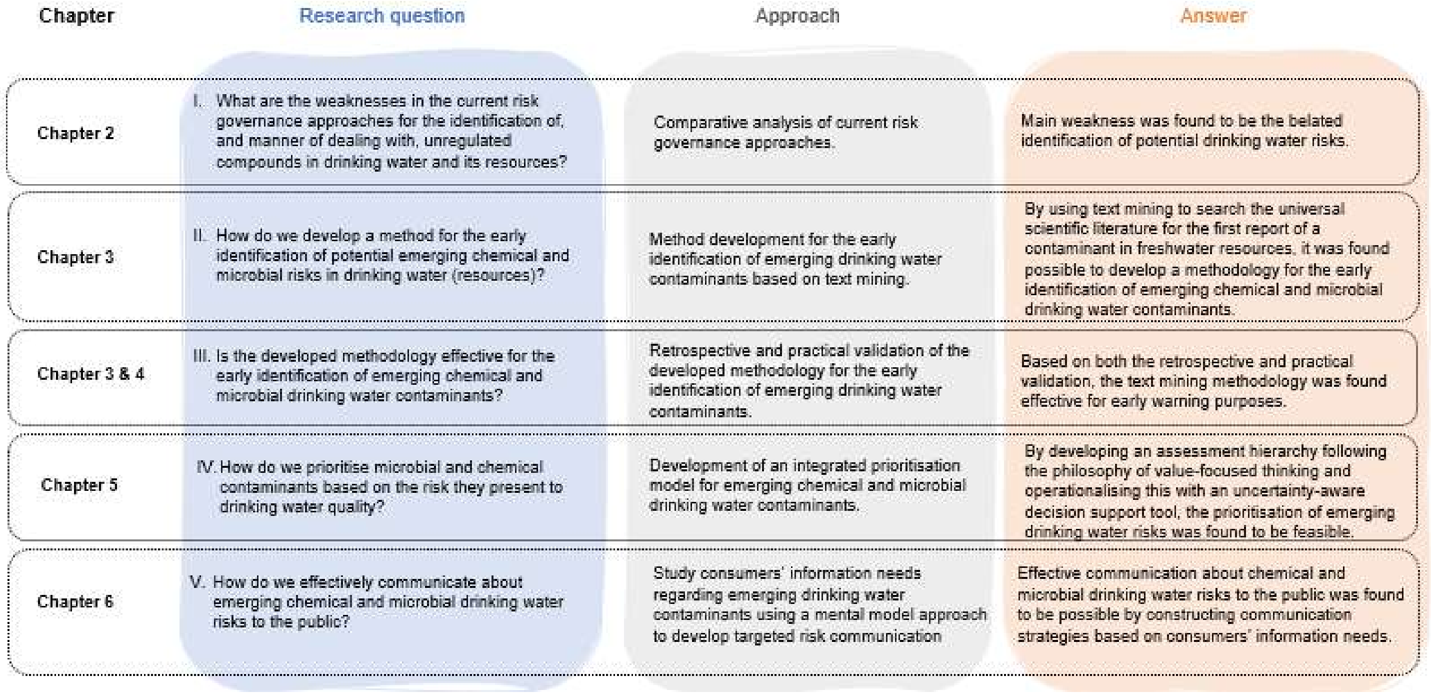
Research question I - *What are weaknesses in the current risk governance approaches for the identification of and dealing with unregulated compounds in drinking water and its resources?* – can be answered using the results of the study presented in Chapter 2 [126] in which policy approaches applied in the Netherlands, Switzerland, Germany and the state of Minnesota during national incidences of perfluorooctanoic acid (PFOA) in drinking water resources were analysed. PFOA is an anthropogenic chemical belonging to the group of PFAS [250]. For details on the national incidences of PFOA, see Section 2.2. Weaknesses in applied risk governance approaches were identified using the risk governance framework of the International Risk Governance Council (IRGC) and the suggestions for best practice in the governance of emerging contaminants proposed by Naidu et al. [100] and Naidu et al. [122].

In the context of this dissertation, the IRGC framework includes the identification, appraisal, management, and communication of, potential human health risks posed .by emerging chemical and microbial drinking water contaminants [151]. The suggestions for best practice as proposed by Naidu et al. [100] and Naidu et al. [122] include: (1) the integration of science into policymaking, (2) the acceptance of the risk governance process by all stakeholders, (3) the defensibility of decisions made, and (4) the consideration of other factors as well as public health-risk reduction when choosing remediation strategies.

The main weakness in the studied risk governance approaches was found to be the belated identification of potential drinking water risks from emerging chemical contaminants (see Section 2.4). Identification is mainly based on screening data and no structured approaches are used for other available information sources, such as the scientific literature. It is concluded that a more timely identification of emerging drinking water contaminants, could improve the risk governance process as it (1) enables suitable risk management options to be taken, (2) allows other factors next to the potential impact on public health, such as cost-benefit analyses, to be included in the deliberation of risk remediation measures, and (3) it can minimise the manifestation of public concern [126].

7.2.2 Screening the scientific literature using text mining is effective for early identification of emerging drinking water contaminants

Research question II - *How do we develop a method for the early identification of potential emerging chemical and microbial risks in drinking water (resources)?* - can be answered using the study presented in Chapter 3 [156]. In this study, a semi-automated text mining methodology was developed to identify the first report in the scientific literature of a contaminant in freshwater resources. Freshwater resources were chosen as these are preferred over saline water by Dutch drinking water companies. Hartmann et al. [154] demonstrated that, by using text mining to search the universal scientific literature for the first report of a contaminant in freshwater



Chapter	Research question	Approach	Answer
Chapter 2	I. What are the weaknesses in the current risk governance approaches for the identification of, and manner of dealing with, unregulated compounds in drinking water and its resources?	Comparative analysis of current risk governance approaches.	Main weakness was found to be the belated identification of potential drinking water risks.
Chapter 3	II. How do we develop a method for the early identification of potential emerging chemical and microbial risks in drinking water (resources)?	Method development for the early identification of emerging drinking water contaminants based on text mining.	By using text mining to search the universal scientific literature for the first report of a contaminant in freshwater resources, it was found possible to develop a methodology for the early identification of emerging chemical and microbial drinking water contaminants.
Chapter 3 & 4	III. Is the developed methodology effective for the early identification of emerging chemical and microbial drinking water contaminants?	Retrospective and practical validation of the developed methodology for the early identification of emerging drinking water contaminants.	Based on both the retrospective and practical validation, the text mining methodology was found effective for early warning purposes.
Chapter 5	IV. How do we prioritise microbial and chemical contaminants based on the risk they present to drinking water quality?	Development of an integrated prioritisation model for emerging chemical and microbial drinking water contaminants.	By developing an assessment hierarchy following the philosophy of value-focused thinking and operationalising this with an uncertainty-aware decision support tool, the prioritisation of emerging drinking water risks was found to be feasible.
Chapter 6	V. How do we effectively communicate about emerging chemical and microbial drinking water risks to the public?	Study consumers' information needs regarding emerging drinking water contaminants using a mental model approach to develop targeted risk communication	Effective communication about chemical and microbial drinking water risks to the public was found to be possible by constructing communication strategies based on consumers' information needs.

Figure 7-1 Overview of answers to the research questions defined in Section 1.8 based on the research presented in chapters 2 to 6.

resources, it is possible to develop a methodology for the early identification of emerging chemical and microbial drinking water contaminants.

Research question III - *Is the developed methodology effective for the early identification of emerging chemical and microbial drinking water contaminants?* – can be answered using the studies presented in Chapters 3 [156] and 4 [176]. The efficacy of the developed text mining methodology for the early identification of emerging chemical and microbial drinking water contaminants was validated both in retrospect [156] and in practice [176]. Retrospective validation was presented using a chemical (the presence of PFOA in drinking water resources in the Netherlands [7, 8]) and a microbial case (the identification of industrial biological wastewater treatment plants as potential infection sources for two Legionnaires' disease clusters in the Netherlands was used as the microbial case [259]). Practical validation included the design of an effective sampling campaign by applying the text mining methodology developed by Hartmann et al. [156] (Chapter 3) to recent literature. Based on both retrospective and practical validations, the developed text mining methodology was found effective for the early identification of emerging chemical and microbial drinking water contaminants.

7.2.3 Risk-based prioritization of emerging microbial and chemical drinking water contaminants is possible using value-focused thinking and an uncertainty aware decision support tool

Research question IV - *How do we prioritise microbial and chemical contaminants based on the risk for drinking water quality?* – can be answered with the study presented in Chapter 5 [51]. By developing an assessment hierarchy and operationalising this with an uncertainty-aware decision support tool, the prioritisation of emerging drinking water risks was found to be feasible. This approach also enables us to overcome the challenges facing an integrated risk-based prioritisation of action to reduce emerging chemic and microbial drinking water contaminants. These challenges include differences in the risk evaluation methods used for chemical and microbial drinking water contaminants (see Section 1.4.2 and 5.1.3) as well as data scarcity for an evaluation of the exposure and hazard potential of emerging contaminants. In Hartmann et al. [51] the assessment hierarchy was set up using the philosophy of value-focused thinking: the overall objective (risk to Dutch drinking water) was disintegrated into sub-objectives (e.g. low microbial or chemical contamination, also referred to as sub-criteria) which are disintegrated further until it is possible to complete a quantitative assessment (e.g. persistence) of alternatives (e.g. contaminants). Suitable indicators (e.g. half-life in water or time to first log reduction) are then chosen to quantify the fulfilment of the lowest level sub [51, 332, 338] (see also Figure 5-1).

By using the concept of value-focused thinking to construct an assessment hierarchy, the challenge of combining different risk evaluation methods for chemical and microbial drinking water contaminants is overcome and the integrated risk-based prioritisation of chemical and microbial aquatic drinking water contaminants on a joint scale becomes possible. The constructed assessment hierarchy is then used to develop a decision support tool to quantify drinking water risk scores for emerging chemical and microbial water contaminants.

The challenge of data scarcity for the risk-based prioritisation of emerging chemical and microbial aquatic contaminants is overcome by calculating risk scores using Decisi-o-rama [353], an open-source Python library for uncertainty-aware decision making. Uncertainty in the context of this study refers to the prediction of indicator levels, where indicators are used to assess the performance of a contaminant on a certain criterion. An example of a criterion in this regard was ‘persistence in surface water’, the indicators used for this criterion were ‘half-life in water’ for chemical contaminants or ‘time to first log reduction’, for microbial contaminants (see also Table 5-1).

A decision support tool is thus developed that calculates (uncertain) drinking water risk scores for emerging chemical and microbial contaminants. These risk scores can then be used for the evidence-based prioritisation of actions on emerging chemical and microbial contaminants by water regulators and drinking water suppliers. Actions should focus on the highly scored contaminants or those contaminants for which the risk scores are the most uncertain. Potential actions depend on the type of contaminant, the actors involved, and whether data is missing on the contaminants’ hazard or exposure potential, but could include targeted monitoring of the contaminant in drinking water (resources). The potential actions were not further evaluated in this dissertation, except for the design of sampling campaigns based on literature mining (see Chapters 4 and 5).

7.2.4 More effective risk communication on emerging drinking water contaminants by tailoring communication strategies to consumers’ information needs

An answer to research question V - *How do we effectively communicate about emerging chemical and microbial drinking water risks to the public?* – was found in Chapter 6 [127]. Effective communication about chemical and microbial drinking water risks to the public was found to be possible by constructing communication strategies based on consumers’ information needs.

In Chapter 6, consumers’ information needs regarding emerging contaminants in drinking water were investigated following the mental models approach to risk communication [127, 400]. The information needs of consumers were identified by comparing a consumer’s mental model with a mental model of drinking water experts. Based on the identified information needs, targeted risk communication was developed. Communication about the presence of GenX, another example of a PFAS, was used as a case study. Identified information needs of consumers included the misconception that safe drinking water is entirely free from contaminants and the knowledge gap surrounding the meaning of a safety limit (see also

Table 6-1). An experiment with 510 participants showed that communication strategies better tailored to consumers' information needs resulted in lower increases in risk perception compared to existing communication strategies on emerging contaminants.

7.3 Reflection on results

7.3.1 Results in relation to the research aim

The overall aim of this dissertation was to improve the risk governance of emerging chemical and microbial drinking water contaminants. It was hypothesised that this could be accomplished by developing and applying an integrated approach for the identification and assessment of, and communication on, emerging chemical and microbial drinking water contaminants. In Chapters 2-6, the development and application of this integrated approach were discussed. Henceforth, the integrated approach refers to a combination of the following:

- early identification of potential emerging chemical and microbial contaminants in drinking water resources using literature mining (Chapters 3 and 4);
- evidence-based prioritisation of policy action on emerging contaminants using the developed decision support tool (Chapter 5);
- risk communication strategies tailored towards information needs of consumers (Chapter 6).

In Hartmann et al. [126] (Chapter 2) the main weakness in the studied risk governance approaches was found to be the belated identification of emerging chemical contaminants. This relates to the first step of the IRGC framework (see Section 2.2.1 for details on this framework). By using the suggestions for best practice put forward by Naidu et al. [100] and Naidu et al. [122], weaknesses of the studied risk governance approaches in other steps of the IRGC framework were also identified. In this section, the added value of the integrated approach developed in this thesis is discussed in regards to overcoming these weaknesses, following the steps of the IRGC framework.

7.3.1.1 Risk appraisal: the hazard, exposure and concern assessment of emerging drinking water contaminants

The risk appraisal step in the IRGC framework is a combination of the hazard and exposure assessment of a contaminant, with the assessment of associations and perceived consequences that the public might have with that contaminant being in drinking water (the concern assessment) [151]. Two weaknesses were identified in Hartmann et al. [126] (Chapter 2) with regards to the appraisal step in current risk governance approaches, namely (1) the international differences between drinking water limits for emerging contaminants, which hampers effective risk communication and (2) the exclusion of a structured concern assessment.

A decision support tool was developed for the evidence-based prioritisation of action on emerging chemical and microbial aquatic contaminants based on their potential risk to drinking water safety (see Chapter 5). The decision support tool is not suitable for calculating drinking water limits so it cannot be used to harmonise international hazard assessment. However, using the philosophy of value focused thinking, values and assumptions used by risk assessors were made explicit which can help to bring forward the discussions on international differences in risk assessment of emerging contaminants and subsequent standard setting [324, 333].

The second identified weakness, namely the exclusion of the concern assessment in the risk appraisal step was also not tackled by the developed decision support tool, as no consumers were included in the development of the assessment hierarchy. This is considered a valuable avenue for future research and is further discussed in Section 7.4.

7.3.1.2 Risk acceptance and risk management of emerging drinking water contaminants

In the IRGC framework [151] the risk acceptance step refers to an evaluation of whether the identified risk is "acceptable", "tolerable" or "intolerable". Risk management is the combination of actions taken to avoid, decrease or retain the potential risk posed by a hazard. During the Hartmann et al. [126] analysis of national incidences of PFOA in drinking water resources, the decision as to whether the risk posed by PFOA was acceptable, tolerable or intolerable was solely based on the human health impact related to drinking water consumption (see Section 2.3.3). Other aspects, such as economic or ecological implications, were not taken into consideration.

The integrated approach developed and presented in this dissertation did not take into account considerations other than the potential impact on human health via drinking water. However the added value of the integrated approach in this regard is the decision support tool [51] as it facilitates a more structured evaluation of whether the drinking water risk posed by an emerging chemical or amicrobial aquatic contaminant is acceptable, tolerable or intolerable. This structured evaluation is achieved by the calculation of risk scores, which can be used to guide the need for risk management options. Extending the decision support tool to include other aspects such as economic or ecological implications is considered a valuable route for future research and is discussed in Section 7.4.

7.3.1.3 Risk communication on emerging drinking water contaminants

Based on the analysis in Hartmann et al. [126] (Chapter 2), belated timing was found to be the weakness in both the identification, and the risk communication step, of current drinking water risk approaches. This was concluded based on the differences in levels of public concern following communication on the presence of PFOA in drinking water resources between Germany and the Netherlands (Section 2.3.4). Based on the results of the experiment discussed in Chapter 6, the differences in the level of public concern may also be caused by differences in communication strategies. The experiment showed the added value of the integrated approach in terms of risk communication.

7.3.2 Relevance of the results for other research in the field of emerging drinking water contaminants

Emerging chemical and microbial aquatic contaminants have been the topic of a wide range of scientific publications over the past years. Because of the high number of articles, it was not feasible to reflect on the results of this dissertation in the light of each of these individual articles. Therefore, a selection of the most relevant articles related to the identification and assessment of, or communication on, emerging chemical and microbial contaminants in the Dutch context, are discussed here.

7.3.2.1 Relevance of the results for other research on using literature mining for early warning purposes

The integrated approach developed in this dissertation included the early identification of yet unknown chemical and microbial aquatic contaminants that might be of risk to human health via drinking water, using literature mining as developed by Hartmann et al. [156]. To the best of my knowledge, the study by Luijckx et al. [415] is one of the few other studies that applied literature mining for early warning purposes for aquatic contaminants. Luijckx et al. [415] focussed on emerging chemical and microbial risks for human, animal and environmental health in the farming of Atlantic Salmon and Pacific Oysters, using a more elaborate text mining methodology. This more elaborate text mining methodology included a set of semantic relationships, whereas in Hartmann et al. [156] only pattern matching was applied. The methodology developed in Hartmann et al. [154] might benefit from further development using a set of semantic relationships as applied in Luijckx et al. [415].

In this regard it is worth noticing that a previous version of the text mining methodology of Luijckx et al. [415] was amended by Sjerps et al [225] to provide early warnings of drinking water contaminants. Sjerps et al. [225] focussed on the identification of emerging chemical drinking water contaminants, but did not include emerging pathogens in the search. Sjerps et al. [225] concluded that the high number of signals, with a high number of false positives, hampered the practical use of the text mining methodology.

By using a combination of the text mining methodologies developed in [156, 225, 415] the number of false positives can potentially be decreased. However, the methodology of Luijckx et al. [415], in contrast to the one developed in the context of this dissertation, is not freely accessible. Researchers willing to take up the task of further developing the text mining methodology presented in this dissertation, should contact the authors of [397] and request access to the methodology.

7.3.2.2 Relevance of the results to other research on designing monitoring campaigns

In this dissertation, literature mining was found to be informative in the design of monitoring campaigns for early warning purposes of emerging chemical and microbial drinking water risks. As the selection of contaminants was based on the potential risk they might pose to drinking water safety in the Netherlands, the process used in Hartmann et al. [176] can be considered an example of a risk-based monitoring approach as mentioned in the revised European *Drinking Water Directive (DWD)* (*Council Directive (EU) 2020/2184, revision of 98/83/EC)*.

Sjerps et al. [416] also presented a workflow for risk-based monitoring, with a focus on chemicals in groundwater as drinking water resource. This relates to the work presented in Hartmann et al. [176] (Chapter 4), with the difference that Hartmann et al. [176] focussed on surface water as drinking water resource and the sampling campaign was based on literature mining. The workflow developed by Sjerps et al. [416] was based on grouping groundwater resources based on data from target analyses and suspect screening. Chemicals identified with *target analyses* were prioritised, based on health-based guideline values as derived by the Dutch National Institute for Public Health and the Environment and, if unavailable, health-based guideline values based on the threshold of the toxicological concern approach. How health-based guideline values for drinking water are calculated based on the threshold of toxicological concern has been explained in detail by Mons et al. [164]. In *suspect screening*, signals need to be further identified as chemicals. The selection of signals to be identified as chemicals was based by Sjerps et al. [416] on whether occurrence concentrations were below effect concentrations derived from *in vitro* toxicity data.

The workflow for risk-based monitoring, developed by Sjerps et al. [416], is a valuable suggestion for a reproducible workflow for the risk-based monitoring of chemicals in drinking water and its resources. The literature mining methodology developed in Hartmann et al. [156] (Chapter 3) could be used to add additional potentially relevant chemicals to the target analysis part of the suggested workflow. The process of choosing contaminants could be based as described in Hartmann et al. [176] (Chapter 4).

Furthermore, the profilers from the QSAR toolbox that were used for the prioritisation of chemicals with potential genotoxic, reprotoxic, mutagenic and endocrine disruption properties in Hartmann et al. [51] (Chapter 5), could be added to the workflow of Sjerps et al. [416] as well. While these profilers do not provide a health-based guideline value, they could be used in parallel with the threshold of toxicological concern approach to identify chemicals that could adversely impact human health based on their molecular structure. Chemicals that would not be prioritised because of their presence in drinking water (resources) above the health-based guideline value based on the threshold of toxicological concern, should still be prioritised when the profilers indicate a toxicological alert for genotoxicity, reprotoxicity, mutagenicity and/or endocrine disruption.

As described by van den Berg et al. [169], the risk-based monitoring approach for microbial risks to drinking water applied by Dutch drinking water suppliers using surface water as a resource, is based on conducting a QMRA every four years. The QMRA is performed for the index pathogens as described in the Dutch Drinking Water Act (2015), namely (Entero)viruses, Cryptosporidium, Giardia and Campylobacter. These index pathogens should not be present in concentrations in drinking water that result in an infection risk which is equal to, or higher than, one in 10,000 people per year. The QMRA includes a system description, the identification of possible microbial hazards and hazardous events, and a monitoring requirement from source to treatment [169]. The literature mining methodology developed by Hartmann et al. [156] (Chapter 3) is a valuable addition to this system for the identification of yet unknown microbial hazards in drinking water.

7.3.2.3 Relevance of the results for other research on evidence-based prioritization of policy action on emerging contaminants

In this dissertation, a decision support tool was developed for the evidence-based prioritisation of emerging chemical and microbial contaminants that might be of risk to human health via drinking water [51].With the decision support tool, uncertain risk scores can be calculated that indicate the potential risk an emerging chemical or microbial contaminant poses to humans via Dutch drinking water. The literature review presented in Hartmann et al. showed that the decision support tool is an improvement on previously published prioritisation approaches for both chemical and microbial drinking water risks as it is the first to be suitable for emerging risks, combining uncertainty awareness with a multi-stakeholder approach and integrating the assessment of chemical and microbial risks into one approach [51]. Here, its relevance for prioritisation approaches for emerging risks that were not yet reviewed in Hartmann et al. [398] is discussed. These prioritisation approaches were not taken into account by Hartmann et al. [398] as they were either not yet published or did not specifically focus on emerging risks to drinking water.

Soeteman-Hernández et al. [417] published an approach for emerging chemical risks to workers, consumers and the environment. Although the approach was developed for emerging chemical risks, it is highly dependent on available experimental toxicity data. Soeteman-Hernández et al. [417] mention the lack of both exposure and toxicity data as the major drawback of the developed approach. The uncertainty-aware decision support tool developed in this dissertation might be useful for improving the suggested approach in this regard. Furthermore, Soeteman-Hernández et al. [417] only focus on risks from chemical contaminants, leaving out the potential risks posed by microbial contaminants. The decision support tool could be used by Soeteman-Hernández et al. [417] to broaden the applicability of their approach.

Cantoni et al. [418] proposed a probabilistic procedure to the risk assessment of chemicals in drinking water, instead of the deterministic approach applied in the regulatory context (see Section 1.4). While the use of probabilistic risk assessment procedures have been shown to be useful before to assess potential health risks in more detail (e.g. by Bokkers et al. [419]), their application to emerging risks is, however, questionable because of the limited availability of toxicity data for these types of contaminants.

Over the past years, several articles [60, 381, 420, 421] have been published on prioritisation approaches for persistent, mobile and toxic chemicals. The added value of [51] in this regard are the sigmoid curved value functions used, which give the model more distinctive power than discrete or linear functions would. Value functions were used to cover the degree of fulfilment of the persistence, mobile or toxicity criterion as a function of the associated indicator(s) (e.g. half-life in water for persistence) on a scale from 0 to 1. Another added value of Hartmann et al. [51] is the inclusion of indicators for toxicity next to the Cramer Classes of the Threshold of Toxicological Concern approach [24]. Because of the advantages of Hartmann et al. [51], a screening approach[24] for persistent, mobile and toxic chemicals is currently being developed based on Hartmann et al. [51].

Bergion et al. [422] developed a risk-based cost-benefit analysis for evaluating microbial risk mitigation for a drinking water supply. Risk mitigation measures were examined combining probabilistic risk assessment and cost-benefit analysis. While this is a valuable approach to the prioritisation of risk mitigation measures in a

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[24] For details see the presentation given during the third Workshop on PMT substances: Screening and prioritising PMT substances: development of a robust T-score (umweltbundesamt.de)

drinking water supply system, Bergion et al. [422] only focussed on risks from microbial drinking water contaminants. The way of estimating the potential impact on human health from exposure to emerging chemical and microbial drinking water contaminants as presented in [51]can be used to broaden the applicability of the decision support tool developed by Bergion et al. [422], for example, by also including chemical drinking water contaminants.

7.3.2.4 Relevance of the results for other research on effective risk communication strategies for emerging drinking water contaminants

In Chapter 6, a strategy was developed for the communication on emerging contaminants in drinking based on information needs identified among consumers. However, research has shown that the 'typical' consumer does not exist [423]. Different types of consumers might have different information needs. Although this is true, it is not feasible for public health institutes such as the Dutch National Institute for Public Health and the Environment (RIVM) to develop web texts for different types of consumers. These institutes often publish just one web text with information about the occurrence of a contaminant in drinking water.

In Hartmann et al. [126] (Chapter 2), the risk governance approach for emerging drinking water contaminants of the Minnesota Department of Health was analysed. This analysis was performed in 2017. Since then, the Minnesota Department of Health has added a Drinking Water Risk Communication Toolkit to its webpage.[25] The toolkit provides practical tools and guidance for drinking water suppliers and health professionals to support the communication about (emerging) drinking water risks. A few of the key principles for effective communication that are mentioned, are in line with the conclusions drawn from the research presented in this dissertation, namely to communicate early, often, fully and consistently. The information needs identified in Chapter 6, see Table 6-1, could be used to add more relevant information to the Risk Communication Toolkit.[26]

7.4 Avenues for future research

In this section, interesting avenues for future research are suggested based on the newly developed integrated approach [51, 126, 156, 176] (Chapters 2 to 6). As a reminder, the integrated approach refers here to a combination of the following:

- early identification of potential emerging chemical and microbial contaminants in drinking water resources using literature mining (Chapters 3 and 4);
- evidence-based prioritisation of policy action on emerging contaminants using the developed decision support tool (Chapter 5);
- risk communication strategies tailored towards information needs of consumers (Chapter 6).

Only the overarching strengths and limitations of the research are discussed, that is, those strengths and limitations that affect either the development or the effective use of the integrated approach. Some of the limitations have already been mentioned in

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[25] Drinking Water Risk Communication Toolkit (state.mn.us)

Section 7.3.1. Other more study specific strengths and limitations have been discussed in detail in Chapters 2 to 6.

Firstly, the analysis of current risk governance approaches as presented in Hartmann et al. [126] (Chapter 2) was based solely on cases of one emerging chemical drinking water contaminant (PFOA). The analysis was not repeated, or mirrored with an emerging microbial contaminant, or with other cases of emerging chemical and microbial contaminants. This raises the question as to whether the identified weaknesses concerning the analysed risk governance approaches were case specific. While the validation of the literature mining methodology was done for both microbial and chemical contaminants, in practice [176] as well as in retrospect [156], if an analysis of current risk governance approaches with the focus on another emerging drinking water contaminant had been conducted, this might have led to the identification of other weaknesses. However, based on the results of this dissertation, the more timely identification of emerging drinking water contaminants is expected to remain the main area for improvement, irrespective of the specific type of contaminant.

Repeating the analysis presented in Hartmann et al. [126] (Chapter 2) with other cases of emerging chemical and microbial drinking water contaminants is thus considered a valuable avenue for future research. Researchers willing to take up this task are also encouraged to use a different risk governance framework then the one proposed by the IRGC. Although the IRGC risk governance framework was proven to be suitable for the analysis of the risk governance of emerging chemical and microbial risks before [152, 153], it would be interesting to investigate whether using a different framework could shed light on other weaknesses. Clahsen et al. [424] present an overview of seven other frameworks that could be used for this purpose.

Secondly, the number of false positives extracted with the developed text mining methodology in Hartmann et al. [156] (Chapter 3) was high, which hampered the practical use of the methodology by drinking water suppliers, research institutes and/or national and regional regulators. Improving the pattern or developing other algorithms to identify first reports of contaminants in the aquatic environment from the longlist of publications extracted from the scientific literature (e.g. using Scopus®) is therefore recommended. The research of Luijckx et al. [415] and [225], discussed in section 7.3.2, could be useful in this regard. Improving the text mining methodology is a valuable avenue for future research as the efficacy of the integrated approach is highly dependent on the efficacy of the text mining methodology for picking up early signals of emerging drinking water contaminants.

Thirdly, while the developed text mining methodology enabled the identification of early signals of emerging chemical and microbial risks to drinking water safety in the scientific literature, its application could be extended. For instance, text mining could just as well be used to search media articles for these early signals. Using media articles for early warning purposes has been applied before by Soeteman-Hernández et al. [417]. The text mining methodology developed in Hartmann et al. [156] (Chapter 3) cannot be directly used for this purpose, but the principle of looking for the first report of a new aquatic contaminant could be used in the context of global newspaper articles as well. The search string[26] used in Hartmann et al. [156] (Chapter 3) could be used to set up search strategies in HowardsHome (https://www.howardshome.com/) and European Media Monitor (EEM, http://emm.newsbrief.eu/overview.html), following the example by Soeteman-Hernández et al. [417], but specifically focussing on early warning for emerging drinking water risks. Developing a text mining methodology for media articles would be a valuable avenue for future research to improve the identification process of emerging drinking water contaminants. Text mining of chemical registration dossiers for yet unknown aquatic contaminants would also be valuable in this regard.

Fourthly, the concern assessment in the IRGC framework [151] was not covered by the integrated approach. The concern assessment includes questions such as ‘what is the public’s risk perception?’ and ‘is there a possibility of political mobilisation or potential conflict?’. These questions were not addressed in the developed decision support tool, as it was developed solely with the input from drinking water experts, risk assessors and representatives of responsible authorities; for practical reasons, consumers were not included. The beliefs, knowledge and misconceptions of consumers regarding drinking water contaminants in general, has been addressed in Chapter 6. For a concern assessment, the consumer mental model, developed in Chapter 6, could be used as a starting point.

The desire to include public risk perception as a separate objective for prioritisation of a contaminant was mentioned by one of the actors during Workshop 2 discussed in Chapter 5, which would also tackle the missing concern assessment. The addition of consumer’s risk perception to the evidence-based prioritisation of chemical and microbial drinking water contaminants is considered to be a valuable avenue for future research. To this end, it is suggested that the methodology as described in Section 5.3 is repeated with a group of consumers to develop a new assessment hierarchy. The suggested approach would be to again follow the philosophy of value-focused thinking, as this would help to elucidate the values and objectives that consumers deem important in prioritising chemical and microbial contaminants. As mentioned above, the consumer mental model developed in Chapter 6 could be used as a starting point to elucidate these values and objectives.

Fifthly, the integrated approach included a decision support tool for the evidence-based prioritization of emerging drinking water contaminants. In this regard, an overarching valuable avenue for future research could be the development of a comparable decision support tool for a different exposure route, such as food. This is valuable as the benefits and challenges of the integrated assessment of emerging contaminants do not only apply to exposure to contaminants via drinking water. The benefits of the integrated assessment of chemical and microbial drinking water contaminants were mentioned in Section 1.1 and include: the identification of actions that are effective for several types of contaminants [50] and the prevention of actions where the elimination of risk posed by one contaminant is traded off against a higher risk posed by another [41], which allows the effective use of scarce public resources.

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[26] The search query can be found here: https://static-content.springer.com/esm/art%3A10.1186%2Fs13750-019-0177-z/MediaObjects/13750_2019_177_MOESM2_ESM.docx

Challenges are: inconclusive evidence on a contaminant’s hazard and exposure potential, differences in methods of risk evaluations and differences in the values and expertise of involved stakeholders. The need for a structured assessment of emerging chemical and microbial risks to food and feedstuffs was mentioned by the European Food Safety Authority (EFSA) [425], which set a special requirement for explicating uncertainty and increasing transparency, which can be achieved by using Decisi-o-rama and following the philosophy of value-focused thinking.

Finally, another valuable avenue for future research would be to amend the developed decision support tool (Chapter 5) so that it could be used to prioritise mitigation measures instead of contaminants. This could be accomplished by using a similar process to the one in Chapter 5. In that model, potential mitigation actions could be prioritised based on different criteria such as costs, human health impact and sustainability, taking into account the effects on both chemical and microbial drinking water risks. The recent study by Bergion et al. [422] could be used as an example in this regard (for further details, see Section 7.3.2). In this study, a tool was developed for the prioritisation of microbial risk mitigation measures for a drinking water supply.

7.5 Relevance for drinking water suppliers, policy makers and researchers

The relevance of this dissertation for the practice of drinking water suppliers, policy makers and research institutes is summarised in this section. First, all interested parties are invited to use the freely accessible literature mining methodology and decision support tool to design risk-based monitoring under the European Drinking Water Directive (DWD) (Council Directive (EU) 2020/2184, revision of 98/83/EC). To keep the number of potential emerging contaminants extracted from the scientific literature manageable, it is suggested that the methodology is run twice a year.

While the decision support tool is not suitable for calculating drinking water limits, using the philosophy of value focused thinking, the values and assumptions used by risk assessors were made explicit which could help bring forward the discussions around international differences in the risk assessment of emerging contaminants [324, 333].

For the purpose of effective early warning practices, it is suggested that policy makers, such as the Dutch Ministry of Infrastructure and Water Management, as well as research institutes, such as the National Institute for Public Health and the Environment and KWR Water Research Institute, drinking water companies, their laboratories and the umbrella organisation VEWIN and other stakeholders from the Dutch drinking water sector start a structural alert platform for early warning of chemical and microbial drinking water risks. The Dutch alert platforms for food safety and for the prevention of infectious diseases could be used as examples. A structural alert platform *integrating* microbial and chemical hazards would be innovative. The new structural alert platform for drinking water hazards could use the integrated approach developed in this dissertation to structure the identification, assessment and communication on emerging chemical and microbial drinking water risks, thereby allowing for more timely risk management options for the effective protection of human health.

What is important for the success of the structural alert platform is that adequate actions are defined and responsibility allocated to a specific party for each relevant signal; transparent assessment of each signal is also important. The documentation of the assessment of each signal is key so that the assessment can also be looked up later. Also, the clarification of roles and responsibilities is key, as these may not in all cases be clear for emerging contaminants (beyond the directly involved actors such as IenW, RIVM and drinking water companies). Furthermore, for such a structural alert platform's early warning function to be helpful, its relationship with other early warning and regulatory systems should be made explicit, be mutually enforced and grounded in working procedures.

For emerging chemical contaminants picked up by the structural alert platform in the Netherlands, the most important actors are drinking water suppliers and national water authorities. The signals that are picked up by text mining, and possibly also by using other information sources, may not yet be present in the monitoring data of Dutch drinking water resources. If the chemical contaminant identified is deemed potentially risky for the supply of safe drinking water in the Netherlands by the members of the alert platform, it should be included in the risk-based monitoring of Dutch drinking water resources (based on potential emission sources). Also relevant is the relationship of the structural alert platform to the guide for emerging chemical contaminants in surface water, which was recently published by the Dutch Ministry of Infrastructure and Water Management [426]. In this guide, a flow diagram is included of the steps that should be taken if an emerging chemical contaminant, or the ecotoxicological effects of that contaminant, are detected in Dutch surface water. The chemical contaminants that will be picked up by the structural alert platform and which will then be monitored in Dutch surface water can, after detection, be further assessed using the flow diagram in the mentioned guide. A final relevant early warning system in regards to the structural alert platform, is the relationship to the protocol for monitoring and review of drinking water resources for the WFD (2015). If signals are deemed relevant by the members of the structural alert platform, these can be included (where relevant) in the monitoring within this protocol.

For emerging microbial contaminants picked up by the structural alert platform, the most important relationship, just as it is for chemical contaminants, is with the risk-based monitoring done by drinking water suppliers and national water authorities. Furthermore, pathogens detected in drinking water and its resources should also be communicated to the structural alert platform for infectious diseases, which is held every Thursday and led by the National Institute for Public Health and the Environment in close collaboration with the Municipal Health Services. The frequency of the occurrence of the structural alert platform for infectious diseases was chosen to enable mitigation action to be taken in a timely manner to prevent the spread of emerging infectious diseases. These two public bodies are responsible for infectious disease preparedness and response and, along with the Centre for Infectious Disease Prevention and Control, should be informed of any adverse health effects.

The importance of a structural alert platform for the assessment of emerging drinking water risks is also made evident in the conclusions made by Wuijts [179]. In her dissertation, it was shown that the lack of interaction between knowledge domains was hindering the improvement of water quality. Wuijts [179] introduced governance conditions to overcome this obstacle, namely stakeholder engagement, balancing different interests and trade-offs, and decision-making. By starting a structural alert platform as introduced above, these governance conditions are partly met, as shown in Table 7.1. Following this added value of the integrated approach, the use of the integrated approach for the structural signalling of emerging risks in other policy domains is deemed interesting as well, e.g. for emerging risks to soil or food (see also Section 7.4).

Table 7-1 Governance condition to improve water quality based on Wuijts [179] and how a structural alert platform based on the integrated approach would assist in meeting the governance conditions.

Category of governance condition following Wuijts [179]	**Governance condition to improve water quality following Wuijts [179]**	**How a structural alert platform based on the integrated approach assists in meeting the governance condition**
Stakeholder engagement	Secure a balanced representation of stakeholders	All relevant stakeholders from Dutch drinking water sector are invited (e.g. water authorities, drinking water companies and research institutes), even representation from microbiology and chemistry.
	Look for a shared value between the stakeholders	The shared value is to protect our drinking water (sources), made explicit with the decision support tool.
	Realise administrative support	One of the members should have the administrative responsibility.
Balancing different interests and trade-offs	Facilitate joint fact finding	The developed decision support tool helps to structure the joint fact-finding process.
Decision-making	Organise and report on decision-making explicitly	Using the developed decision support tool facilitates transparent assessment of each signal. The definition of adequate actions with specific parties responsible for each relevant signal facilitates explicit reporting on decision-making process.

As the research presented in this dissertation was carried out in the context of the Dutch drinking water sector, these suggestions for policy and drinking water practice are rather specific to the Dutch context. However, the suggestion of an interdisciplinary alert platform for emerging chemical and microbial drinking water risks is relevant in other national settings as well. The added value of having a structural meeting between stakeholders from different disciplines and practical backgrounds, is relevant to guide effective risk management. If other countries are willing to use the integrated approach for this purpose, they are welcome to do so. However, the decision support tool uses quite specific treatment efficiencies for the

Dutch context, especially for the microbial contaminants. This should be checked and, if needed, adjusted to the national situation at stake.

7.6 Concluding remarks

This dissertation aimed to improve the integrated risk governance of emerging chemical and microbial drinking water contaminants. Based on a comparative analysis of current risk governance approaches, it is concluded that the main area for improvement is more timely identification of potential new drinking water risks from chemical and microbial aquatic contaminants. The results of this dissertation indicate that screening the scientific literature is valuable in this regard. Literature mining was found to be a valuable tool in the design of risk-based monitoring campaigns. This is shown by the sampling campaign, designed using literature mining in the context of this dissertation, in which four out of six contaminants were detected for the first time in surface water or wastewater in the Netherlands.

The results also indicate that prevailing difficulties in the evidence-based decision-making of emerging drinking water contaminants, namely the issues of data scarcity and varying risk assessment methods, can be tackled by using a value-focused approach and an uncertainty aware decision support tool. This dissertation thus illustrates that an integrated risk-based prioritisation of action on emerging chemical and microbial drinking water contaminants is possible, but it also raises the question of which (group of) stakeholders would be most suitable for taking up this task. At this moment, no structural alert platforms are in place in the Netherlands for early warning of chemical and microbial drinking water risks.

Furthermore, this dissertation shows that risk communication on emerging drinking water contaminants can be improved by tailoring communication strategies to consumers' information needs. Although the effectivity of tailored risk communication strategies was only assessed for one case of a chemical emerging contaminant, the results provided insight into the importance of concerns about contaminants, acceptance of norms and regulation and restrictions in water use, in regard to the efficacy of communication about drinking water safety. This is in sharp contrast to what is often thought by experts, who consider knowledge to be the major factor of influence.

Based on these conclusions, drinking water suppliers should consider combining literature mining with the risk-based prioritisation of contaminants when designing monitoring campaigns. All actors communicating to consumers about emerging contaminants in drinking water are invited to tailor their risk communication towards the information needs of consumers identified in this dissertation. Finally, the Dutch Ministries of Health, Welfare and Sport and Infrastructure and Water Management and the National Institute for Public Health and the Environment, and other stakeholders from the Dutch drinking water sector, should consider implementing a structural alert platform for the early warning of chemical and microbial drinking water risks. This structural alert platform could use the integrated approach to structure the identification, assessment and communication on emerging drinking water risks.

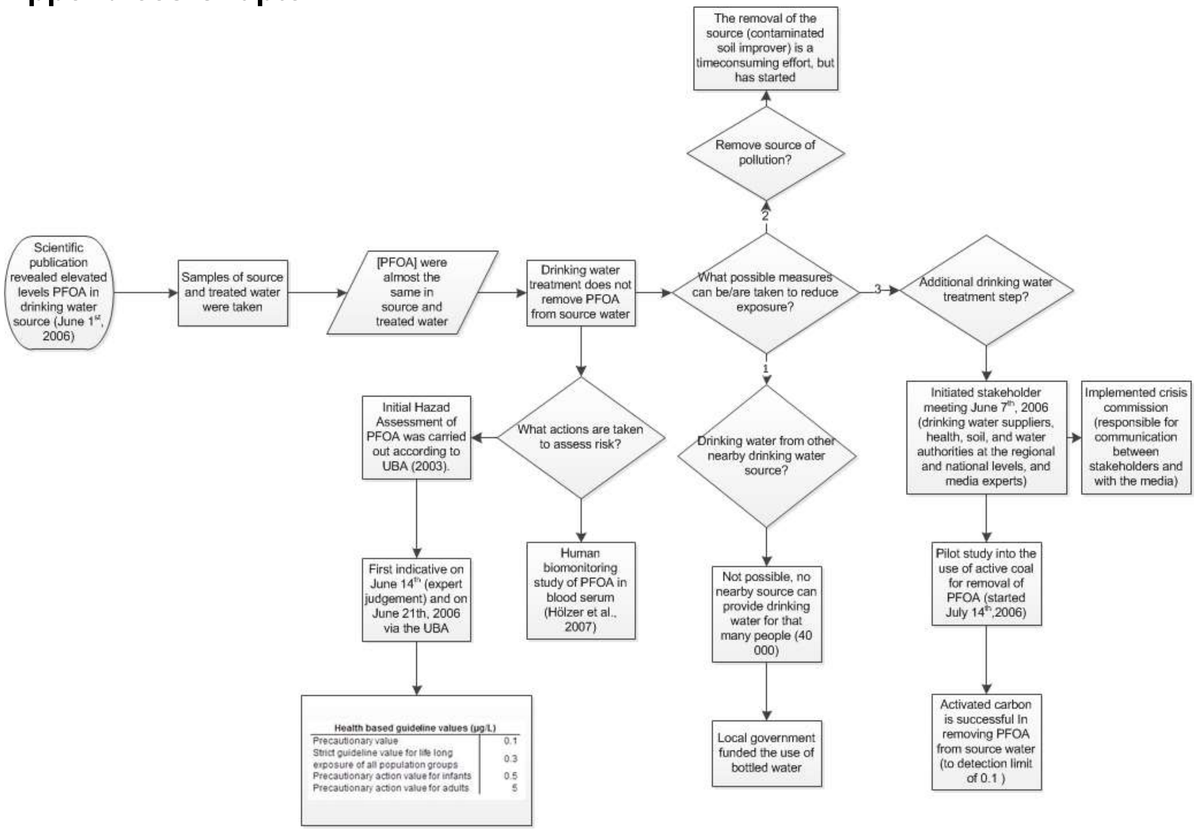
To better understand the implications of the presented results, further research focussed on analysing the risk governance approaches applied in other cases of chemical and microbial drinking water contaminants is suggested. Another valuable avenue for future research would be to extend the text mining methodology to other information sources, such as media articles, and to further improve the effectiveness of the text mining methodology for identifying early signals of emerging drinking water risks. The extension of the decision support tool to other exposure routes, such as food, or to prioritising mitigation measures instead of contaminants, is also deemed interesting. A final valuable avenue for future research was found to be the use of the presented value-focused thinking approach to develop a decision support tool for emerging drinking water contaminants that also takes into account consumer's concerns about a contaminant.

This dissertation has closed some of the knowledge gaps that have prevented the effective integrated risk governance of emerging drinking water contaminants. Firstly, the decision support tool for the evidence-based prioritisation of chemical and microbial drinking water contaminants enhances the limited research on integrated assessment strategies. Secondly, there are currently few methodologies for the proactive identification of potential new risks to drinking water safety, so it is hoped that the presented literature mining approach can make a significant contribution. By using literature mining to design sampling campaigns, sampling campaigns are more likely to include the most recently identified aquatic contaminant that might be relevant for drinking water. This breaks the vicious circle of 'no monitoring means no data, and no data means no regulations' [33]. Finally, the absence of scientific evidence on how to effectively communicate the (absence of) risk associated with emerging contaminants in drinking water is compensated for by the development of an effective communication strategy for emerging drinking water contaminants based on tailoring risk communication to information needs of consumers.

With the development of the integrated approach, this dissertation has thus overcome some of the key challenges of protecting human health from emerging environmental risks and has taken a first step towards developing more structured and proactive risk governance of emerging chemical and microbial drinking water contaminants.

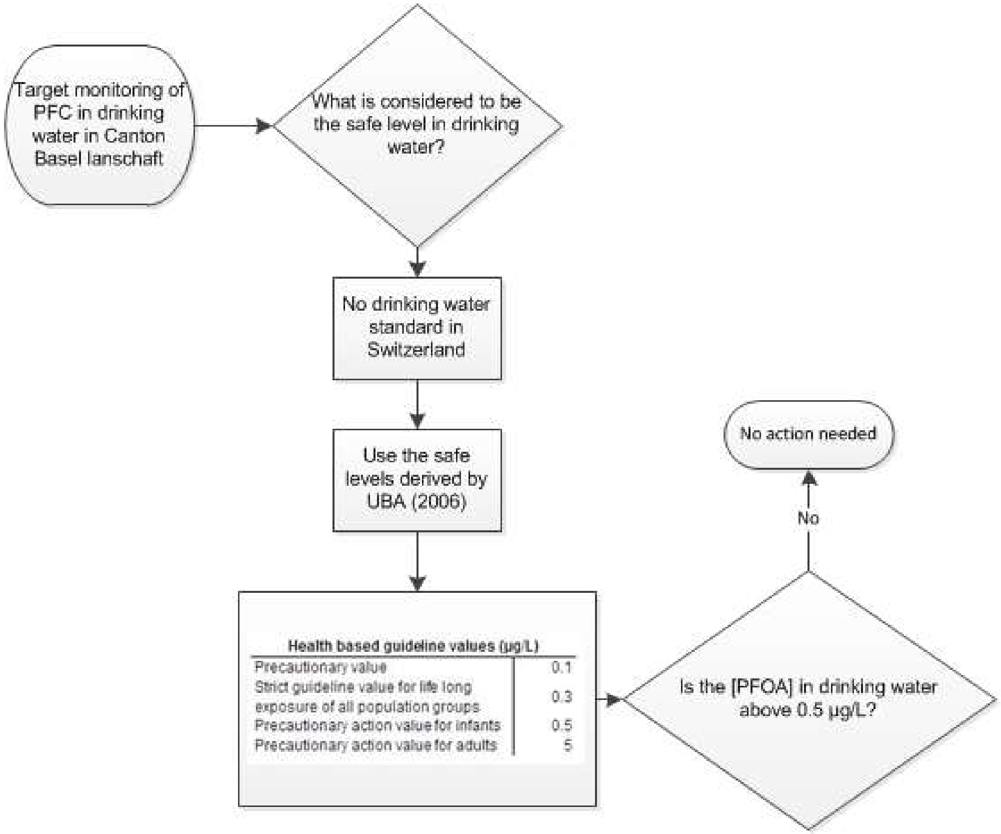
APPENDICES

Appendices Chapter 2



Health based guideline values (µg/L)	
Precautionary value	0.1
Strict guideline value for life long exposure of all population groups	0.3
Precautionary action value for infants	0.5
Precautionary action value for adults	5

Figure A-1 Overview of the risk management process in the German case analysed in Chapter 2 (based on Kleeschulte et al. [2])



Health based guideline values (µg/L)	
Precautionary value	0.1
Strict guideline value for life long exposure of all population groups	0.3
Precautionary action value for infants	0.5
Precautionary action value for adults	5

Figure A-2 Overview of the risk management process in the Swiss case analysed in Chapter 2 (based on Wiedemann [13] and Zwick and Ackerman [12])

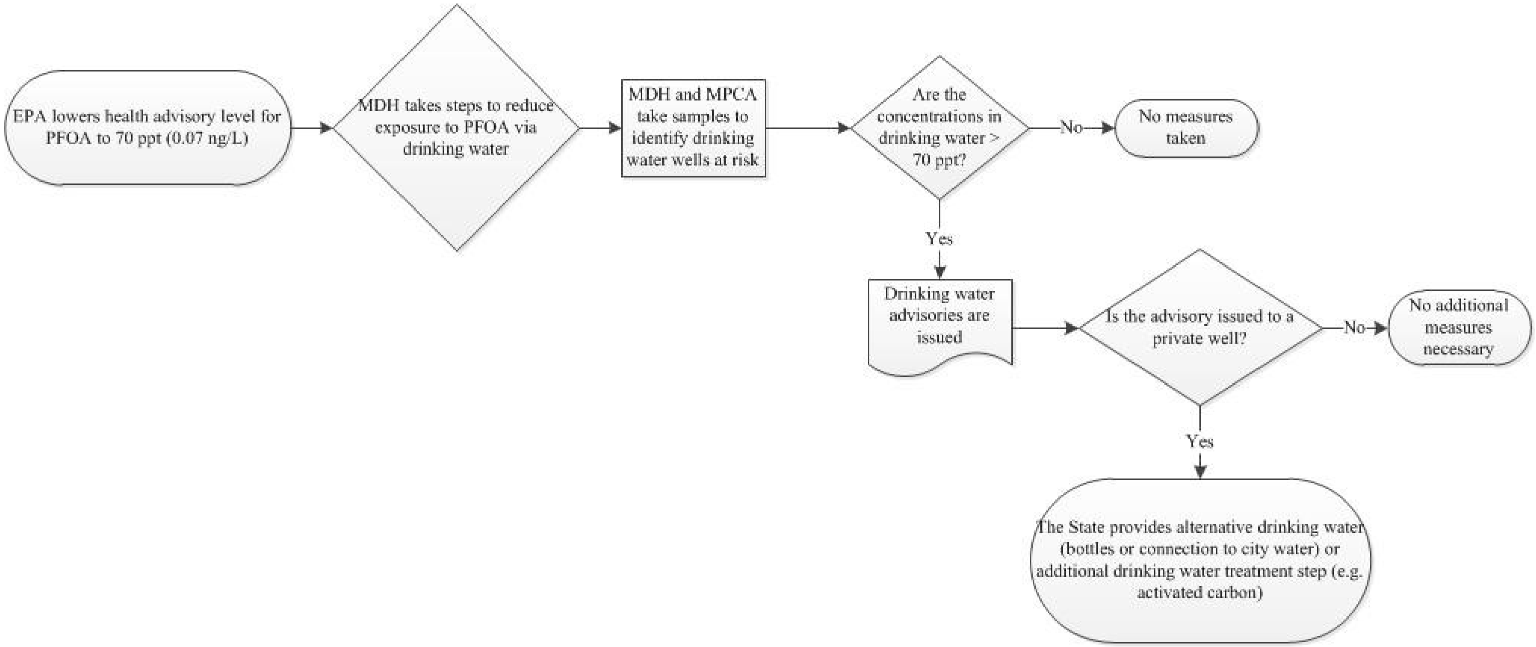


Figure A-3 Overview of the risk management process in the Minnesotan case analysed in Chapter 2 (based on information on MDH CEC website).

Appendices Chapter 4

Table A-1 Detailed information on reason for selection sampling locations for the analysis performed in Chapter 4.

Location code	**Reason for selection of sampling location**
C1L1	Location used by the national water authority as sampling location to monitor PFAS concentration in water upstream of the perfluorochemical company and the WWTP in Dordrecht (corresponding to location H05M in [427])
C1L2	Location used by the national water authority as sampling location to monitor PFAS concentration in water upstream of the perfluorochemical company and the WWTP in Dordrecht (corresponding to location H13M in [427])
C1L3	Location used by the national water authority as sampling location to monitor PFAS concentration in water upstream of the perfluorochemical company and the WWTP in Dordrecht (corresponding to location H12M in [427])
C1L4	Location used by the national water authority as sampling location to monitor PFAS concentration in water upstream of the perfluorochemical company and the WWTP in Dordrecht (corresponding to location H12LO in [427])
C1L5	Location used by drinking water company Evides to monitor potential influence of wastewater perfluorochemical company on drinking water production location Gat van de Kerksloot (personal communication May 10th 2019)
C1L6	Location used by the national water authority to monitor effect of wastewater discharges by perfluorochemical company and WWTP in Dordrecht on PFAS concentration in Nieuwe Maas River (corresponding to location H08RO in [427]
C1L7	Location used by the national water authority to monitor effect of wastewater discharges by perfluorochemical company and the WWTP in Dordrecht on PFAS concentration in Nieuwe Maas River (corresponding to location H18RO in [427])
C1L8	Location used by the national water authority to monitor effect of wastewater discharge by perfluorochemical company and the WWTP in Dordrecht on PFAS concentration in Nieuwe Merwede River (corresponding to location H20M in [427])
C1L9	Location used by the national water authority to monitor effect of wastewater discharge by perfluorochemical company and the WWTP in Dordrecht on PFAS concentration in Noord River (corresponding to location H07LO in [427])
C1L10	Location used by the national water authority to monitor effect of wastewater discharge by perfluorochemical company and the WWTP in Dordrecht on PFAS concentration in Noord River (corresponding to location H07RO in [427])
C1L11	Location used by the national water authority to monitor effect of wastewater discharge by perfluorochemical company and the WWTP in Dordrecht on PFAS concentration in Wantij River (corresponding to location H19M in [427])
C1L12	Location used by the national water authority to monitor effect of wastewater discharge by perfluorochemical company and the WWTP in Dordrecht on PFAS concentration in Oude Maas River (corresponding to location H06RO in [427])
C1L13	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company onsite (corresponding to location W13 in [427])
C1L14	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company onsite (corresponding to location W5 in [427])
C1L15	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company onsite (corresponding to location W6 in [427])

C1L16	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company onsite (corresponding to location W8 in [427])
C1L17	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company onsite (corresponding to location W14 in [427])
C1L18	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company onsite (corresponding to location W11 in [427])
C1L19	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company onsite (corresponding to location W9 in [427])
C1L20	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company onsite (corresponding to location W4 in [427])
C1L21	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company onsite (corresponding to location W15 in [427])
C1L22	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company onsite (corresponding to location W1 in [427])
C1L23	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company before it enters the WWTP in Dordrecht (corresponding to location G20 in [427])
C1L24	Location used by the national water authority to monitor PFAS concentration in wastewater perfluorochemical company before it enters the WWTP in Dordrecht (corresponding to location G20 in [427])
C1L25	Municipal wastewater influent WWTP in Dordrecht
C1L26	Effluent WWTP in Dordrecht (corresponding to location G01 in [427])
C1L27	Intake water used by the drinking water company (after riverbank filtration), sampling location chosen in consultation with drinking water company
C1L28	Drinking water before it enters the distribution network, sampling location chosen in consultation with drinking water company
C2L1	Sampling location chosen approximately 3km upstream of WWTP Maastricht-Limmel
C2L2	Sampling location chosen around WWTP Maastricht-Limmel
C2L3	Sampling location chosen around WWTP Maastricht-Limmel
C2L4	Sampling location chosen around WWTP Maastricht-Limmel
C2L5	Influent WWTP Maastricht-Limmel (wastewater is known to influence drinking water production downstream [428])
C2L6	Influent WWTP Maastricht-Limmel (wastewater is known to influence drinking water production downstream [428])
C2L7	Effluent WWTP Maastricht-Limmel (wastewater is known to influence drinking water production downstream [428])
C2L8	Effluent WWTP Maastricht-Limmel (wastewater is known to influence drinking water production downstream [428])
C2L9	Influent industrial WWTP that collects and treats wastewater from 150 chemical companies (discharging wastewater from this industrial WWTP is known to influence drinking water production downstream [149])
C2L10	Effluent industrial WWTP that collects and treats wastewater from 150 chemical companies (discharging wastewater from this industrial WWTP is known to influence drinking water production downstream [149])
C2L11	Intake water used by the drinking water company, sampling location chosen in consultation with drinking water company WML
C2L12	Drinking water sampled before it enters the distribution system, sampling location chosen in consultation with drinking water company WML

Appendices Chapter 5

Table A-2 Overview of stakeholders consulted during workshops 1 and 2.

Stakeholder #	**Profession at the time of the workshop(s)**	**Affiliation**	**Workshop(s) participated**	
			1 (n =25)	*2 (n = 36)*
1	Advisor drinking water	Dutch National Institute for Public Health and the Environment	X	X
2	Expert Process Technology	Drinking water company Vitens	X	X
3	Toxicologist	KWR Watercycle Research Institute	X	X
4	Advisor drinking water resource protection	Drinking water company Evides	X	X
5	Researcher	Dutch National Institute for Public Health and the Environment	X	X
6	Professor of Drinking Water Engineering & head of the Strategic Centre of Waternet	Delft University of Technology & Drinking water company Waternet	X	X
7	Water quality advisor	Rijkswaterstaat (national water authority)	X	
8	Specialist water quality	Aqualab Zuid	X	X
9	Manager chemistry department	Aqualab Zuid	X	
10	Senior consultant biology	Het Waterlaboratorium	X*	
11	Expert mathematical disease modelling & Professor of Epidemiology	Dutch National Institute for Public Health and the Environment & Utrecht University	X	
12	Senior advisor pharmaceuticals and the environment	Dutch National Institute for Public Health and the Environment	X*	X
13	Toxicologist	Drinking water company Waternet	X	
14	Head of the environmental department at the RIVM National Institute for Public Health & Professor 'Global changes and environmentally transmitted infectious diseases’	Dutch National Institute for Public Health and the Environment & Institute for Risk Assessment Sciences (Utrecht University)	X	
15	Advisor drinking water quality	Drinking water company Vitens	X	X
16	Hydrologist	Drinking water company Oasen	X	
17	Consultant chemical water quality	Het Waterlaboratorium	X	X
18	Director RIWA Rijn	Association of River Waterworks for the Rhine (RIWA Rijn)	X	X
19	Specialist Research and Development	Drinking water company Oasen	X	

20	Senior Risk Assessor	Dutch National Institute for Public Health and the Environment	X	X
21	Molecular biologist	Aqualab Zuid	X	
22	Professor of Environmental Ecology	University of Amsterdam	X	
23	Principal microbiologist	KWR Watercycle Research Institute	X*	X
24	Senior researcher and policy advisor on water quality, drinking water and the environment	Dutch National Institute for Public Health and the Environment	X	
25	Policy advisor	Ministry of Infrastructure and Watermanagement	X	X
26	Policy advisor	Association of River Waterworks for the Meuse (Riwa Maas)		X
27	Strategic advisor	Water board Limburg		X
28	Inspector discharge permits	Human Environment and Transport Inspectorate		X
29	Project manager	Dutch Board for the Authorisation of Plant Protection Products and Biocides		X
30	Senior inspector discharge permits	Human Environment and Transport Inspectorate		X
31	Water management	Province of Utrecht		X
32	Senior communications advisor	Drinking water company Dunea		X
33	Communications advisor	Drinking water company Evides		X
34	Manager Drinking Water Technology & Source Protection	Drinking water company Evides		X
35	Senior advisor drinking water quality	Drinking water company Vitens		X
36	Technologist drinking water	Drinking water company PWN		X
37	Senior consultant	Het Waterlaboratorium		X
38	Senior Consultant Process Engineering	RoyalHaskoning DHV		X
39	Senior advisor industrial wastewater discharge permits	Rijkswaterstaat (national water authority)		X
40	Junior advisor public affairs	Dutch National association of water companies		X
41	Senior advisor	Ministry of Infrastructure and Water management		X
42	Researcher microbial water quality	Dutch National Institute for Public Health and the Environment		X
43	Modeller & Professor by special appointment for Quantitative Microbiological Water Safety	Dutch National Institute for Public Health and the Environment & Utrecht University		X
44	QSAR/Read Across/Category approaches/Alternatives to animal experiments expert	Dutch National Institute for Public Health and the Environment		X

45	Head of department for Sustainability, Drinking water and Soil	Dutch National Institute for Public Health and the Environment		X
46	Researcher team drinking water	Dutch National Institute for Public Health and the Environment		X
47	Researcher release and exposure assessment of biocides and industrial chemicals.	Dutch National Institute for Public Health and the Environment		X

* = stakeholders were consulted individually prior or after the workshop.

Appendices Chapter 6

Texts and infographic used in the experiment

Three conditions were tested in the experiment:

- Condition 1: Existing website text
- Condition 2: Alternative website text
- Condition 3: Alternative website text and infographic.

Each condition started with basic information on Dutch drinking water. Below, we present the text both in Dutch and as a literal translation into English to avoid the introduction of language with a slightly different meaning. This could imply, however, that the use of the English language is somewhat 'rustic'.

Basic information

Dutch

Het drinkwater in Nederland is van goede kwaliteit. Wel is er reden tot zorg over de kwaliteit van de bronnen voor drinkwater; oppervlaktewater, grondwater of duinwater. In deze bronnen voor drinkwater kunnen resten van medicijnen, bestrijdingsmiddelen of chemische afvalstoffen van de industrie zitten. De drinkwaterbedrijven proberen bij de productie van drinkwater zoveel mogelijk van deze stoffen uit het water te halen door zuivering, maar met sommige stoffen lukt dat niet helemaal. Eén van die stoffen is GenX, dat gebruikt wordt om coatings voor bijvoorbeeld pannen te maken. Deze stof is in hele hoge doseringen mogelijk kankerverwekkend voor de mens.

English

The drinking water in the Netherlands is of high quality. There is however concern about the quality of the resources for drinking water production, such as surface water, groundwater and dune water, as traces of pharmaceuticals, pesticides and industrial chemicals have been identified in these drinking water resources. Drinking water companies try to remove these contaminants as much as possible during treatment, but some contaminants cannot be completely removed. One of these contaminants is GenX. This contaminant is used, for example, in non-stick coatings in frying pans. In high dosages, GenX is possibly carcinogenic to humans.

Existing website text

Dutch

[Published on https://www.rivm.nl/genx/drinkwater]

Uit onderzoek van het RIVM (Rijksinstituut voor Volksgezondheid en Milieu) blijkt dat GenX in drinkwater bij drie Nederlandse drinkwaterbedrijven verhoogd is, maar veilig. De concentratie GenX in drinkwater zal in de toekomst de richtwaarde nét niet overschrijden bij de hoeveelheid GenX die nu door bedrijven, conform de vergunning, wordt uitgestoten. Het RIVM heeft deze richtwaarde afgeleid op basis van de dagelijkse toelaatbare inname van de GenX stoffen bij levenslange inname via drinkwater.

Indicatieve richtwaarde

Het RIVM heeft in 2016 een indicatieve richtwaarde afgeleid voor GenX in drinkwater. Deze waarde ligt op 150 nanogram per liter water. Bij het bepalen van deze waarde heeft het RIVM gekeken naar de dagelijkse toelaatbare inname van de GenX stoffen bij levenslange inname via drinkwater. Er wordt hierbij ook rekening gehouden met inname via andere routes, zoals lucht. Bij een concentratie van 150 nanogram per liter drinkwater zijn er geen negatieve gevolgen voor de gezondheid te verwachten.

English

Research by the Dutch National Institute for Public Health and the Environment (RIVM) shows that levels of GenX in drinking water from three Dutch drinking water companies are elevated, but safe. In the future, the concentration of GenX in drinking water is expected to, only barely, not exceed the guideline value for the amount of GenX that is currently emitted by industries, in accordance with the permit. RIVM based the guideline value on the acceptable daily intake of GenX over a lifetime intake of drinking water.

Indicative guideline value

RIVM defined an indicative guideline value for GenX in drinking water in 2016. This value was 150 nanogram per litre of water. RIVM based the health-based guideline value on the acceptable daily intake of GenX over a lifetime intake of contaminated drinking water. Exposure to GenX via other exposure routes such as air was also taken into account. At a concentration of 150 nanograms per litre drinking water, no negative health effects are expected.

Alternative website text

Dutch

Het drinkwater van drie drinkwaterbedrijven in Zuid-Holland en Zeeland (Oasen, Evides en Dunea) bevat kleine hoeveelheden GenX. Deze stof is afkomstig van bedrijven die een vergunning hebben voor een beperkte uitstoot. De hoogst gemeten hoeveelheid GenX in het drinkwater is op dit moment 40 nanogram per liter (= 0,00000004 gram per liter). Dat is minder dan de veilige norm van 150 nanogram per liter die op basis van RIVM onderzoek is vastgesteld. Dit betekent dat ook bij levenslang dagelijks water drinken van deze drie bedrijven geen negatieve gevolgen voor de gezondheid door GenX te verwachten zijn.

English

The drinking water of three drinking water companies in the provinces Zuid-Holland and Zeeland (Oasen, Evides and Dunea) contains small quantities of GenX. This contaminant originates from industrial companies who have a permit for limited emission. At this moment, the highest concentration of GenX measured in drinking water is 40 nanograms per litre (= 0. 00000004 gram per litre). This is below the safe guideline value, which is based on RIVM research, of 150 nanograms per litre. This means that even over a lifetime intake of drinking water from the three mentioned drinking water companies, no negative health effects due to GenX are expected.

Infographic

Dutch

Kraanwater in Nederland is veilig en gezond: *hoe weten we dat?*

ER IS EEN VERONTREINIGING GEVONDEN. WAT NU?

1 **WAT IS DE BLOOTSTELLING**

Hoe worden mensen blootgesteld?

- Drinken
- Contact
- Inademen (bij douchen)

Wat is de mate van blootstelling?

- Aantal glazen
- Hoe lang blootgesteld
- Hoe vaak

2 **WAT ZIJN DE EFFECTEN VAN DE VERONTREINIGING?**

Heeft de verontreiniging schadelijke eigenschappen?

Wat weten we van de gezondheidseffecten?

...Bij onzekerheden in de data gebruiken we een veiligheidsmarge

Wat betekent dit op de korte en lange termijn voor mensen?

...Vooral aandacht voor kwetsbare mensen

Wanneer is drinkwater veilig en gezond?

- Bij dagelijks en levenslange inname of contact
- Ook bij andere blootstelling via lucht en voeding

VOORSTEL VOOR NORM
Op basis van inschatten risico

VASTSTELLEN NORM OP BASIS VAN:

- Voorstel voor norm
- Zorgen uit de maatschappij
- Maatschappelijke afwegingen
  - veilig & gezond
  - technisch & economisch haalbaar
- Beschermen van toekomstige generaties (zo laag mogelijke norm)

Voor meer informatie zie https://www.rivm.nl/drinkwater

English

Tap water in the Netherlands is safe and healthy: how do we know that?

CONTAMINATION IN DRINKING WATER. WHAT TO DO?

1

WHAT IS THE EXPOSURE?

How are people exposed?

What is the duration of exposure?

- No. of glasses
- Duration of exposure
- How often

2

WHAT ARE THE EFFECTS OF THE CONTAMINATION?

Does the contaminant have hazardous properties?

What do we know about the health effects?

...In case of uncertain data we use safety margins

What does it mean for people in the short and long term?

...Special attention for vulnerable people

When is tap water safe and healthy?

- Considering daily and lifetime exposure
- Considering other intake routes like air and food

PROPOSAL FOR LIMIT

Based on risk estimation

LIMIT IS SET BASED ON:

- Limit proposal
- Societal concerns
- Societal considerations:
  - safe & healthy
  - technical & economical feasibility
- Protecting future generations (setting the limt as low as possible)

For more information see https://www.rivm.nl/drinkwater

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Other professional publications

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Conference presentations

Poster presentation at the Young Water Professionals Conference, Ghent, 2017: Emerging chemical and microbial contaminants, in search for common ground (IWA Regional Young Water Professionals Conference Benelux - International Water Association (iwa-network.org))

Oral presentation at the Water & Health Conference, The Water Institute at UNC, 2017: Risk Governance of Emerging Contaminants in Drinking Water and its Resources

Oral presentation at SETAC, Helsinki, 2019: Early identification of both chemical and microbial contaminants in the aquatic environment using scientific literature text mining (number 172; https://orbit.dtu.dk/files/184207454/SETAC_Helsinki_Abstract_Book_2019.pdf)

Oral presentation at the third PMT Workshop " Getting control of PMT and vPvM substances under REACH", online, 2021: Screening and prioritising PMT substances: development of a robust T score (Screening and prioritising PMT substances: development of a robust T-score (umweltbundesamt.de))

DANKWOORD (IN DUTCH)

Dit is het dan. Het misschien wel meest gelezen hoofdstuk van dit proefschrift. Voor iedereen die aan dit hoofdstuk begint met de vraag ‘Is ze mij niet vergeten?’ en die vervolgens teleurgesteld gaat worden, bij deze: BEDANKT! Het is absoluut geen waardeoordeel als ik je vergeten ben, want er hebben zo ongelofelijk veel mensen een bijdrage geleverd. Dus mocht je gehoopt hebben op een kort dankwoord, ook dan moet ik je teleurstellen…

Allereerst wil ik mijn (co-)promotoren Susanne Wuijts, Ana Maria de Roda Husman en Jan Peter van der Hoek van harte bedanken. Zonder jullie was er nu geen proefschrift om te verdedigen. Bedankt voor jullie geduld, de tips, het delen van jullie kennis en netwerk en, niet te vergeten, jullie niet nalatende aanmoediging om het tot een goed einde te brengen. Susanne, elke 2 weken (en soms nog vaker) maakte je weer tijd voor me vrij. Je hebt me meer dan eens geholpen om knopen door te hakken en ‘om te denken’. Ik ben je daar dankbaar voor en hoop dat we ook in de toekomst nog geregeld een kopje koffie zullen drinken of een wandeling maken om bij te praten. Ana Maria, je hebt er alles aan gedaan om mij de wondere wereld van de microbiologie uit te leggen en deze wereld in dit proefschrift ook een plek te laten hebben naast de chemie, dank daarvoor. Jan Peter, met een achtergrond in de milieuchemie en toxicologie was de drinkwaterwereld nieuw voor mij. Bedankt voor het delen van je kennis over die drinkwaterwereld en het betrekken van mijn onderzoek bij de praktijk en bij de TU Delft.

Ook wil ik alle leden van mijn promotiecommissie bedanken voor het lezen van mijn proefschrift en het mogelijk maken van de verdediging. Prof. Farnleitner a special thanks to you for travelling all the way from Austria to Delft, it is highly appreciated.

Inge en Nina, jullie hebben mijn promotietraject van dichtbij meegemaakt. Nina, jij vanaf de eerste dag en Inge, jij niet alleen vanaf de zijlijn, maar je bent ook coauteur van één van de papers. Naast collega’s, zijn we ook vrienden geworden en wat is er mooier dan samenwerken met vrienden. Bedankt voor alles wat jullie de afgelopen jaren voor me hebben gedaan, voor de gezelligheid en natuurlijk voor het naast me staan tijdens mijn verdediging.

Dit onderzoek heb ik mogen doen als onderdeel van het Strategisch RIVM project PS-DRINK (S/121014). Theo, bedankt voor deze mogelijkheid. Ook het PS-DRINK projectteam wil ik heel hartelijk bedanken voor hun bijdrage. Verder zijn er in het kader van het PS-DRINK project verschillende workshops georganiseerd. Ik wil bij deze nogmaals alle deelnemers bedanken. Uw zicht op en kennis over opkomende risico’s voor de drinkwatervoorziening hebben geholpen om vorm te geven aan dit proefschrift.

Ik wil alle co-auteurs van de verschillende hoofdstukken bedanken voor hun belangrijke bijdrage aan dit proefschrift, met in het bijzonder: Lisa Scholten, bedankt voor alle ‘rational decision making’-lessen, ik heb genoten van onze gesprekken, zowel de inhoudelijke als de persoonlijke. Juan Carlos, thank you for helping me to implement our decision tree in Decisi-o-rama, without you, Chapter 5 would not have been such a success. Gretta, Paul, Sharona, Willemijn, Fabio, Harold en Hetty bedankt voor jullie hulp bij het analyseren van de watermonsters voor hoofdstuk 4. Ik wil hier ook nogmaals mijn dank uitspreken naar Soesila Ganeshi (RWS), Peter van As (RWS), Rosa Sjerps (Oasen), Gerdien de Kloe (Aqualab Zuid), Ralph Bröcheler (Waterschapsbedrijf Limburg), Pim Kruijen (Waterschapsbedrijf Limburg) en Peter van Diepenbeek (WML), zonder jullie was het onderzoek wat ten grondslag ligt aan hoofdstuk 4 niet mogelijk geweest. Liesbeth, bedankt dat ik onze paper over het verbeteren van de risicocommunicatie over opkomende stoffen in drinkwater mocht opnemen in dit proefschrift. Ik heb er met heel veel plezier met jou en Susanne aan gewerkt.

Geen coauteur, maar wel een heel belangrijke bijdrage aan dit boekje: Evelien, bedankt voor je creatieve hulp bij het opmaken van mijn proefschrift. Mariska, ook jij bedankt voor het ontwerpen van de uitnodiging.

Natuurlijk wil ik ook mijn (andere) RIVM collega's bedanken. Allereerst natuurlijk mijn (oud-) drinkwatercollega's, Monique, Harald, Robin, Sandra, Annemarieke, Mathijs, Ans en Jappe, bedankt voor alle tips, het meedenken en meeleven. Verder wil ik de volgende VSP en Z&O collega's speciaal bedanken voor het samenwerken en delen van hun kennis en ervaring: Els Smit, Eric Verbruggen, Emiel Rorije, Pim Wassenaar en Jack Schijven.

Irene, bedankt voor het vertrouwen in mij om jou te ondersteunen bij Equal-Life en voor je interesse in mijn promotietraject. Ik geniet van onze gesprekken en van het samenwerken met jou. Alle DMG-youngers, bedankt voor, helaas door corona met name de eerste jaren, de kopjes koffie, etentjes en borrels. Eva en Carlijn, bedankt voor jullie inzet tijdens jullie stages. Marieke, geen RIVM-collega maar een medepromovendus van de TUD, door de gesprekken met jou waren mijn bezoekjes aan de TUD altijd nog iets leuker, dank daarvoor! Tenslotte, voor alle andere RIVM collega's, van DMG en daarbuiten, bedankt voor jullie interesse in en hulp bij dit proefschrift.

Ook wil ik mijn dank uitspreken aan mijn (schoon)familie voor hun interesse in de voortgang van het onderzoek de afgelopen jaren. Lieve papa, helaas is ook dit weer een mijlpaal die zonder jou gevierd moet worden. Mijn liefde voor de bètavakken heb ik van jou en je hebt me altijd aangemoedigd om daar iets mee te doen. Bedankt voor alles.

Zonder vrienden was ik nergens. Lieve Agnes, Anna, Anneke, Bonnie, Camilla, Danne, Emma, Hannah, Jesminne, Kim, Lotte, Shayla en Tessa, bedankt voor de gezelligheid, de goede gesprekken en het lachen en dansen de afgelopen jaren. Jullie zijn toppers. Judith, onze wandelingen op de hei waren de laatste jaren een welkome afwisseling van het werken aan mijn proefschrift, dank daarvoor. Auke, we zijn al 100, of nee wacht, 20 jaar vriendinnen. Ik zou je vriendschap voor geen goud willen missen.

Tot slot, Remy, al bijna 14 jaar ben jij mijn rots in de branding. Dankjewel voor je humor, je rust, je steun, het meedenken en voor het afremmen, en dat niet alleen tijdens mijn promotie. Zonder jou en Howie had ik het niet gered. Daarbij hebben we natuurlijk aan het einde van mijn promotietraject ook nog het mooiste cadeautje ooit gekregen. Lieve Ole, bedankt dat je er bent. Ik hoop dat je net zo gelukkig gaat worden in je leven als dat ik ben met jou.

CURRICULUM VITAE

Julia Hartmann was born in Helmond, the Netherlands on August 5th, 1989. She completed her secondary education at Carolus Borromeus College in Helmond in 2007. In 2012, she completed her bachelor in interdisciplinary sciences with a major in chemistry at the University of Amsterdam. Julia holds a MSc degree with distinction in toxicology and environmental health from the University of Utrecht. She works as a researcher at the National Institute for Public Health and the Environment (RIVM) focussing on current and future threats to the quality of our drinking water sources, such as persistent, mobile and toxic chemicals.