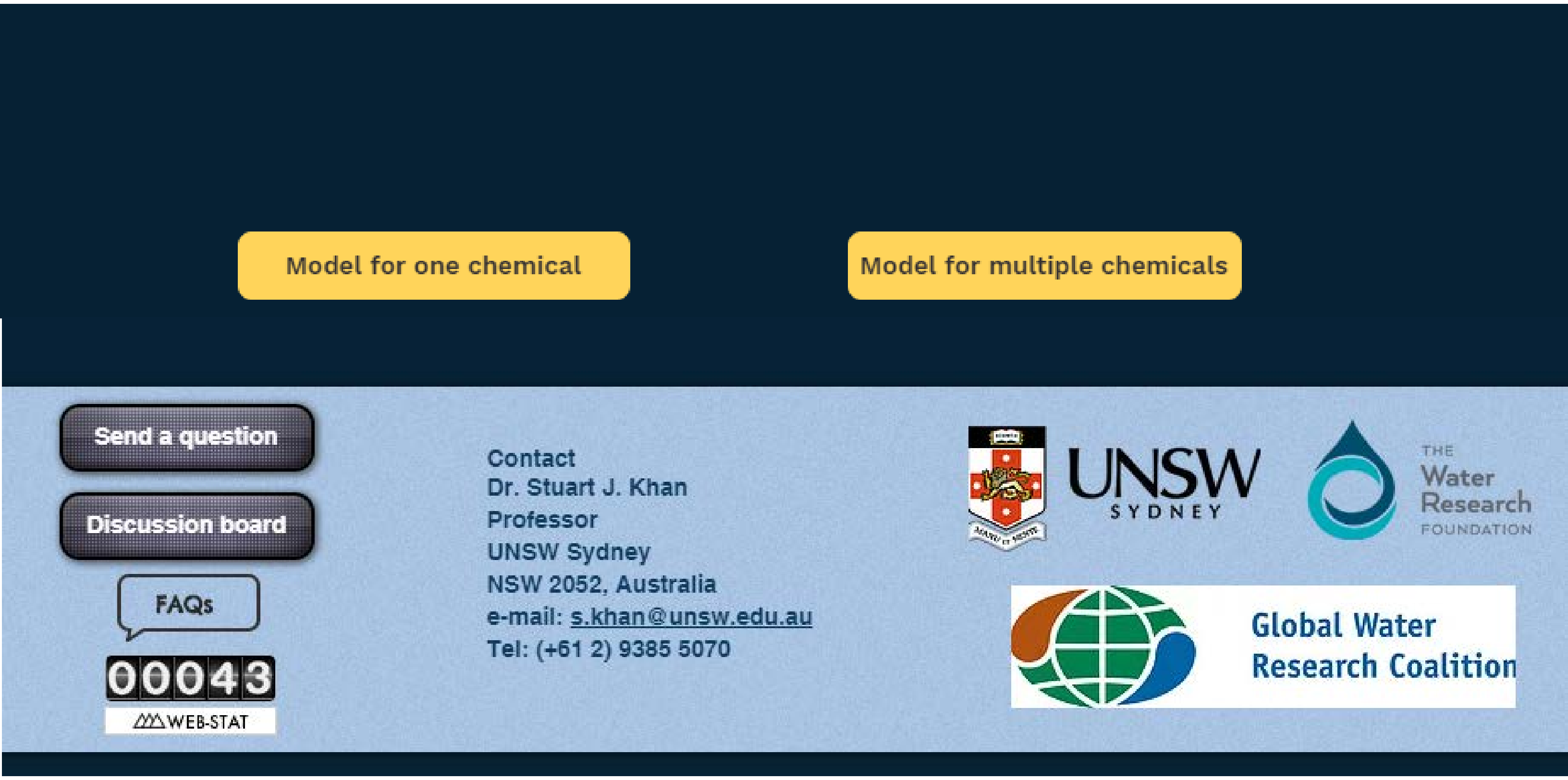

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Decision-Making Framework for the Prioritization of Research into Constituents of Concern

Decision-Making Framework for the Prioritization of Research into Constituents of Concern

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2019

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Global Water Research Coalition

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Abstract and Benefits

Abstract:

A framework was developed for the prioritization of further research on candidate trace chemical contaminants. This framework is available as a Bayesian Network running in freeware software (Netica). It is intended to be applied to organizations including water and wastewater utilities and others including water research providers and water research agencies.

Benefits:

- Demonstrates that application of a prioritization framework facilitates transparent decision making.
- Demonstrates that the framework enables a decision making problem to be clearly structured, thereby facilitating the necessary thought process.
- Demonstrates that the framework provides a clear record of the factors that were influential in the decision outcomes.
- Demonstrates that Decision making tool provides an opportunity for enhanced communication to stakeholders, including the community, regarding why particular chemicals have been priorities for further research effort and expenditure.

Keywords: Constituents of concern, multi-criteria decision analysis (MCDA), trace chemical contaminants, research prioritization, Bayesian networks.

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Acronyms and Abbreviations

ADWG	Australian drinking water guidelines
BCF	Bioconcentration Factor
CCL	Candidate contaminant list
CEC	Constituent of emerging concern
CMP	Chemical Management Plan
CPI	Combined prioritization indicator
DM	Decision maker
EQS	Environmental quality standards
HACCP	Hazard Analysis and Critical Control Points
Kow	Octanol-water partitioning coefficient
LOQ	Limit of quantitation
MCDA	Multi-criteria decision analysis
MFT	Microcontaminant Fate and Transport
NICNAS	National Industrial Chemicals Notification and Assessment Scheme
NORMAN	Network of reference laboratories, research centres and related organizations for monitoring of emerging environmental substances
PNEC	Predicted No Effect Concentration
REACH	Registration, Evaluation, and Authorization of Chemicals
SFPUC	San Francisco Public Utilities Commission
WHO	World Health Organization
WWTP	Wastewater treatment plant

Executive Summary

Due to their large number and diversity, large knowledge gaps persist regarding the significance of many constituents of emerging concern (CECs), which may occur in water and wastewater systems. Research is needed to gain understanding of the health and environmental effects of these CECs and how their harm can be minimized. However, with limited funding, decision-making criteria for how to prioritize which chemicals are researched are pivotal. While it is technically possible to remove most of these CECs at wastewater or drinking water treatment facilities, additional treatment may often be required to do so, which is often expensive and energy-intensive. Therefore, the long-term effects of CECs on health and the environment need to be assessed to identify if such advanced treatment is necessary. Many advanced treatment processes may introduce additional contaminants, such as those formed as by-products from some treatment processes. While the knowledge on effects are not yet fully understood, monitoring, advanced treatment or other reduction measures may be undertaken from a precautionary approach. In many cases, high levels of potential exposure may lead to concern regardless of known or shown effects. Either way, prioritization of research needs is required.

The work presented in this report was undertaken in order to develop a framework for the prioritization of research efforts. Research requirements could include efforts to improve the understanding of CEC occurrence (e.g., monitoring), ecotoxicity, public health risks, treatment process performance, or other aspects relating to the management of CECs in water and/or wastewater systems.

Prioritization among a large number of candidate chemicals is a subjective matter, dependent upon the roles, function, values and preferences of individual organizations. Nonetheless, work presented here has shown that a small number of key criteria can be applied to capture the most important considerations for many organizations. Having identified those criteria, it is then necessary for an organization to consider how important each of them is – in a relative sense – to the particular organization. If each candidate chemical can then be assessed against those criteria, it is possible to then rank each chemical in terms of a prioritization indicator. Following this process, the prioritization indicators for each chemical may be compared to derive a final prioritization list for the full suite of candidate chemicals.

The advantage of using a formalized multi-criteria decision analysis (MCDA) framework for this application is that it structures the decision making processes, thus providing transparency for each of the steps involved. This transparency can aid in the justification of which decisions were made (i.e., which chemicals were prioritized for research) to stakeholders and the community in general. The process also allows for revision and updating as priorities or circumstances change, or more information becomes available.

Two versions of a 'tool' were produced from this work, both based on the same Bayesian Network concept to run the MCDA process. The first Bayesian Network model was developed using software package Netica (v6.0 Norsys Software Corp). The model incorporates current methodology MCDA with additional capabilities to incorporate uncertainty in criteria scores and weightings, and hence in final combined prioritization indicators. A fully functional freeware copy of Netica is available to run this Bayesian Network (www.norsys.com/download.html). Files developed for use with Netica from this project are all available here:

https://www.dropbox.com/sh/c8tmk8cb2cnjf0y/AAAPhnMPVUbyAQBE1JlJvTLda?dl=0

In order to increase accessibility to this tool further, further steps were taken to produce a fully functional version as a website. The web-based tool can be accessed at: http://bncecs.tk/

It is proposed that the web-based tool is the most user friendly for most users. Key advantages include the lack of any need to download or develop familiarity with any software package. Furthermore, the process can be run almost entirely by downloading Excel spreadsheets and then re-uploading completed versions of those spreadsheets. The disadvantage of the online tool is that the internal processing is less transparent than it is with the Netica-based tool. However, the Netica-based tool also remains available for users who prefer the higher degree of transparency.

CHAPTER 1

Background and introduction

GWRC held a workshop on "Emerging Contaminants and Pathogens" in Karlsruhe, Germany on the 9th and 10th of June 2015. An objective of that workshop was to identify and highlight research needs regarding emerging water quality CECs (including chemicals and microbial organisms). While numerous specific issues were indeed identified, it was broadly acknowledged that the ability of water utilities to prioritize research needs is hindered by the lack of a clear framework for prioritization. Such a framework would assist utilities in identifying appropriate criteria for prioritization, techniques for 'weighting' of balancing those criteria, techniques for assessing options against the criteria and techniques for drawing conclusions on research prioritization. The development of such a framework was considered to have a number of potential advantages. These included:

- An improved basis for research priority decision making.
- Improved decision-making justification to stakeholders (including the community).
- Informed policy making.

CECs are substances, typically detected at concentrations ranging between 1 ng/L and 1 µgL (Pal, He et al. 2014), that researchers are beginning to suspect may cause harm. There are three main reasons driving interest in CECs and their transformation products: new synthesis of chemicals, changes in use of chemicals and improved detection technologies that can detect CECs at ever lower concentrations.

Due to their large number, in the order of thousands (Thomaidis, Asimakopoulos et al. 2012), and diversity, little is known about the health effects of many CECs. Research is needed to gain understanding of the health and environmental effects of these CECs and how their harm can be minimized. However, with limited funding, decision-making criteria for how to prioritize which chemicals are researched are pivotal. While it is theoretically possible to remove most of these CECs at wastewater or drinking water treatment facilities, additional treatment may often be required, which is often expensive and energy-intensive. Alternatively, other control measures may be implemented such as well-resourced and managed source control programs. While the knowledge on effects are not yet fully understood, monitoring, advanced treatment or other reduction measures may be undertaken from a precautionary approach. In many cases, high levels of potential exposure may lead to concern regardless of known or shown effects. Either way, prioritization of research needs is required.

CHAPTER 2

Online Stakeholder Survey

A stakeholder survey was developed as an initial means of gathering information regarding current practices and further industry needs. A full list of the original survey questions is presented in Appendix A.

The survey was constructed using an online survey tool (SurveyMonkey) and the online address was distributed by email. Distribution was targeted to a range of international individuals/organizations with known interests in water and wastewater management.

In all, 35 survey responses were received from a variety of industry bodies, research organizations, State Government departments and agencies, health regulators, drinking water utilities, local governments and private companies. Participants from Australia, Canada, EU, U.S., and Singapore participated in the survey.

As a consequence of the broad range of participants, an equally broad diversity of opinion was captured within the survey results, which are summarized below.

2.1 Existing Screening Processes for Constituents of Concern Based on Expected Environmental Fate

QUESTION: Does your organization apply a process for screening chemicals of concern based on expected environmental fate? If so, please describe the basic concepts and/or intrinsic parameters (Kow, water solubility, molecular charge, etc.) that are used.

A variety of processes, and intrinsic parameters were identified. These included processes based on external frameworks, and were generally dependent on the organizations legal requirements.

2.1.1 No Existing Process

40% of participants responded that their organizations are not applying a process for screening CECs based on expected environmental fate. Of those that identified a reason, most indicated that it was not within the scope of their organization to do so or that the processes applied was not “formalized” for this purpose. For example, organizations identified literature references or used standard risk management frameworks.

> *“We would not do such screening ourselves. If the threat were ranked sufficiently high to require further knowledge we would engage experts to do this assessment.”*
>
> *“Our current discharge licenses do not include this requirement.”*
>
> *“This level of review of CECs is outside our mission/scope.”*
>
> *“Not really a process, a risk assessment process is used to screen hazards.”*
>
> *“No formal process is in place; however, a variety of factors play a role. One important piece is analytical methods and the ability to capture a variety of chemicals with a subset of methods. Regulatory standards/guidelines that exist (for other medium) would first be evaluated, followed by evaluating Kow and H20 solubility etc., in order to see where the chemicals will partition in the environment/Wastewater Treatment plant.”*
>
> *“Literature references may be consulted, if required, but use of models to predict adherence to biosolids vs liquid phase e.g., STP or SimpleTreat are not used.”*

In addition, one organization identified that such a process does not exist currently, but there are plans to incorporate one based on international best practice.

> *"Plan to apply such a process based on parameters used by other agencies that represent international best practice."*

2.1.2 External Guidelines/Frameworks

Many respondents identified that their organizations rely on external guidelines or frameworks to manage CECs. It was mentioned that organizations would only test for chemicals if they were already prescribed in existing regulatory standards, for example in the Australian Drinking Water Guidelines (NHMRC & NRMMC 2011) and REACH regulations (European Commission 2006) in Europe.

> *"Regulatory standards/guidelines that exist (for other medium) would first be evaluated, followed by evaluating Kow and H20 solubility etc. in order to see where the chemicals will partition in the environment/Wastewater Treatment plant."*

> *"Currently we only test for chemicals that are included in drinking water or wastewater regulations/licenses. Targeted testing is undertaken when issues arise."*

> *"Currently the process is to screen and manage CECs according to the appropriate water quality guidelines (e.g., Australian Drinking Water Guidelines, (NHMRC & NRMMC 2011))."*

> *"Screen for chemicals as prescribed in the Australian Drinking Water Guidelines, not based on environmental fate, but rather impact upon consumption."*

> *"For Europe - this is a process which is conducted by the Chemicals Regulation Agency and controlled under REACH Regulations (European Commission 2006). Note this is primarily concerned with chemicals rather than biological contaminants."*

> *"HACCP principles and working with organizations upstream from ours that have direct impact."*

Various organizations identified specific existing prioritization methods that are utilized to manage CECs. These frameworks are specific to particular regions, for example NORMAN (Network of reference laboratories and related organizations for monitoring and bio-monitoring of emerging environmental substances) is utilized in Europe (Dulio and von der Ohe 2013).

> *"According to prioritization methods defined in the joint research programme of the Dutch water sector (BTO) in collaboration with [Our organization]."*

> *"Our organization relies on [Australian National Health and Medical Research Council] processes for reviewing national guidelines."*

> *"[Our organization] is member of the European NORMAN Association and is committed in the Working Group on Prioritization of Emerging Substances."*

2.1.3 Specific Chemical Characteristics

Some organizations apply a process of screening based on key chemical characteristics.

> *"We are using primarily Kow, water solubility, and other properties that would also indicate whether it would co-precipitate as a particle."*

> *"Though specific for groundwater replenishment where we use Kow, molecular charge, molecular size."*

> *"Our current research project on prioritization focusses on the log D (pH 8), whether there is significant proportion of cationic species (also at pH 8, relevant for cationic exchange and removal of contaminants by e.g., clay minerals in the subsurface), the molecular mass (small molecules*

tend to be more mobile than large molecules), and persistence (we use a combination of the Biowin 1-6 models embedded in the EPA EPI-Suite)."

Some rely upon expectations of environmental persistence, usually based on simple predictive measures:

"Relative environmental persistence (e.g., environmental half-life, persistence through wastewater treatment) are considered."

"The expected environmental fate for screening chemicals is a critical consideration including persistence."

"Our current research project on prioritization focusses on persistence (we use a combination of the Biowin 1-6 models embedded in the EPA EPI-Suite)."

"Whether or not the contaminant is metabolized in the environment, the persistence and toxicity/biological activity of the metabolites."

"The expected environmental fate for screening chemicals is a critical consideration including … degradation by-productions."

2.1.4 Technical Constraints

A key factor identified was that available technical information and analytical methods determined the screening processes utilized.

"The environmental fate of "new/existing contaminants with emerging concern" is assessed based on available technical information (compound characteristics etc.) and analytical protocol to detect the compound in various water matrices."

"Whether there are testing methods … are also considered."

"One important piece is analytical methods and the ability to capture a variety of chemicals with a subset of methods."

2.2 Existing Frameworks for CECs Research Prioritization

QUESTION: In addition to the answer provided in Question 4 [See Appendix A], are you aware of any existing frameworks for emerging contaminant research prioritization? If so, please provide details.

A range of existing frameworks and projects were identified globally. The format of these frameworks varied and included: utility, government and non-government organization publications, chemical lists, and formal prioritization frameworks. About 40% of participants identified that they were not aware of any existing frameworks for CECs research prioritization. Participants also made clear the importance of locally receiving input from experts in the field.

"Locally we receive input on plans from an Environmental Monitoring Committee that includes academics, representatives from health authority, environment, etc."

"Experts can provide assessments of known or likely properties of potential chemicals of concern."

One participant highlighted that it is not whether these frameworks exist that is the issue, but rather that the gaps in this area are related to providing guidance about appropriate usage of such frameworks.

"We are aware that there are expert approaches to assessing known impact levels and likelihoods as well as forecasting likely impacts. I think the gap is more on providing guidance when and how an organization might use these approaches once it has decided that it needs to do something.

And what it does and when it does it will depend on the way it assesses the above criteria in its threat management framework."

2.2.1 Formal Frameworks

The formal frameworks identified by the survey participants are outlined in Table 2-1.

Table 2-1. Prioritization Frameworks Identified by Survey Participants.

Framework	Region of Origin
Chemical Management Plan	Canada
REACH	Europe
NORMAN	Europe
San Francisco Public Utilities Commission Screening framework for prioritizing groups of CECs	USA
NICNAS Multi-tiered Assessment and Prioritization (IMAP)	Australia

"Chemical Management Plan in Canada is a formal prioritization framework. Similarly REACH in Europe. Locally we receive input on plans from an Environmental Monitoring Committee that includes academics, representatives from health authority, environment, etc."

Current Projects/Publications

One respondent outlined that they use publications from a range of sources (utility, government, NGO) as tools to guide the prioritization of chemicals based on toxicity and occurrence data.

"We also refer to utility, government and NGO publications that provide rankings or highlight certain contaminants of concern based on toxicity and occurrence data, for example the Water Research Foundation's "A Water Utility Primer on EDCs/PPCPs (Bruce 2015)", the WHO's "Pharmaceuticals in Drinking Water" (World Health Organization 2012) reports and "State of the Science on Endocrine Disrupting Chemicals - 2012" (World Health Organization 2012). We also refer to journal publications which prioritize contaminants based on toxicity and/or occurrence, e.g., Murray, Thomas et al. (2010)."

In addition to these existing publications, respondents outlined numerous projects that are underway or that have recently been completed, as outlined in Table 2-2.

Table 2-2. Relevant Completed and Current Research Projects.

Project Name	Organization/ Author	Details	Progress
Current and proposed paradigms to control constituents of emerging concern in the United States and internationally - WRF Project # 4494	Rauch-Williams, Snyder et al. (2016)	*"Refers to risk assessment / risk management approaches developed and used in Australia and Europe and contrast these approaches with those of the USA, for example. The risk assessment approaches cover a range of methods for estimating the potential for harm from chemicals"*	Published one discussion paper and held a web seminar in 2016 [Note: this project is now complete and the final report is published on the Water Research Foundation Website].
A comprehensive overview of EDCs and PPCPs in water- WRF Project #4387b	Bruce and Pleus (2015)	*"provided expert reviews and prioritization of likely endocrine disruptors of concern for drinking water. This covered the literature on these compounds and the ways of assessing their likely harm via the identified exposure route (drinking water)"*	Complete, 2015
A national approach to health risk assessment, risk communication and management of chemical hazards from recycled water	Chapman, Leusch et al. (2011)	*"Outlined an approach to assess the potential chemical hazards in recycled water"*	Published
R&D prioritization	Water Services Association of Australia	N/A	N/A
R&D prioritization	Water Research Australia	N/A	N/A
R&D prioritization	Global Centre for Environmental Remediation	N/A	N/A
N/A	Veolia Australia New Zealand, University of Melbourne and Coliban Water	Developing a chemical decision framework for CECs	N/A
Draft Framework	Het Waterlaboratorium, Haarlem, NL	N/A	N/A

N/A = No information was provided in survey.

Chemical Lists

Participants emphasized the importance of reviewing certain chemical lists, as listed below:

- Regulated drinking water contaminant list Safe Drinking Water Act (SDWA).
- Candidate Contaminant List (1, 2, 3, and 4) Safe Drinking Water Act (SDWA) (both chemical and micro).
- Toxic and Priority pollutants (Clean water act).
- European Commission Drinking Water Directive 98 WHO IPCS.
- The Contaminant Candidate List (CCL).

"The Contaminant Candidate List (CCL) is a list of contaminants that are currently not subject to any proposed or promulgated national primary drinking water regulations, but are known or anticipated to occur in public water systems. Contaminants listed on the CCL may require future regulation under the Safe Drinking Water Act (SDWA). EPA announced the Final CCL 4 on November 17, 2016."

"We refer to the Contaminant Candidate Lists and Unregulated Contaminant Monitoring Rule lists"

2.3 Current or Previous Research

QUESTION: Are you aware of any other current or previous research on the prioritization of emerging contaminant needs

The majority of respondents were not aware of any current or previous research on the prioritization of CEC needs.

Some were aware of research into CECs but not on research for a prioritization framework:

"We are aware of techniques for assessing the threat from various chemicals that are carried out by experts. Where we see the gap is in providing guidance on what criteria decision makers might use to prioritize the need to do anything at all and then how to get the knowledge that they need and communicate it."

However, some were aware of other research:

"Yes, there are several more recent frameworks that have been published since we produced our own and are therefore not listed above. However, we plan to consider them when we revise our program in 2018: (Caldwell, Mastrocco et al. 2014, Gaw and Brooks 2016, Helwig, Hunter et al. 2016, Naidu, Arias Espana et al. 2016, Naidu, Jit et al. 2016)."

"Kennedy Jenks (2015) undertook a Biosolids Risk Assessment where they undertook a prioritization study to narrow their focus for their Risk Analysis. BCRAM model is being developed by the U.S. EPA. A screening tool for different biosolids applicators. NWRI does research in this field. REACH in Europe as well as Chemical Management Plan in Canada undertake research on prioritization of emerging contaminant needs.

A Framework to Prioritize Trace Organics for Human and Eco-Toxicity Studies (Kumar 2017).

"KWR Watercycle Research Institute is constantly doing research on this subject."

"Yes. Mainly in the field of organic contaminants and microplastics."

"WRF had a study on CEC prioritization which we reviewed for the above SFPUC framework."

"Veolia were involved in the [Australian Water Recycling Centre of Excellence] "Robust Recycling" project, of which the development of screening criteria and a chemical decision framework were a major component."

Two respondents were aware of the current study being undertaken by GWRC and UNSW.

2.4 Suitable Methodology

QUESTION: Can you propose a suitable methodology (in general terms) that could be adopted for the prioritization of emerging contaminant research needs?

Various methodologies were suggested, most were a type of ranking system based on specified criteria relevant to the user.

> *"A 'scoring system' can be tabulated based on the ranking of criteria applicable to user-defined organizational needs."*
>
> *"Tiered approach that increases research needs based on..[criteria]."*
>
> *"Develop ranking system (est. 3-5 levels) for various categories to help with prioritization."*

Some participants identified that the style of existing methodologies (HACCP, NORMAN and *SFPUC*) could be used to approach CECs. It was identified that these existing models would need to be adapted from their existing form.

> *"We are of the belief that it should be possible to adopt a HACCP style approach to CECs, along the same lines as for pathogen management. Hence, LRV for specific chemical groups could be assigned on the basis of the chemical removal mechanisms for a given technology. The removal of said chemical could then be managed through HACCP risk registers, CCP plans and water quality management plans."*
>
> *"Can be developed in the same spirit of Norman framework but be more open to different water bodies and alternatives water schemes in a more larger scale as proposed in the first open survey (different water use) : the final idea would aim : which quality for which use (including all available water conventional + alternative uses)"*
>
> *"Refer to above [San Francisco Public Utilities Commission] framework, which SFPUC could provide. Basically, CECs have to be broken into groups (e.g., nanomaterials) because there are too many individual compounds. Then the groups are prioritized. A high priority group could be broken into further subgroups, perhaps some subgroups are low priority."*

The respondents identified criteria that could be appropriate for a prioritization system. "*Human health, environmental, and social impact*" as well as technical ability emerged as key themes that were important for the identification of priority chemicals. Three respondents identified that the criteria presented in part of the survey could be used and built upon in the development of a method, such as a decision tree.

> *"Questions listed in [this survey] could be used in the development of a decision tree."*
>
> *"Building particularly on the answer to [a question in this survey]."*
>
> *"Classifying issue against agreed criteria as per [question presented in this survey.]"*

Key criteria identified by respondents were: occurrence, toxicological relevance, public/consumer perception, current regulator state, exposure routes, current technologies, chemical properties, and current research. Further details are outlined in Table 2-3.

Table 2-3. Identified Prioritization Criteria.

Criteria	Details
Occurrence	"Is the contaminant present in detectable proportions?" "There has to be sound evidence first of their occurrence in the environment" "Scale against known/theoretical concentration/exposure in environment, in relation to dose response "
Toxicological Relevance	"Is the contaminant toxic at concentrations found (acutely? chronically?)" "There has to be sound evidence first of their … impact on ecology or Public Health." "Chronic/acute health and/or environmental risk categorization" "Acute vs chronic impacts" "Cumulative impact to downstream organizations/customers"
Public/Consumer Perception	"Is the contaminant of specific concern to the public?" "Recognizable by Public?" "Consumer concern"
Current regulatory state	"Is the contaminant regulated in other arenas of regulation (contaminated sites regulation, etc.)?" "international recognition of concern"
Exposure routes	"By what exposure routes can the hazard cause harm" "Is there a plausible exposure pathway that could cause harm in our system?" "If the exposure pathway is related to treatment process, are there any trade-offs that by acting to reduce harm from one risk, we increase the potential for harm from another risk (e.g., difficult to completely eliminate DBPs as disinfection is an essential process to manage microbial risk). "
Current technologies	"likelihood of rejection/removal through conventional treatments " "Availability of testing methods or analytical standards" "Remove any for which no testing methods or analytical standards are currently available"
Chemical properties	"Consider if the contaminant is metabolized" "The prioritization should be based on the chemical structure and chemical properties the contaminants"
Current Research	"Suitability/accuracy of research to date (gaps)" "Understand internationally what research is currently occurring and why to help with public expectation"

Two respondents outlined the importance of the "threat versus investment balance" as follows:

Need to consider "Time to undertake research vs benefits."

"At this point a review would take place to calculate the threat versus investment balance: Does this emerging hazard represent a sufficiently likely threat to our business or customers to warrant further investigation?"

One respondent emphasized that research should be focused on reducing uncertainty related to our ability to predict concentrations of CECs within the model parameters.

"From our side, we believe that scientific research should focus on reducing the uncertainty in the model parameters used to predict concentrations of emerging contaminants in rivers (Gimeno et al., 2017, under review in Water Research). Aimed to know where to focus research needs, we performed a sensitivity analysis on the model parameters to evaluate which one contributes the most to the overall uncertainty in predicted concentrations."

A few participants outlined a detailed summary of a suitable methodology and are outlined in the following flow charts.

Suggestion 1:

"Set priorities for each of the selected criteria and move through them in order (e.g., might consider contaminants that are/may be regulated first and always include them regardless of how they rank in terms of risk in the next step)."

↓

"Set threshold values for risk and select all contaminants above this thresholds. Then group related compounds and select only one or two of the highest risk as representatives for the groups."

↓

"Add on any 'special interest' contaminants, e.g., contaminants with most questions from customers, ones of interest to research collaborators, etc."

↓

"Remove any for which no testing methods or analytical standards are currently available"

↓

"Consider if the contaminant is metabolized and if the parent compound or metabolite or both should be examined by weighing relative occurrence and toxicity"

Suggestion 2:

"Start by leading a utility or organization through a series of questions/considerations that help the utility/organization think through what is of value/concern to them (e.g., protecting environmental health, protecting public health, understanding the impact of emerging contaminants whose impact is currently unknown, better understanding how to manage contaminants whose impact is known, etc.). "

↓

"Next, have a series of questions that can be used for each contaminant being considered that helps the utility/organization prioritize the contaminants based on these priorities/values (and other considerations). "

↓

"The prioritization could be done logically (e.g., through a flowchart that results in each contaminant being classed into either a high, medium, or low priority) or numerically (e.g., by assigning or calculating numerical values/weights) – the final method should be based on what is most useful to the target audience and should be relatively straightforward for the user. "

Suggestion 3:

"An initiation would involve an initial review: What is known about the hazard? Is it known to cause adverse outcomes? What is the level of confidence that it causes adverse outcomes? What are the proposed adverse outcomes? Are the proposed or known adverse outcomes acute or chronic? By what exposure routes can the hazard cause harm? At what levels of exposure can the hazard cause harm? Is there a plausible exposure pathway that could cause harm in our system? If the exposure pathway is related to treatment process, are there any trade-offs that by acting to reduce harm from one risk, we increase the potential for harm from another risk (eg difficult to completely eliminate DBPs as disinfection is an essential process to manage microbial risk). Are there known controls to reduce the levels of the hazard? Do we have those controls in our system and are they operating at a level that could reduce the hazard to safe levels?

"At this point a review would take place to calculate the threat versus investment balance: Does this emerging hazard represent a sufficiently likely threat to our business or customers to warrant further investigation?"

"If the answer is yes, then the next action would be to determine what action was required: Is an active watching brief of developments and an updated threat assessment at a future date sufficient? Is preliminary monitoring data in our system needed (on the assumption that sufficient is known that monitoring can be done to clarify the risk)? Are suitable methods available? If not, is research required to develop a method in an appropriate time frame?"

"The next section could be on 'how to do the research or investigations'. Where a number of organizations agree on the need for more knowledge it can be useful to collaborate, locally, nationally or internationally to leverage funding, obtain quality research and demonstrate the extent of concern ie, it's not just a local problem."

A few respondents outlined barriers to the implementation of such a framework. These barriers were related to the universal scope of the framework, and the constantly evolving suite of information available.

"We had trouble ourselves coming up with a universal and practical framework or methodology. Plus it's also difficult to stay current with all the global information that continues to come out that could revise the prioritization."

"It would take some research and time to create"

"This may have to be tailored to regulatory jurisdictional practices"

2.4.1 Miscellaneous

"If there is consensus that the biological test systems are suitable enough to detect significant potential of health impairment (I am no toxicologist so I don't know) I think we should focus more on the occurrence part of the risk assessment. There are still gaps in the mobility and persistence forecast. Furthermore, in silico screening of compound lists (containing structural information such as SMILES, etc.) for the applicability of technical strategies (ozonation, chlorination, etc.) should be encouraged. I know of an approach of the EAWAG, which is close to publication."

"In the case of pharmaceuticals, research should focus on describing better the human rate consumption and body excretion and the removal rate in WWTPs and rivers. We found that existing uncertainty in Microcontaminant Fate and Transport (MFT) models biases decision-making for the removal of microcontaminants towards the installation of tertiary treatments in WWTPs. We demonstrated that other interventions (secondary treatment upgrades) only become a suitable alternative when parameter uncertainties decrease."

"Results from High Throughput Screening, used in the drug-discovery process, could provide a meaningful initial screening tool. "

2.5 Importance of Developing a Prioritization Framework

QUESTION: How important or useful do you consider it will be to develop a broadly available framework for prioritization of emerging contaminant research needs?

The vast majority of respondents indicated that it was extremely important to develop a framework to prioritize research into CECs. Most highlighted the benefits it would bring in pooling research resources:

"Would help pool resources to focus on and prioritize the research."

"It would be very useful as a consensus would lead to the opportunity that enough people could come together to fill a common database with compound characteristics efficiently. Furthermore, the therein defined criteria could be used by authorities to harmonize national and international standards."

Some highlighted the benefits of an increase in transparency and better communication to stakeholders:

"An initial framework can serve as a guide for single organizations or multiple organizations working together to assess the need for research and communicate the process transparently of prioritizing research. This is useful for communication to all stakeholders. It can be useful for industry to engage with researchers and show how they are determining their priorities. It could also be useful to demonstrate to stakeholders why an emerging contaminant may be a high priority for some organizations but a low one for others (e.g., no known source of the contaminant in the area of operations)."

"Hopefully it would allow systematic ranking of existing classes of water contaminants and enhance transparency, and at the same time leveraging resources amongst different coalition members."

Others highlighted the significantly improved outcomes for public health from an improved research prioritization framework:

"The framework would be both useful and important. Research funds could then be directed towards areas where there is greater scope to deliver improved outcomes and benefit by addressing priority issues."

"Very important due to the limited resources dedicated to research, and typically the limited information available on emerging contaminants. On the utility side, there is a significant gap on the knowledge and understanding of the relative public health impacts of contaminants, and a framework that would provide some context or direction would be very critical for the prioritization of research."

One respondent expressed concern at ensuring the framework could be tailored to local conditions:

"A trustworthy (industry standard?) prioritization framework would be useful, in the very least to give our group ideas/direction on our current challenges for prioritizing contaminants of concern.

It would also help us prioritize academic research for funding and coordinate research being accomplished. However, it is important that the framework be able to be tailored to local conditions/constraints, yet specific enough in order to be useful."

2.6 Interest in Prioritization Framework

QUESTION: How interested do you think you (or other members of your organization) will be to use a prioritization framework that might be developed from this research project?

The vast majority of respondents expressed strong interest in using the framework:

"Very interested."

"Highly interested."

"I would be very interested to use it, as it would help us directed our resources to the most critical contaminants."

"Extremely. Would assist with preparedness to manage/monitor emerging contaminants and prioritization with current and future planning (budget (O&M and CAPEX), resource capability)."

"It would be useful for us and save us time. We could update our priorities annually if it existed."

Others expressed their interest with the caveat that they would likely adapt it to their existing frameworks:

"We would be interested to review the framework and where it makes sense adapt our process."

"I would be interested in reviewing and incorporating aspects of the framework for our use. Since we already have a framework in place, we would be interested in using this as a resource to build upon and improve our existing framework."

One respondent conveyed interest in the framework depending on how it compared with existing ones:

"It would depend on how it compared against the REACH Framework used in Europe. This is well established and supported."

The only respondents who did not express interest were utilities that did not conduct much research themselves:

"Small interest only as PWC does not do much research and rely more on gathering information from others."

"Our role in the industry is not primarily research. We would wait for direction from our regulatory bodies, by which time the majority of this research would have been completed."

2.7 Important Features for a Prioritization Framework

QUESTION: Describe any particular features of a research prioritization framework that would be important to you or your organization

2.7.1 Flexibility and Continued Improvement

Respondents indicated that the framework must be flexible and adaptable so that it can be suited to a variety of contexts and business systems and processes. It was also identified that the framework needs to be continually updated and improved, it was suggested this could be achieved through benchmarking procedures.

> *"That the framework is flexible – i.e., that it can be adapted, as needed, to reflect different priorities/values. For example, one utility or organization may place more value on researching contaminants where there are many unknowns about the contaminant and its effects, whereas other organizations may place more value on further understanding how to deal with emerging contaminants that have (or are suspected to have) certain health or environmental effects. These organizational priorities/values are affected by many external factors and may change over time"*

> *"It needs to be a dynamic and updatable framework. Who would have stewardship? It would need relevance to disparate parts of the world - production vs use; high population density vs low; developed vs developing etc."*

> *"A framework that has the flexibility to be adapted to a particular organization's business systems and processes."*

> *"Framework needs to be flexible to respond to immediate and urgent needs."*

> *"Applicable to tropical environments."*

> *"Responsiveness to emerging research needs."*

> *"Benchmarking - identifying gaps in our process. Improvements in confidence level of prioritization of research activities."*

> *"It needs to be continually updated."*

> *"Open: to allow users to add other considerations as necessary (e.g., directions from regulators or government) Show key issues to be considered when making decisions."*

2.7.2 Simplicity

Numerous respondents identified the process must be clear, user friendly and easy to use.

> *"Straightforward."*

> *"Would need to be simple."*

> *"User friendly."*

> *"Easily understood and user friendly framework."*

> *"Step-by-step process that is practical and easy to use."*

> *"It is important to be able to have clear methods of prioritization that are specific at least to chemical groups and/or effects (e.g., endocrine disrupting compounds)."*

2.7.3 Integration with Existing Research

A few respondents indicated that it would be very important for the framework to be able to leverage existing literature and research.

> *"Who is already addressing what; where the research gaps are; how sound the evidence of harm is (environment or Public Health); some rating of the research already in existence to show how reputable or robust it is."*

> *"Incorporation of the state-of-the-art knowledge to get a more realistic idea about the mobility of compounds! E.g., I noticed that many people seem to be kind of "married" to the log Kow without giving any attention to the molecular charge. Therefore, another important characteristic of an effective framework would be that its validity is checked every "x" years and that new results from the literature are acknowledged."*

> *"A systematic approach that is able to leverage the known body of peer-reviewed literature to its fullest extent".*

2.7.4 Widely Accepted

Two respondents identified that it would be of great importance for the framework to be adopted and accepted by a range of organizations and regulatory bodies.

> *"Accepted: A framework that is used by many organizations as a standard carries more weight."*

> *"Adoption of the framework by other reputable organizations and acceptability by regulatory bodies."*

CHAPTER 3

Current Practices

Although there is no international formal framework, the results of this study, and review of the literature reveal that there are formal frameworks in various geographical regions. 21% of survey participants revealed their organization uses a formal framework for prioritization and 32% responded that informal frameworks were utilized. Figure 3-1 shows current practice regarding prioritization frameworks for research into CECs.

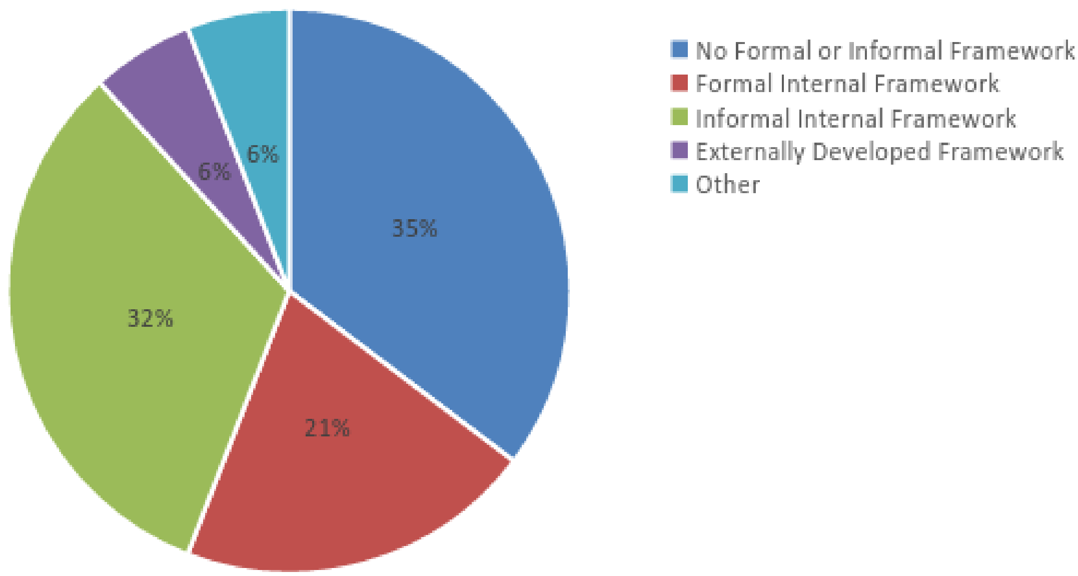


Figure 3-1. Current Practice Regarding Research Prioritization Frameworks.

Figure 3-2 shows the break-up of survey respondents by country and region (in the case of the EU).

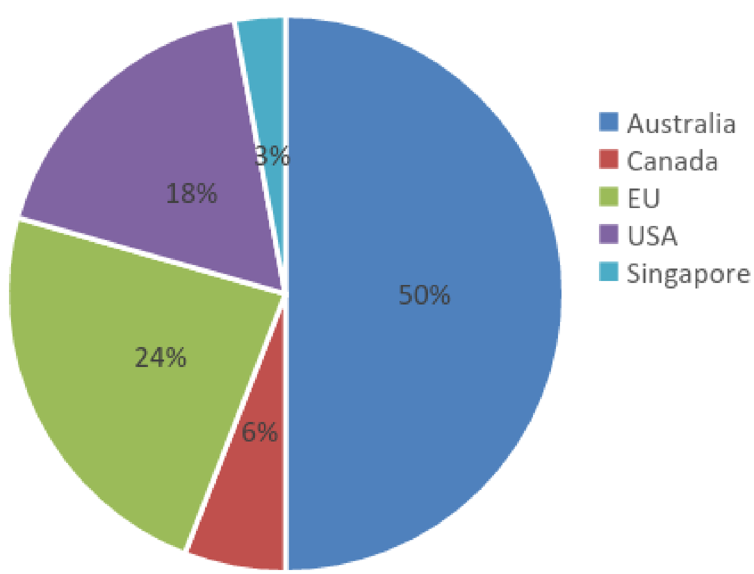


Figure 3-2. Break-Up of Survey Respondents by Country and/or Region.

The following sections outline the main frameworks currently used in the countries that responded to the survey.

3.1 Australia

Due to the abolition of the National Water Commission there has been a lack of a clear national framework for research throughout the water industry (Water Services Association of Australia 2016). The recent publication of the National Urban Water Research Strategy attempts to co-ordinate research at a national level however, it is not detailed enough to specifically address research into CECs.

3.1.1 Australian Drinking Water Guidelines (ADWG)

In Australia, utilities mainly rely on the Australian Drinking Water Guidelines (ADWG) which have been developed by the National Health and Medical Research Council (NHMRC & NRMMC 2011) and the Australian Guidelines for Water Recycling (NRMMC, EPHC & NHMRC 2008) to manage their water quality responsibilities. The ADWG undergo a rolling review process for new CECs to ensure they reflect the latest scientific understanding. Both the ADWG and the Australian Guidelines for Water Recycling use a hazard analysis and critical control point (HACCP) system which is also widely used in the food industry. In the Australian Guidelines for Water Recycling, the disease severity parameter, disability adjusted life year (DALY), is used for pathogens, but not for CECs (Rauch-Williams, Snyder et al. 2016).

3.1.2 Other Frameworks in Australia

On a smaller scale, local authorities will sometimes develop their own guidelines to cater for particular research needs. For example, the survey showed that a prioritization tool was developed for the Groundwater Replenishment Trial conducted by Western Australia Water Corporation. Other survey results showed that current practice involves targeted testing when issues arise.

3.2 European Union (EU)

A number of important initiatives have been developed in the EU, including REACH regulatory approach and the NORMAN prioritization methodology, as described in the following sections.

3.2.1 Registration, Evaluation, and Authorization of Chemicals (REACH):

The Registration, Evaluation, and Authorization of Chemicals (REACH) regulation was introduced in order to establish a scientific database of the hazards and risks posed by chemicals contained in the products in the European Union. It is mandated that companies input their own data for the substances contained in their products made in the EU and their imports (Eurpean Chemicals Agency 2017). The REACH framework is an improvement on the legislation that came before it as it has created a regulatory framework to ensure data is obtained on the chemicals that people in the EU are currently exposed to (Ruden and Hansson 2010). Secondly, for legislative reasons it is not required to procure data on substances produced or imported in quantities of < 1 metric tonne per year (Ruden and Hansson 2010). Furthermore, the requirement for information is connected to the status of the product and is reduced when, for example, a substance can be declared as intermediate. By not requiring data for these substances because of practical enforcement realities, the framework is limited in its comprehensiveness and thus its usefulness.

3.2.1 NORMAN Prioritization Methodology

NORMAN is a network of reference laboratories and related organizations for monitoring and bio-monitoring of emerging environmental substances and is an interface organization between science and policy in this field (Dulio and Slobodnik 2015). The NORMAN process (refer to Figure 3-3) uses the following steps:

1. An initial categorization of the substances into a defined number of action categories (categorization is determined by grouping compounds based on similar knowledge gaps).
2. A subsequent ranking of the substances within each action category.
3. A review process to validate the results of the overall prioritization exercise and allow constant upgrading of the overall process.

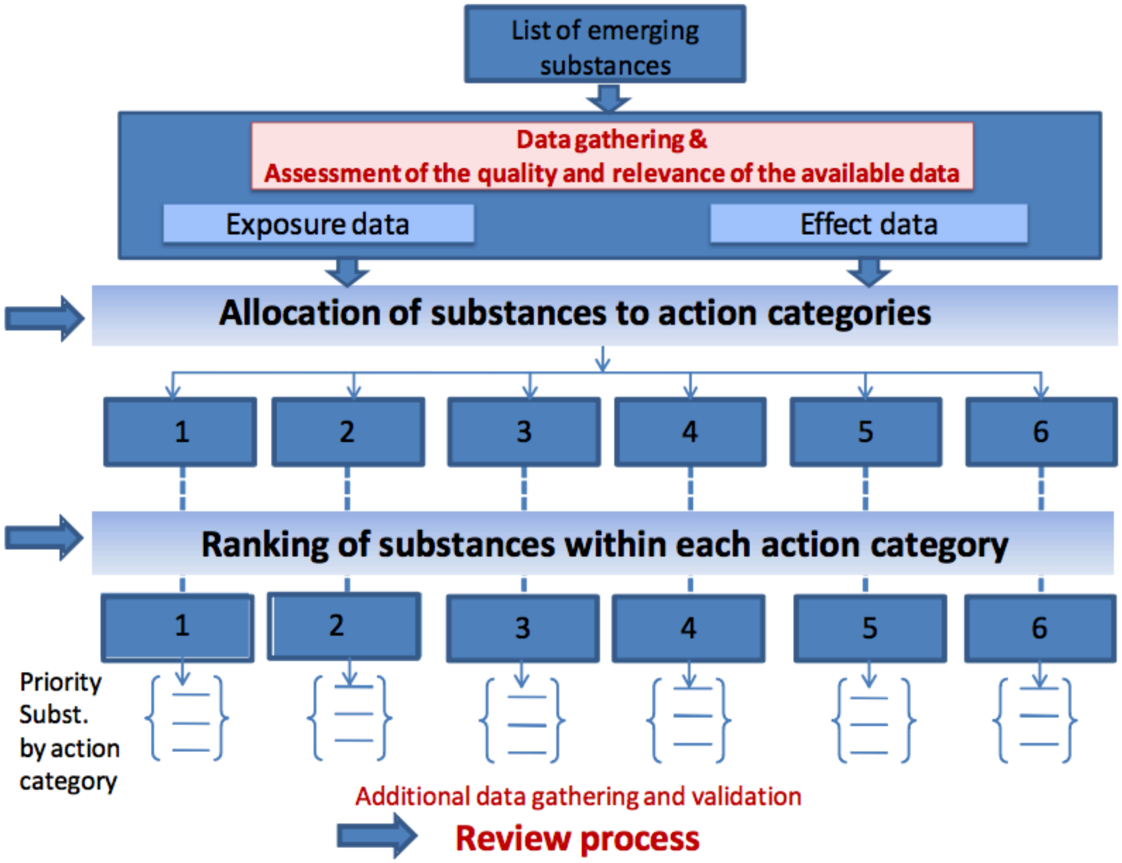


Figure 3-3. Flowchart of the NORMAN Methodology for Categorization and Ranking of CECs.
Dulio and von der Ohe 2013.

The main advantage of NORMAN is that it addresses the main difficulty in creating a research prioritization decision-making framework; that is the lack of information on hazard and risk properties of CECs. By assigning substances into "action categories" before ranking them it ensures that CECs are not excluded from research based on insufficient evidence of risk (Dulio and von der Ohe 2013).

Another advantage is the constant revision of the framework that ensures it always takes into consideration the latest information – this is a key point that was raised in the survey.

This technique is limited to simpler decision-making models as each additional criterion expands the tree exponentially. Another limitation is that the process of building a decision-making tree relies on certainty to get from specific decision nodes to specific outcomes. In a research field with many unknowns, due to data unavailability, this would be a disadvantage. Another disadvantage is that there is "restricted formalism" (Quinlan 1990) as each decision is limited to a straightforward division based on a single attribute.

The prioritization applied in the NORMAN methodology is primarily focused on ecotoxicity endpoints with effects assessed primarily by no observed effect concentrations (NOECs).

3.3 United States of America (U.S.)

There are many diverse approaches to contaminant research prioritization in the U.S. and these vary significantly among states and individual agencies. An example of one approach, developed by the San Francisco Public Utilities Commission (SFPUC) is presented in the section.

3.3.1 Screening and Recommended Actions for CECs – San Francisco Public Utilities Commission

The San Francisco Public Utilities Commission (SFPUC) Water Quality Division (WQD) developed a framework for grouping, screening, and prioritizing unregulated CECs. For high priority contaminants, recommendations and further actions could be developed and followed. An example of such an action could include water quality monitoring.

The approach is intended to (San Francisco Public Utilities Commission 2013):

1. Help the SFPUC manage contaminants that are not being covered by existing regulations.
2. Help prioritize limited resources on CECs of concern to SFPUC.
3. Provide a framework for involving the Commission, stakeholders and the public in CEC decisions.

The framework is outlined in Figure 3-4. Due to the high quantity of CECs and lack of specific water quality information, the framework utilizes grouping and indicators. It is qualitative when compared to frameworks for regulated contaminants that have quantitative water quality criteria. The results of this prioritization methodology are a rating of low, medium or high priority (San Francisco Public Utilities Commission 2013).

Prioritization is based on (San Francisco Public Utilities Commission 2013):

- Health risks;
- Occurrence in source and treated waters, and
- Expected removal during treatment.

To evaluate the prioritization of CECs for the SFPUC drinking water system, the framework includes the use of screening, expert and stakeholder reviews and public consultation. This information comes from: research papers, government agencies, professional associations and research foundations, and SFPUC studies (San Francisco Public Utilities Commission 2013).

Due to expected increased knowledge in the area of CECs, periodic updates of the 2013 CEC Report were planned and executed, as per the 2016 Update (San Francisco Public Utilities Commission 2016).

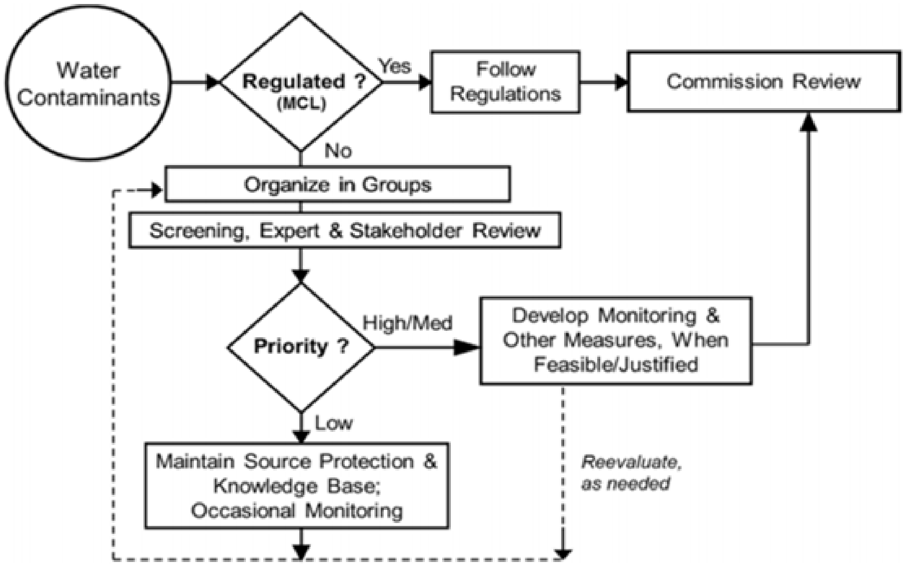


Figure 3-4. Flowchart of SFPUC CEC Approach for Drinking Water.

3.4 Canada

Canada's formal prioritization framework is the Chemical Management Plan (CMP) that was created by the Government of Canada in 2006. The CMP "*assesses environmental and human health risks posed by chemical substances, and develops and implements measures to prevent or manage those risks*" (Government of Canada 2016). It makes these assessments by utilising management tools from a range of federal laws, consisting of but not limited to:

- Canadian Environmental Protection Act, 1999.
- Canada Consumer Product Safety Act.
- Food and Drugs Act.
- Pest Control Products Act.

The main components of the CMP are outlined in Figure 3-5.

- Risk assessment.
- Risk management.
- Compliance and enforcement.
- Research and monitoring.
- Stakeholder engagement and outreach.

Figure 3-5. The CMP Cycle.

The ongoing prioritization process uses a set of guiding principles and considerations, not prescribed criteria. The types of considerations that guide the decision to select a substance as a priority for assessment are outlined in Table 3-1.

The process utilises a variety of information sources and expert judgment to support the identification of urgent concerns and prioritizes substances requiring additional consideration.

Table 3-1. Considerations in the CMP Prioritization Process.

Guiding Principles

- Information is relevant and scientifically reliable.
- Prioritization is risk-based – greater priority is assigned to substances for which there is new information suggesting a potential concern for both exposure and hazard.
- Higher weight may be given when new information comes from multiple sources.
- Information is reviewed in the context of other domestic and international assessment or information-gathering activities that could provide an opportunity for efficiencies, collaboration and/or alignment.
- Information is reviewed in the context of the assessment and management activities of other federal, provincial and territorial programs to determine the most appropriate course of action under CEPA 1999.
- Information is reviewed in the context of past assessment conclusions.
- Information is reviewed in the context of existing risk management, as well as risk management actions that are under development.
- Information is reviewed in the context of existing Chemicals Management Plan commitments; allocation of resources toward additional priorities is done in consideration of existing commitments and other program priorities.

Considerations

- Are there critical data gaps? Does the program have the right tools and information to conduct an assessment, or is other activity required first?
- Under what acts or regulations could the issue be addressed?
- How do the potential risks compare with the risks associated with substances for which there are existing commitments?
- Does the substance fit within the scope of a current risk assessment group?
- Does the recently acquired information refute a key assumption in a past decision or recommendation?
- Does the acquired information result in a markedly different interpretation of the health hazard potential (for example, classification by a competent authority for a previously unrecognized hazard, data indicating a greater toxicological potency)?
- Does the new information suggest a greater ecological hazard (in other words, higher inherent toxicity, persistence and/or bioaccumulation potential)?
- Does the new information suggest a new source of exposure, or an increasing trend in exposure to humans or to the environment in Canada?
- How widespread is the exposure likely to be? (For example, is the substance produced/imported in high volumes domestically or abroad, are there known uses suggestive of direct exposure to the general population or high releases to the environment?)
- Does the new information suggest that a relevant regulatory limit (or an interpretative guideline) is being exceeded – either for environmental monitoring or bio-monitoring results?

3.5 Existing Research Prioritization Frameworks in Industrial Chemistry

The Australian Department of Health uses a research prioritization framework as part of The National Industrial Chemicals Notification and Assessment Scheme (NICNAS). The scheme's aim is to assess the human health and environmental impacts of previously unassessed chemicals listed on the Australian Inventory of Chemical Substances (AICS). AICS is a database of chemicals available for industrial use in Australia. Their prioritization framework, termed the Inventory Multi-tiered Assessment and Prioritization (IMAP), uses a tiered risk-based model to screen chemicals against risk-based criteria. This framework ensures that there is a rapid assessment of existing chemicals of concern, however the scheme uses hazard data that that is not readily available for CECs and because of this, CECs would not be given prioritization for research if a similar scheme was used for their prioritization.

CHAPTER 4

Decision Analysis

Decision analysis is the science and art of designing or choosing the best alternatives based on the goals and preferences of the decision maker (Zarghami and Szidarovszky 2011). Making a decision implies that there are alternative choices to be considered. In such cases, the objective is not to identify only as many of these alternatives as possible but to choose the one that best fits the decision-makers goals, desires, values, and so on. The field of decision analysis, as a formal science, has developed throughout the twentieth century, with a number of key schools of thought. Some of the most prominent are described below.

4.1 Decision-Tree Analysis

Decision-tree analysis is used in many decision-making processes from artificial intelligence to medicine (Quinlan 1990). It involves a number of pathways - each of which leads to a different outcome based on a series of sequential decisions. This technique is most useful in clearly setting out how decisions lead to specific outcomes, especially in a way to ensure that all alternative decisions and their consequences can be easily evaluated (Linkov, Sahay, et al. 2005).

Decision trees provide a graphical method for performing a decision analysis. They are useful when the number of courses of action is not large and the number of possible states of nature is not large. An example of a decision tree is presented in Figure 4-1. In this case, a decision maker is concerned with the selection of a course of action between “bring and umbrella” or “leave umbrella at home”. The utility of decision (i.e., whether the decision maker will get wet) is partially dependent upon the likelihood if rainy weather. If values can be ascribed to the outcomes of getting wet or staying dry (with or without an umbrella), such a decision tree may be numerically solved accounting for probabilities among the states of nature. This type of decision tree is most commonly used when it is possible to describe such values in monetary terms.

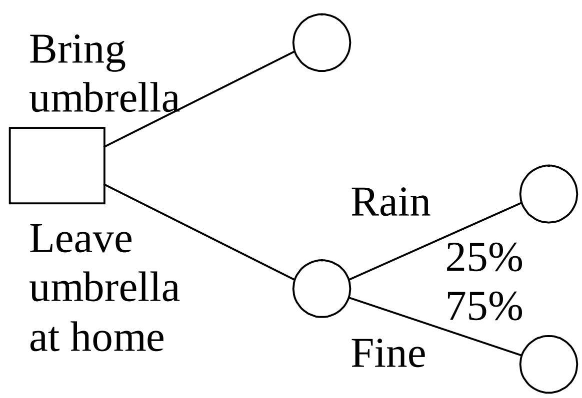


Figure 4-1. Example of a Decision Tree, Courses of Action, and States of Nature.

4.2 Risk-Based Analysis

Many research prioritization schemes currently use risk-based assessment such as that used by the European Water Framework Directive (WFD).

A risk-based methodology, as can be seen in Figure 4-2, has been applied in Europe to develop legally binding thresholds referred to as environmental quality standards (EQS) for specific pollutants as part of the European Water Framework Directive. An EQS is defined as "*the concentration of a particular pollutant or group of pollutants in water, sediment, or biota that should not be exceeded in order to protect human health and the environment.*" (Daginnus, Gottardo et al. 2011).

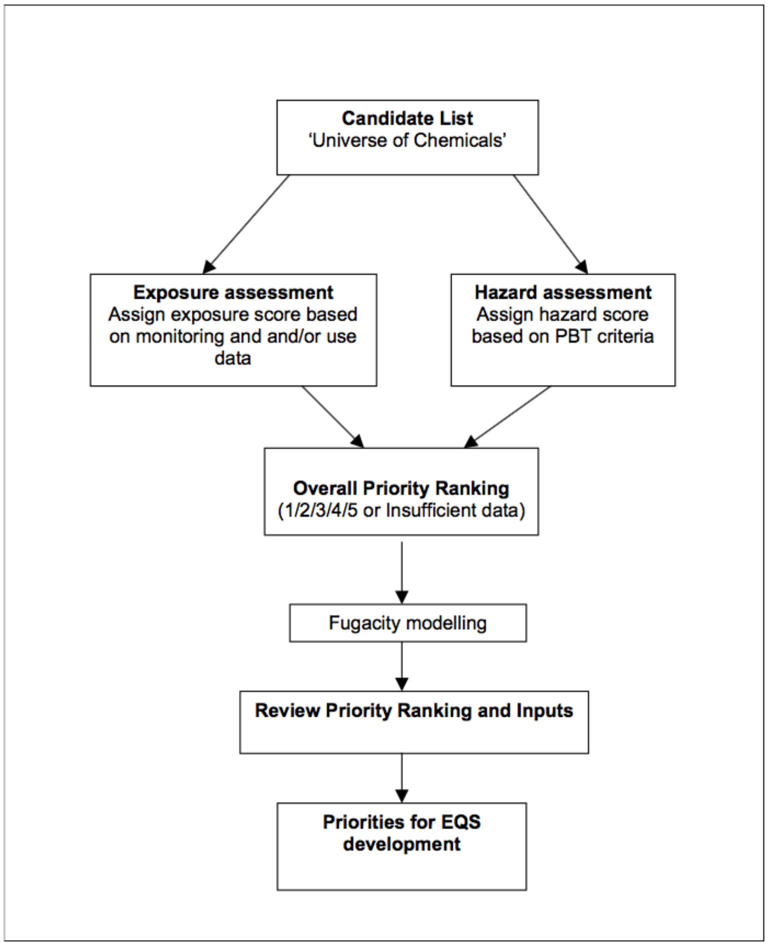


Figure 4-2. Outline of Prioritization Methodology as Applied in the European Union for the Development of Environmental Quality Standards.

This approach involved first assessing the exposure of a contaminant. The industrial production tonnage and use was analyzed – for example, if it is likely that the contaminant is released directly into the environment. Monitoring data from both surface water and groundwater were used, for example, if the contaminant is detected above its Predicted No Effect Concentration (PNEC) derived under the Existing Substances Regulations (ESR). One difficulty that arose in the monitoring data was whether to use the Maximum Allowable Concentration or the long-term Annual Average (AA) standard for each contaminant.

The second part of the process involved a hazard assessment to quantify the effects on aquatic life and human health. The three main criteria that were used included:

- "Persistence – half lives in water and sediment and ready biodegradability.
- Bioaccumulation – log K_{ow} and Bioconcentration Factor (BCF) values in aquatic biota.
- Toxicity – acute and chronic toxicity to aquatic organisms and endocrine disrupting potential" (Wilkinson, Sturdy et al. 2007).

After this was applied the contaminants were then given a priority ranking from 1 (highest priority) to 5 (lowest priority). This approach makes sense for prioritizing chemicals based on potential risk outcomes, but that is not equivalent to prioritizing chemical based on current research needs and opportunities.

There were a number of drawbacks to this method. Many contaminants were excluded from the priority substances list because of insufficient evidence of risk (Wilkinson, Sturdy et al. 2007). This has also been observed in other studies. For example, in the revision of the list of priority substances under the WFD, about half of contaminants were discarded without any EQS being developed because of insufficient data quality (Dulio and von der Ohe 2013).

Furthermore, there are many additional disadvantages in using risk-based assessment. Firstly, the hazard data that is important to gain knowledge on such as persistency, bioaccumulation and endocrine effects is controversial (Heiss and Küster 2015).

Other challenges include:

- How to treat data below the limit of quantification (LOQ).
- Whether to use maximum or average concentrations.
- How to consider the bioavailability of a substance (i.e., freely dissolved concentrations).
- How to aggregate the data based on a certain percentile." (von der Ohe, Dulio et al. 2011).

Although risk-based approaches are widely used in the industry for prioritizing research into chemicals, CECs are unique for the lack of hazard and exposure data available. Therefore, even though it has many advantages, the risk-based approach has not been considered further for the decision-making framework. However, as more research is done and more data becomes available on the health and environmental risks of these contaminants, it would be possible to develop a risk-based framework for these contaminants and further prioritize research and regulations based on this approach.

4.3 Multi-Criteria Decision Analysis

The main objective of multi-criteria decision analyses (MCDA) is to systematically evaluate and choose from alternatives based on multiple defined criteria.

MCDA techniques have been adopted for many diverse applications with relevance to water management. These include water supply planning (Azarnivand and Chitsaz 2015, Scholten, Maurer et al. 2017), flood mitigation planning (Daksiya, Su et al. 2017, Mostafazadeh, Sadoddin et al. 2017, Zhu, Zhong et al. 2017), development of water quality indices (Jhariya, Kumar et al. 2017, Zahedi, Azarnivand et al. 2017), equitable freshwater allocation (Yong, Li et al. 2017), sustainability assessment of urban water planning (Ren and Liang 2017, Wu, Mao et al. 2017), selection of water treatment and remediation technologies (Wang, Cai et al. 2017), and site selection for water harvesting and artificial recharge (Singh, Jha et al. 2017).

Any MCDA problem has three main components: decision maker(s), alternatives and criteria. The classification of an MCDA problem depends on the types of these elements. The definitions of the three components are as follow:

4.3.1 Decision Makers

The first element is identifying the decision makers. For a particular problem, there may be a single person who is responsible for deciding what to do or several people or organizations being involved in the decision-making process. In the first case, there is only one decision maker; in the second case, there may be multiple decision makers. When more than one decision maker is involved, then they might have different preferences, goals, objectives and criteria, so no decision outcome is likely to satisfy every decision maker equally. In such cases, a collective decision has to be made. In the case of a single decision maker and only one criterion, the problem reduces to a single-objective optimization problem. Typical MCDA problems arise when a single decision maker considers several criteria simultaneously.

4.3.2 Alternatives

Alternatives are the possibilities one has to choose from. The set of all possible alternatives is called the decision space. In many cases, the decision space has only a finite number of elements. For example, selecting chemicals from a finite list to prioritize for further research. In other cases, the decision alternatives may be characterized by continuous decision variables that represent certain values about which the decision has to be made. For example, reservoir capacity could be any real value between the smallest feasible value and the largest possibility.

4.3.3 Criteria

Criteria are the characteristics or requirements that each alternative must possess to a greater or lesser extent. The alternatives are usually rated on how well they possess the criteria.

4.3.4 Classification of MCDA

In such a case as research prioritization, the decision space is finite. This means that the discrete case of MCDA can be used, and the “constriction of the feasible decision space is simple” (Zarghami and Szidarovszky 2011). The feasibility of each alternative is calculated by determining how well it satisfies specified criteria. The discrete alternatives, criteria and evaluation of the alternatives with respect to the criteria can be displayed in a matrix (the decision matrix). Figure 4-3 outlines a summary of the process for formulating and solving a mathematical model for a discrete MCDA problem.

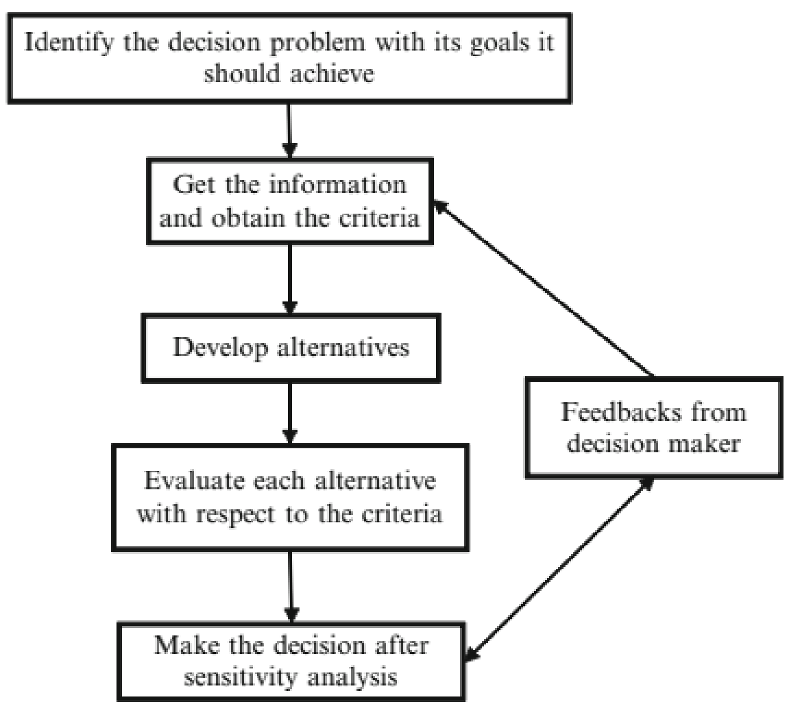


Figure 4-3. Steps of Formulating and Solving MCDA Problems.
(Zarghami and Szidarovszky 2011)

4.3.5 Selection of Criteria

The selection of appropriate criteria should be an iterative process, and should continue until a commonly approved criterion set is decided upon by stakeholders. The set of criteria should provide a simplification of real world phenomenon and as Keeney and Raiffa (1993) outline the set must be "decomposable, non-redundant, and minimum size".

4.3.6 Solution Methods

Various MCDA methods exist for prioritizing alternatives, specifically, different weighting methods that can be used to emphasise the decision makers' priorities. Six frequently used solution methods for deterministic discrete MCDA problems are outlined in Table 4-1. "In deterministic models the evaluations of the alternatives, the criteria weights and all other parameters are assumed to be certain and known" (Zarghami and Szidarovszky 2011).

Table 4-1. Solution Methods for Deterministic Discrete MCDA Problems.

Method	Weighting
Dominance Method	N/A: An alternative dominates another if it results in an equal or superior value in all criteria and in at least one criterion it is strictly better.
Sequential Optimization	Ordinal preferences of the criteria- The decision maker wants to satisfy first the most important criterion as well as possible, and then to satisfy the second with keeping the first at its most favorable level.
The e Constraint Method	Most important criteria are identified and minimum acceptable levels for the remaining are defined.
Simple Additive Weighting	The relative importance weights of each criterion are specified. Criteria must be normalized.
Distance Based Methods	N/A: The subjective or computed worst or most ideal values of the criteria are specified. The alternative with the largest or smallest distance, respectively, is then selected as the best choice.
The Analytic Hierarchy Process	Pair-wise comparisons of criteria are utilized to formally select weights. Weights must be normalized.

In MCDA problems, a number of decision alternatives are each evaluated by n criteria (Zarghami and Szidarovszky 2011). If a_{ij} denotes the evaluation of alternative *j* with respect to criterion *i*, then the "goodness" of this alternative can be characterized by the evaluation vector $X_j = (a_{1j}, a_{2j},\ldots, a_{nj})$.

In the case of a single-objective optimization problem, each alternative is evaluated by only one criterion, so vector X_j has only one element, $X_j = (a_j)$ and the solution to the problem is trivial. If j_1 and j_2 are two alternatives, then their evaluations (a_{j1} and a_{j2}) can be easily compared, in terms of whether one is greater than the other, or they may be equal.

Unfortunately, this problem is less simple when there are multiple criteria by which to judge each alternative. For example, in the case of n = 2 assume that the evaluation vector of these alternatives are $X_{j1} = (1,2)$ and $X_{j2} = (2,1)$. Alternative j_1 may be better than j_2 in the second criterion but worse in the first. So these alternatives cannot be compared directly. In order for a decision maker to select between alternatives j_1 and j_2 it is necessary to decide whether a unit loss in one criterion is compensated by a unit gain in the other. This kind of decision becomes much more complicated if the gains and losses are given in different units and more than two criteria are present.

There are a number of different numerical methods being used, in various applications, for best alternative selection (Zarghami and Szidarovszky 2011). These vary primarily in the ways in which a decision maker may wish to express his/her priorities and preferences.

Simple Additive Weighting (SAW)

A simple and appropriate method to specify the relative importance (i.e., weightings) of all criteria is known as Simple Additive Weighting (SAW). Conceptually, the criteria together may represent 100% of the interest of the decision maker, thus weightings are selected to add to one. This is conventionally presented as shown:

$$F_j = \sum_{i=1}^{n} w_i a_{ij}$$

Where F_j is the "overall" evaluation of alternative *j*. w_i is the percentage of interest for criterion *i* (of *n* total criteria) and a_{ij} is the evaluation of alternative *j* with respect to criterion *i*, as described above.

In most applications, the a_{ij} values represent very different phenomena, such as dollars, number of people and geologic suitability in our earlier examples. In such cases, the objective function presented above has no direct meaning, since it involves adding different things. Another difficulty of applying this function is the fact that by changing the unit of any of the objectives, its weight changes automatically. In such cases, normalization to a consistent scale, ranging between an identified minima and maxima is necessary.

In the current application (prioritization of chemical CECs for research), both of the above problems can be avoided. This is because all of the criteria related to the same effective units (importance/interest for research) and can be logically rated on a consistent scale (e.g., from "not important at all" to "very important"). As long as each criterion is identified as "positive" or "negative", in terms of whether it makes a chemical more (as opposed to less) important for further research, prioritization can be achieved by comparing the magnitude of the total function Fj for each alternative.

4.4 Practical Requirements of an International Framework

The following themes emerged from the compilation of the survey results as requirements for the research prioritization framework:

- Adaptability in order to be relevant to each country's individual conditions.
- Flexibility to respond to immediate needs and different business structures of various water utilities.
- User-friendly.
- Meets the requirements of industry regulators.
- Constant monitoring of validity to ensure that new research results are acknowledged and there is potential to change based on this new information.
- Possibility of becoming a risk-based model.

In order to achieve the features outlined above, it has been considered that a Bayesian Network could be utilized to construct an international framework. This would enable various elements, such as criteria weighting to be adapted considering a country's individual conditions. Various decision-making framework types could be constructed within the network using its built-in programming functions.

CHAPTER 5

Bayesian Network Tool for Prioritization

A Bayesian Network model was developed using software package Netica (v6.0 Norsys Software Corp). This model can be used to prioritize (by numerical rank order) further research on CECs. The model incorporates current methodology for multi-criteria decision analysis (MCDA) with additional capabilities to incorporate uncertainty in criteria scores and weightings, and hence in final combined prioritization indicators. A fully functional freeware copy of Netica is available to run this Bayesian Network (www.norsys.com/download.html). Files developed for use with Netica from this project are all available here: https://www.dropbox.com/sh/c8tmk8cb2cnjf0y/AAAPhnMPVUbyAQBE1JlJvTLda?dl=0

Note that a web-based version of same tool is subsequently described in Chapter 6.

5.1 General Description of Bayesian Networks (BNs)

Bayesian networks (BNs) are probabilistic graphical models represented by "Directed Acyclic Graphs" (DAGs), which can model non-recursive causal relationships in complex systems and facilitate inferential reasoning. A BN structure is defined by directional connections, known as "arcs", which specify the dependence and independence assumptions between random variables, termed "nodes" (Figure 5-1). These interdependencies determine what information is required to specify the probability distribution among the random variables of a network. Two variables are identified as related "parent" and "child" nodes if there is an arc from the former to the latter. When a variable has parents, a set of conditional probabilities must be defined in the child node for each combination of parent node "states" which may be categories, values or value ranges. Nodes without parents (root nodes) only require marginal probabilities. BNs reduce the quantity of information required to define a joint probability distribution through factorization conducted using the chain rule as shown in Equation 5-1.

$$P(X_1, X_2, \ldots, X_n) = \prod_{i=1}^{n} P\left(X_i | X_{pa[i]}\right)$$ Equation 5-1

Where $P(X_1,X_2,\ldots,X_n)$ is the joint probability distribution of variables $(X_1, X_2,\ldots,X_n)$, X_i corresponds to a random variable represented by the node i in {1,…,n} and *pa*[*i*] denotes the parents of node *i*, $X_{pa[i]}$ indicates a set of random variables associated with *pa*[*i*]. Each node from a BN has mutually exclusive discrete states which are associated to marginal probabilities (indicated by the red filled rectangle in Figure 3-1). These marginal probabilities are obtained by marginalising the joint probability distribution.

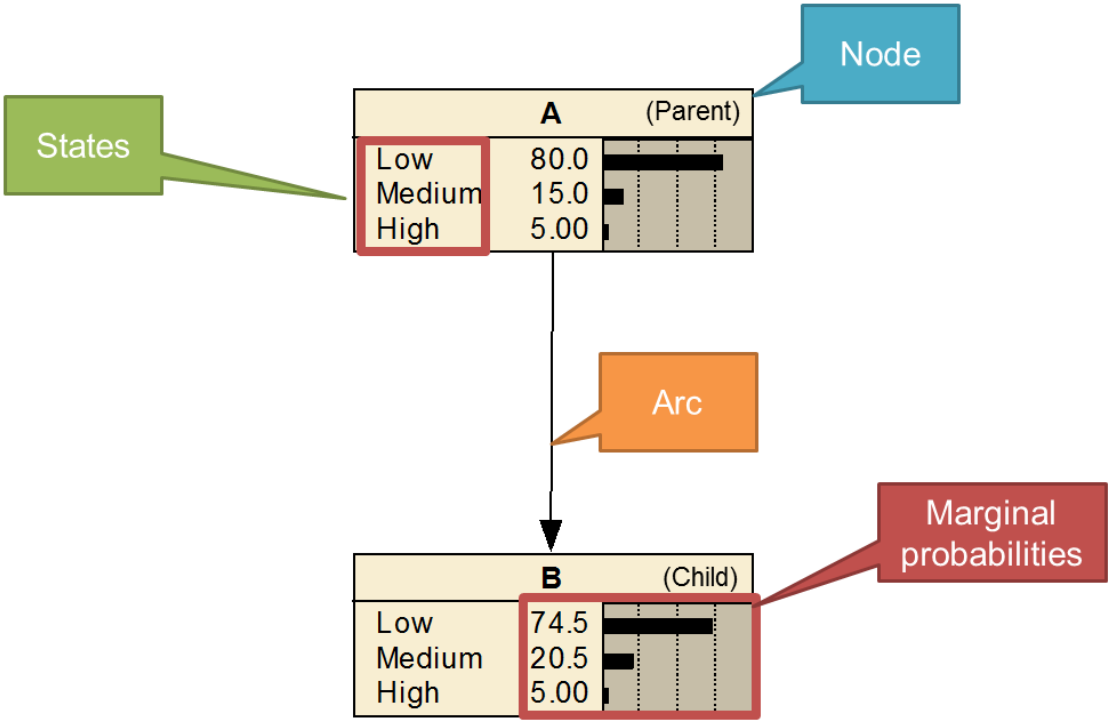


Figure 5-1. Structure and Main Components of a Bayesian Network.

5.2 Problem Description

Many organizations, including water utilities, public health and environmental regulators, universities and other research agencies, have an interest in developing new knowledge on a range of CECs. However, CECs are diverse in the issues that they present in terms of potential environmental, public health or other risks. Furthermore, various organizations will have differing priorities, in terms of which knowledge gaps are most essential or urgent to address. Therefore, in order to develop a tool to assist prioritization, it is necessary to consider both the priorities of the organization, as well the attributes of each potential chemical to be investigated, as they relate to those priorities.

5.3 Prioritization Criteria

The importance of various prioritization criteria were assessed by means of a stakeholder survey. This survey was conducted online using SurveyMonkey and responses were received from 36 organizations. Respondents were asked to rate the importance of each of a list of 20 potential criteria and were provided an opportunity to identify additional criteria. From this approach, a final 11 criteria were selected for priority assessment of CECs. These are (in no specific order):

- Whether the contaminant has been (or is it likely to be) regulated by a relevant regulatory agency to the organization.
- Whether the contaminant is known or suspected to cause acute or chronic health risks.
- Whether there is a lack of information regarding health risks.
- Whether there is evidence for widespread or emerging public concern regarding this contaminant.
- Whether the contaminant is known to be present (occasionally or consistently) in water the organization supplies or discharges.

- Whether the contaminant is known or suspected to be produced during drinking water treatment.
- Whether the contaminant is known or suspected to be produced during wastewater treatment.
- Whether the contaminant is expected to present (somewhat) unique challenges to the organization.
- Whether there are existing analytical techniques available with suitable limits of detection.
- Whether the contaminant appears to be difficult to manage by existing/conventional treatment processes.
- Whether there is information available regarding removal by existing/conventional treatment processes.

5.4 Multi-Criteria Decision Analysis (MCDA)

Established techniques for multi-criteria decision analysis (MCDA) were coded into a Bayesian Network. This enables the user (or "prioritizing decision maker") to consider each chemical against each of the 11 criteria. These considerations are then combined with user-defined weightings for the importance of each criterion. These two types of information are then combined for each of the 11 criteria to provide a final combined prioritization indicator for each CEC.

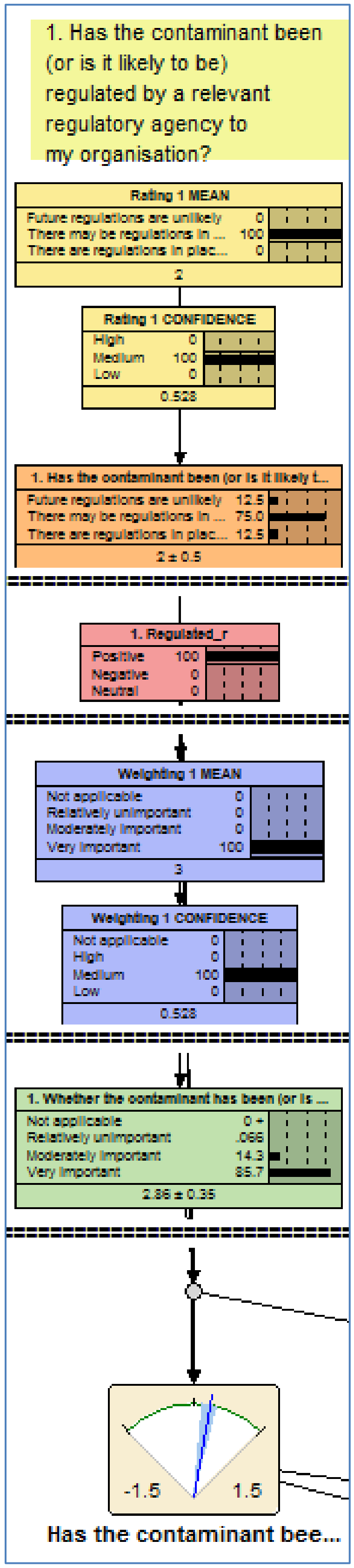


Figure 5-2. The Development of a Criterion-Specific Prioritization Indicator for a Candidate Chemical.

5.4.1 Prioritization Criteria Posed as Questions to the Prioritizing Decision Maker

To facilitate the assessment of each specific CEC against each criterion, the 11 criteria are presented in the form of questions to the prioritizing decision maker. The 11 questions are then:

- Has the contaminant been (or is it likely to be) regulated by a relevant regulatory agency to my organization?
- Is the contaminant known or suspected to cause acute or chronic health risks?
- Is there a lack of information regarding health risks?
- Is there evidence for widespread or emerging public concern regarding this contaminant?
- Is the contaminant known to be present (occasionally or consistently) in water my organization supplies or discharges?
- Is the contaminant known or suspected to be produced during drinking water treatment?
- Is the contaminant known or suspected to be produced during wastewater treatment?
- Is the contaminant expected to present (somewhat) unique challenges to this organization?
- Are there existing analytical techniques available with suitable limits of detection?
- Does the contaminant appear to be difficult to manage by existing/conventional treatment processes?
- Is there current information available regarding removal by existing/conventional treatment processes?

5.4.2 Chemical-Specific Criteria Scores (Selection and Degree of Confidence)

For each chemical, the prioritizing decision maker must consider the degree to which each criteria question is true or not. For example, for the criterion question *Has the contaminant been (or is it likely to be) regulated by a relevant regulatory agency to my organization?* The user may select whichever of the following responses most accurately represents the answer for the particular chemical:

- Future regulations are unlikely (score = 1).
- There may be regulations in the future (score = 2).
- There are regulations in place or under development (score = 3).

Uncertainty in this response is captured by the user then rating their degree of “confidence” that the most appropriate criteria score was selected. Degrees of confidence may be rated as “high”, “medium” and “low”. This choice applies a variable degree of “spillage” from the selected criteria score to adjacent criteria scores. If “high” confidence is selected, 100% of the probability density is allocated to the criteria score selected. If “medium” confidence is selected, 75% of the probability density is allocated to the selected criteria score and the remaining 25% is shared equally between adjacent criteria scores. If “low” confidence is selected, 50% of the probability density is allocated to the selected criteria score and the remaining 50% is shared equally between adjacent scores.

5.4.3 Type of Influence (Positive, Negative, Neutral)

For each criteria question, the user must consider what type of influence that criterion would have on their prioritization. For example, the fact that there are existing analytical techniques available for a chemical may make one organization more likely to want to undertake research on it (a “positive” influence). However, it may also make another organization less likely to want to undertake research on it (a “negative” influence). For a third organization, this may not be a significant consideration at all (a "neutral" influence). The prioritizing decision maker is required to define each criterion by designating its influence as positive, negative or neutral.

5.4.4 Criteria Weighting (Selection and Confidence)

Having defined the type of influence each criterion has for the prioritizing decision maker, it is then necessary to define a weighting for the relative degree of importance for each criterion. The following weightings are available:

- Not applicable (weighting = 0, automatically selected for criteria selected to have "neutral" influence).
- Relatively unimportant (weighting = 1).
- Moderately important (weighting = 2).
- Very important (weighting = 3).

Uncertainty is again captured by allowing the user to indicate their degree of confidence in this weighting selection as a rating of "high" "medium" or "low". This step has the same effect for the criteria weightings as the uncertainty descriptions had for chemical-specific scores, as described above.

5.4.5 Criterion-Specific Prioritization Indicator

The contribution of each criterion is then calculated according to the selections made by the prioritizing decision maker. Chemical-specific criteria sores are applied (1-3), with spillage to adjacent scores, as described by the application of uncertainty ratings. Similarly, criteria weightings are applied (0-3) with spillage to adjacent weightings according to selected uncertainty ratings. These data are then combined to determine the overall contribution of each criterion to the final prioritization indicator for each chemical.

5.4.6 Combined Prioritization Indicator

The calculated contributions of each criterion are combined to produce an overall combined prioritization indicator for each CEC, according to the 11 criteria used in the assessment. Combined prioritization indicators may be negative or positive, depending on whether negative or positive types of influence were predominantly selected and the relative weightings that were applied to them. The combined prioritization indicator is presented with a mean and standard deviation, to indicate both the magnitude the degree of confidence in the combined prioritization indicator. The graphical representation of the result provides further insights to how much of combined prioritization density is determined to be contained within each one of six discretized bands (<-2, -2 to -1, -1 to 0, 0 to 1, 1 to 2, >2). Combined prioritization indicators and their associated uncertainty may then be compared among multiple chemicals to produce a prioritization ranking.

5.5 Batch Processing of Contaminants

Prioritization ranking is only meaningful when combined prioritization indicators of multiple CECs are compared against one another. To facilitate this, batch processing of CECs is possible. In this case, the chemical-specific criteria scores (and associated confidence rating) may be conveniently entered in an Excel spreadsheet, referred to as the "case file", as shown below.

	A	B	C	D	E
1	IDnum	Criterion 1 Score	Criterion 1 Confidence	Criterion 2 Score	Criterion 2Confidence
2	1	3	Low	1	Low
3	2	2	High	1	Low
4	3	2	Medium	2	High
5	4	1	High	3	Medium

Once complete, the prioritizing decision maker can batch process these CECs in Netica by selecting [Cases] → [process cases] and then selecting a "control file", which governs the output (and is provided along with the Netica software file). Then the "case file" may be selected and finally a "results" file designated. This approach will quickly generate a prioritization score for all CECs.

5.6 MCDA Through Bayesian Networks

All required calculations to perform MCDA were encoded into a BN model. Through a BN, stochastic inputs and outputs were used, allowing uncertainty and variability to be incorporated in the MCDA results. This section presents the model settings and equations used in the BN for CECs prioritization.

5.6.1 Confidence in Criteria Scores and Weightings

Confidence ratings were applied to both the criteria scores and weightings to incorporate uncertainty in the prioritization assessment. Higher confidence in the input estimates results in higher certainty in the particular score or weighting selected. As observed in Table 5-1 for criteria scores (first row), when the confidence is high, the score in the child node is the same as the score selected in the parent node, whereas when the confidence is low, there is only a 50% certainty that the score in the child node is the same as the parent node. The remaining percentage to complete 100% is allocated to adjacent states as shown in Table 5-1.

Table 5-1. Conditional Probability Table for Criteria Scores.
Bold rectangle shows the probabilities.

Parents' States		**Child Node's States**		
Confidence	Score	Score=1	Score=2	Score=3
High	1	100	0	0
High	2	0	100	0
High	3	0	0	100
Medium	1	75	25	0
Medium	2	12.5	75	12.5
Medium	3	0	25	75
Low	1	50	50	0
Low	2	25	50	25
Low	3	0	50	50

For criteria weightings, the conditional probabilities are slightly different because they are affected by the type of influence. When the type of influence is selected as neutral, then the confidence and weighting (parent node) are automatically set to “Not applicable” and zero, respectively. A weighting of zero with 100% of certainty in the child node’s states is obtained by either a “Not applicable” confidence or a weighting of zero.

Table 5-2. Conditional Probability Table for Criteria Weightings.
Bold rectangle shows the probabilities.

Parents’ States		**Child Node’s States**			
Confidence	Weighting	Weighting=0	Weighting=1	Weighting=2	Weighting=3
Not applicable	0 [1]	100	0	0	0
Not applicable	1	100	0	0	0
Not applicable	2	100	0	0	0
Not applicable	3	100	0	0	0
High	0	100	0	0	0
High	1	0	100	0	0
High	2	0	0	100	0
High	3	0	0	0	100
Medium	0	100	0	0	0
Medium	1	12.5	75	12.5	0
Medium	2	0	12.5	75	12.5
Medium	3	0	0	25	75
Low	0	100	0	0	0
Low	1	25	50	25	0
Low	2	0	25	50	25
Low	3	0	0	50	50

5.6.2 MCDA Calculations

Nodes with equations in Netica were used to calculate the combined prioritization indicator (CPI). The CPI combined the criteria scores and weightings with the type of influence to obtain the final result. The equation used to calculate the prioritization indicator is presented in Equation 5-2.

$$CPI = \sum_{i=1}^{n} \frac{CW_i \cdot TOI_i}{\sum CW_i} \cdot CS_i$$

Equation 5-2

Where CPI is the combined prioritization indicator, CW_i is the criterion weighting (1, 2, or 3) for the criterion i, TOI_i is the type of influence for the criterion i (-1 for negative, 0 for neutral, or 1 for positive), and CS_i is the criterion score (1, 2, or 3) for the criterion i. The summation adds the contribution of all individual factors (i) from a total of n criteria.

BNs have the limitation of only accepting a limited number of parent nodes (also a limited number of states in the parent nodes) because the size of the conditional probability table in the child nodes grows exponentially. As CPI is a summation, it can be separated into two or more terms by the associative property. Separation of the terms in the summation was used to prevent the exponential growth of the BN. This technique is called parent divorcing in BN terminology and consists of incorporating intermediate variables that summarises the impact of parents on a child node.

[1] Zero is automatically selected when the type of influence is neutral.

Bayesian Network Model for Prioritization of Constituents of Emerging Concern (CECs).

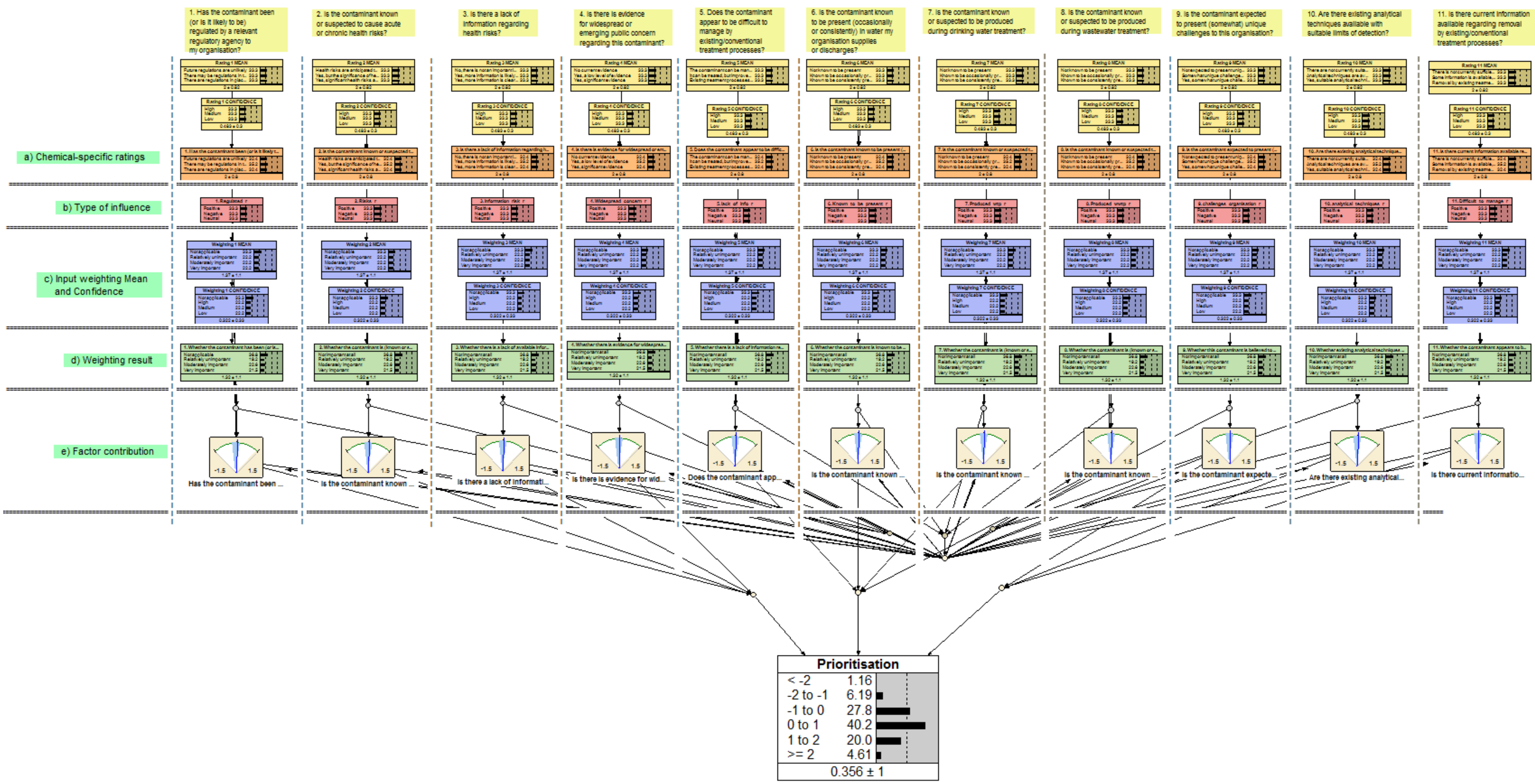


Figure 5-3. Overall Bayesian Network for Prioritization of Constituents of Emerging Concern.

5.6.3 Illustrative Example

As an illustrative example, consider that an organization has only two key criteria for the prioritization of CEC research:

1. Whether the contaminant has been (or is it likely to be) regulated by a relevant regulatory agency to the organization.
2. Whether the contaminant is known or suspected to cause acute or chronic health risks;

In this example, both criteria are classified as "positive" since CECs that meet either (or both) of the criteria will be deemed a higher priority for research. Criteria 1 is considered to be "very important" with a "high" degree of confidence. Criteria 2 is considered to be "moderately important" with a "medium" degree of confidence. All other criteria may be ignored by setting the "type of influence" to "neutral".

The organization has two CECs which are being considered as for the subject of future research, Chemical A and Chemical B, as shown in Table 5-3.

Table 5-3. Illustrative Example, Chemicals A and B.

	Criterion 1		Criterion 2		Prioritization	
	Response	Confidence	Response	Confidence	Mean	Standard Deviation
Chemical A	There are regulations in place	High	Significant health risks are anticipated	High	2.44	0.37
Chemical B	Future regulations are unlikely	Medium	Significant health risks are anticipated	High	2.14	0.58

In this example, significant health risks are anticipated for both chemicals with a high degree of confidence. This may reflect known toxicological evaluations of the two chemicals. The key difference is that for Chemical A, there are currently regulations and place and for Chemical B, future regulations are considered to be unlikely. Since the existence or prospect of regulations was identified as a very important criterion, making research a higher priority, this difference has led to differences in the prioritization ranking.

The combined prioritization indicator is higher (2.44) for Chemical A, compared to the figure (2.14) for Chemical B. This is to be interpreted that Chemical A is determined to be of greater priority for research, relative to Chemical B, reflecting the priorities of the decision maker.

The Standard deviations around the prioritization indicators provide additional insights. The Standard deviation for Chemical A (0.37) is smaller than the standard deviation for Chemical B (0.58). This reflects the fact that both criterion responses were determined to be selected with a "high" degree of confidence, while the prospect of future regulations being unlikely for Chemical B was selected with only a "medium" degree of confidence. The overall distributions of the combined prioritizations indicators, as defined by their means and standard deviations involve a significant degree of overlap. This may be interpreted as a degree of 'fuzziness' in the final prioritization rankings, derived from uncertainty in the data used to inform the decision.

CHAPTER 6

Development of an Online Tool

An online form of the MCDA Bayesian Network tool was developed and is freely available:

http://bncecs.tk/

The key advantage of the online version is that it eliminates the need for software to be downloaded and installed. The user interface will also be more familiar to most users, compared to Netica (as described in Chapter 5). However, it should be noted that in simplifying the interface, the internal functions of the model are much less visible to the user. This may present the impression of a 'black box' model to users unless the details, from this report, are also consulted.

The 'front page' of the online Bayesian Network tool is presented in Figure 6-1. The user is first presented with a choice of a "Model for one chemical" and a "Model for Multiple chemicals". There is also a function to "send a question" regarding the operation of these models. Selecting this button will open a template to post an email to the project leader, Stuart Khan. Furthermore, a "Discussion Board" has been provided so that questions and other discussion regarding the tool may be referred to by all users.

Figure 6-1. "Front Page" of the Online Bayesian Network Model.

6.1 Model for One Chemical

The "Model for one chemical" is provided in cases where a decision maker may wish to determine the Combined Prioritization Indicator for a single chemical at a time. Note that in order to have a meaningful prioritization, it is necessary to process the model for more than one chemical. Therefore, this aspect of the tool is only useful if it is used more than once, for a number of CECs.

The instructions for the one chemical model are provided as follows:

1. Start responding to the questionnaire from left to right and from top to bottom.
2. There are three main groups of variables which are:

   Rate means and confidence,

   Type of influence, and

   Weighting means and confidence.
3. Results are read on the top panel in three different formats.
4. Select Plot to visualize a histogram, Summary to visualize the main statistics and Table to visualize the raw data of the Combined Prioritization Indicator (CPI).

For Step 1, the user must select from one of chemical-specific criteria scores for each of the Prioritization Criteria presented in Section 5.4.1. The first two are shown as examples in Figure 6-2. Following each chemical-specific criteria score, the user must indicate their degree of confidence in selecting that criteria score, as either “high”, “medium”, or “low”.

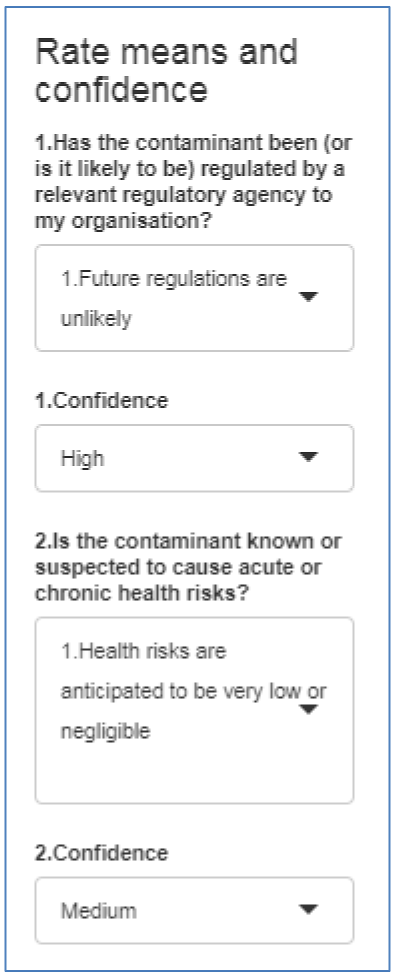


Figure 6-2. Chemical-Specific Criteria Scores (Selection and Degree of Confidence).

Following the assignment of chemical-specific criteria scores and associated confidence, the user must indicate the "Type of Influence" for each criterion. That is, they must indicate whether conformance with each individual criterion would make a particular CEC more highly prioritized for research ("positive"), less highly prioritized for research ("negative"), or would neither more or less highly prioritized for research ("neutral"). Examples for the first two criteria are shown in Figure 6-3.

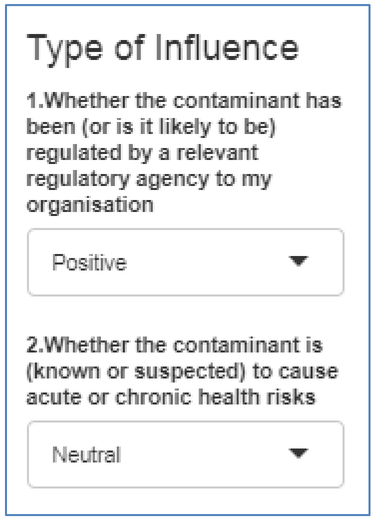


Figure 6-3. Type of Influence Categorization (Positive, Negative, or Neutral).

Finally, the user must stipulate the (relative) importance of each of the 11 criteria as "Criteria Weightings". If the "neutral" has been selected for the Type of Influence, only "neutral" can be selected for the Criteria Weighting. If either "positive" or "negative" have been selected, each criteria weighting must be selected as any one of "relatively unimportant", "moderately important", or "very important". Following each Criteria Weighting, the user must indicate their degree of confidence in selecting that criteria weighting, as either "high", "medium", or "low". Examples are shown in Figure 6-4.

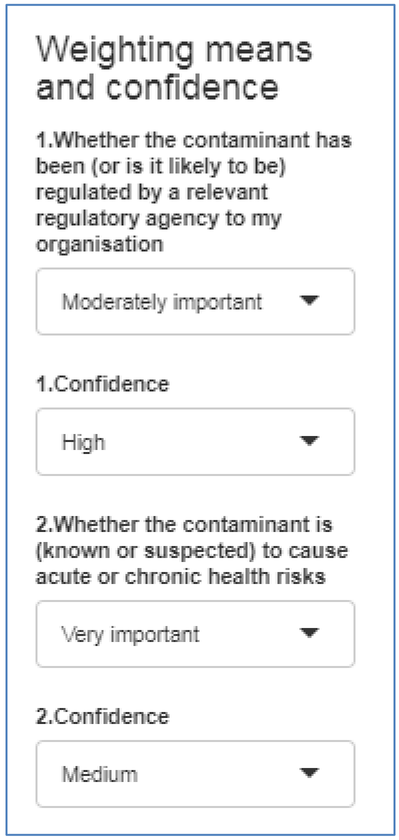


Figure 6-4. Criteria Weighting (Selection and Confidence).

The Combined Prioritization Indicator (CPI) for the individual chemical may then be observed from the "plot" presented. Accounting for the user-entered degrees of confidence in the selection of chemical-specific criteria scores and criteria weightings, the CPI is presented as a distribution (or histogram), rather than as a single figure (Figure 6-5).

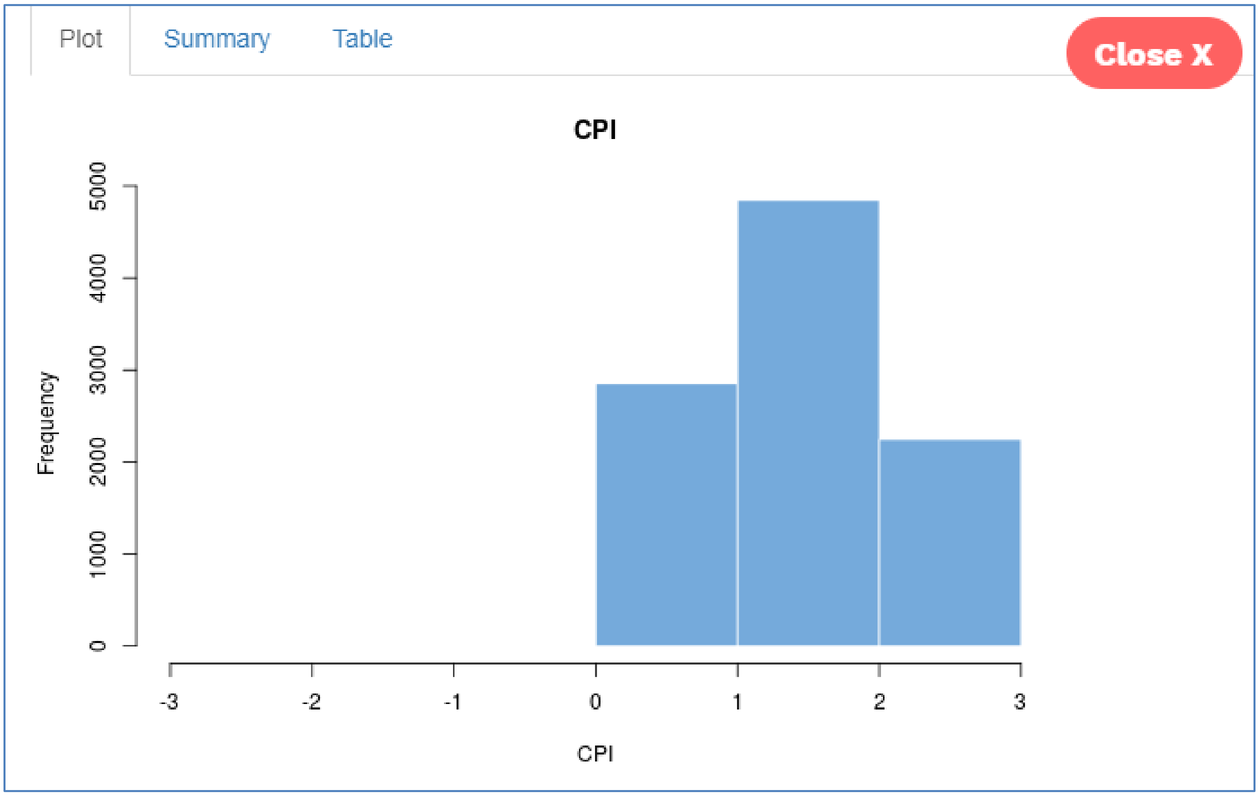
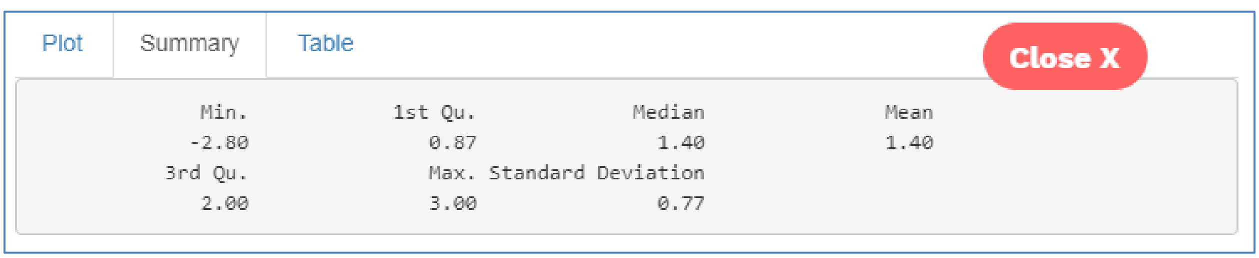


Figure 6-5. Plot of Combined Prioritization Indicator (CPI).

The numerical values for the Combined Prioritization Indicator are presented in the "Summary" section as shown in Figure 6-6. The most important values are the Mean (1.40 in this example) and standard deviation (0.77 in this example).



Min.	1st Qu.	Median	Mean
-2.80	0.87	1.40	1.40
3rd Qu.	Max.	Standard Deviation	
2.00	3.00	0.77	

Figure 6-6. Summary Numerical Values for Combined Prioritization Indicator (CPI).

As descried above, a CPI value is not a useful or meaningful number for a single chemical. It is necessary to run this model for numerous chemicals and compare the results in order to develop a prioritization. To do that, it is expected that most users will find the "Model for multiple chemicals" as described in the following sections more useful.

6.2 Model for Multiple Chemicals

The "Model for multiple chemicals" is provided to facilitate the development and compilation of chemical-specific criteria scores for a list of candidate CECs for prioritization. This approach is expected to be most useful in most circumstances since prioritization relies on comparing numerous candidate CECs with each other.

The instructions for the multiple chemicals model are provided as follows:

1. Download this spreadsheet to enter the data for the "Rating Mean and Confidence" and this other spreadsheet for the "Type of Influence and Weighting"
2. Complete both spreadsheets writing down the names of the chemicals (for the first spreadsheet) and select the drop-down options accordingly.
3. Save the file in .CSV format, open it and save it again.
4. Open the .CSV file in the right side window (Choose CSV File).
5. Wait until the results appear on the right side (check the progress bar on the right bottom corner).
6. Read CPI (mean and standard deviation) and the two most important criteria from the output table.
7. You can copy the results and paste them in a spreadsheet.

In this case, data are not entered directly into the website, but instead they are entered into two downloadable Excel spreadsheets. These spreadsheets must then be saved and uploaded to the website in order to be processed and for a result to be produced.

The first spreadsheet is used to enter the chemical-specific criteria scores and associated confidence as depicted in Figure 6-7. It is anticipated that considerable time may be required to collect the information required to complete this spreadsheet, and that the Excel spreadsheet format will facilitate that requirement.

ID	Name of compound	1.Has the contaminant been (or is it likely to be) regulated by a relevant regulatory agency to my organisation?	Degree of confidence	2.Is t know caus heal
1	Dibutyl phthalate	1.Future regulations are unlikely	High	1.He
2	Dicofol	3.There are regulations in place or under development	High	3.Yes
3	Dicyclohexyl phthala	2.There may be regulations in the future	High	1.He

Figure 6-7. Excel Spreadsheet for Entering Chemical-Specific Criteria Scores and Associated Confidence.

The second spreadsheet is for entering the Type of Influence categorization (positive, negative, or neutral) and Criteria weighting (selection and confidence) for each of the ii criteria. It is proposed that these ratings might be made by an individual, or more likely, in a workshop scenario, where they may be derived to describe the priorities of a group of people representing an organization as a whole. In this case, the values entered for "weighting confidence" may be used to reflect the degree of consensus or disagreement among multiple decision makers.

No.	Criteria	Type of Influence	Weighting	Weighting confidence
1	Whether the contaminant has been (or is it likely to be) regulated by a relevant regulatory agency to the organisation	Positive	Relatively unimportant	High
2	Whether the contaminant is known or suspected to cause acute or chronic health risks	Positive	Very important	Medium
3	Whether there is a lack of information regarding health risks	Positive	Very important	High
4	Whether there is evidence for widespread or emerging public concern regarding this contaminant;	Positive	Moderately important	Medium
5	Whether the contaminant is known to be present (occasionally or consistently) in water the organisation supplies or discharges	Neutral	Not applicable	Not applicable
6	Whether the contaminant is known or suspected to be produced during drinking water treatment	Negative	Moderately important	Low
7	Whether the contaminant is known or suspected to be produced during wastewater treatment	Neutral	Not applicable	Not applicable
8	Whether the contaminant is expected to present (somewhat) unique challenges to the organisation	Neutral	Not applicable	Not applicable
9	Whether there are existing analytical techniques available with suitable limits of detection	Negative	Moderately important	Medium
10	Whether the contaminant appears to be difficult to manage by existing or conventional treatment processes	Neutral	Not applicable	Not applicable
11	Whether there is information available regarding removal by existing or conventional treatment processes	Neutral	Not applicable	Not applicable

Figure 6-8. Excel Spreadsheet for Entering Type of Influence Categorization (Positive, Negative, or Neutral) and Criteria Weighting (Selection and Confidence).

Once the two spreadsheets are completed, they must both be saved in .CSV format. Please note that they need to then be opened and then resaved. This only takes a moment to do.

The CSV files can then be uploaded to the website under the section labelled "Upload Input Data" as shown in Figure 6-9. This is done by clicking "Browse…" and then navigating to select the correct file in each case. Once that is done, the website will automatically begin processing the data, with progress indicated by a status bar in the bottom right corner.

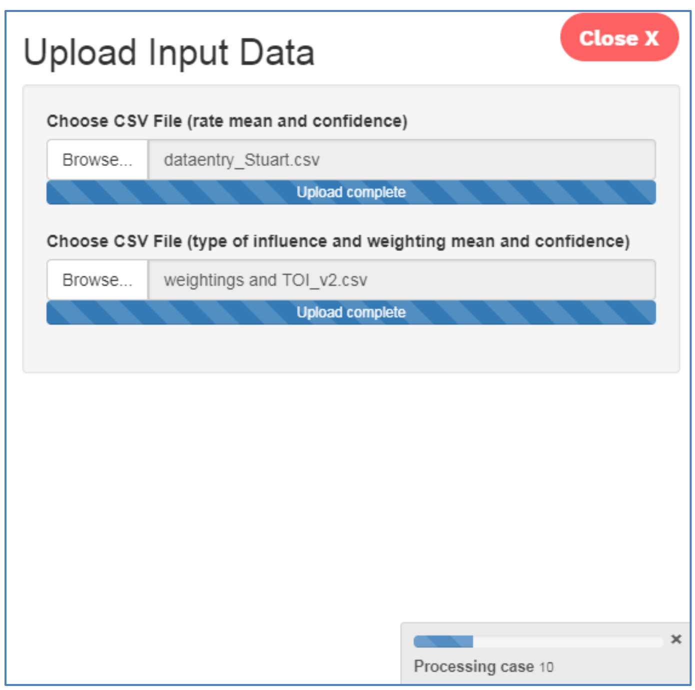


Figure 6-9. Upload Input Data Dialogue Box.

Once the processing has been completed, the prioritization results are displayed on the screen as shown in Figure 6-10. These may then be copied and pasted into an Excel Spreadsheet to save.

Chemical	CPI mean	CPI standard deviation	Most important criterion	Second most important criterion
Perfluorooctanoic acid (PFOA)	2.19	0.59	10. Analytical techniques	5. Management by conventional treatment
Manganese	2.11	0.65	10. Analytical techniques	1. Regulations
alpha-Hexachlorocyclohexane	2.09	0.66	10. Analytical techniques	1. Regulations
Microcystin-LR	2.08	0.66	10. Analytical techniques	1. Regulations
Chlorothalonil	2.08	0.66	10. Analytical techniques	1. Regulations
Saxitoxin	2.08	0.66	10. Analytical	1. Regulations

Figure 6-10. Prioritization Results.

The CECs are presented in descending order from highest CPI to lowest CPI. In addition to the mean value for the CPI and the CPI standard deviation, the results include an indication of the most important and second most important criteria that contributed to the overall CPI. These should provide an indication of which areas of knowledge are considered to be important and/or lacking, and hence what type of research (in order to fill which knowledge gaps) has effectively been prioritized for the particular CECs.

CHAPTER 7

Case Study Example

A case study was undertaken in order to test the functionality and usefulness of the tool. This case study was undertaken by having a research manager at a small Australian drinking water utility complete the two spreadsheets developed for the "Model for multiple chemicals".

The Research Manager is responsible for prioritizing research needs for a drinking water utility based on the North Coast of New South Wales, Australia. Prior to gathering information, the objectives and general process were explained in detail to the research manager. The Type of Influence categorization (positive, negative or neutral) and Criteria weighting (selection and confidence) selected by the Water Utility Research Manger are presented in Table 7-1.

Table 7-1. Type of Influence Categorization (Positive, Negative, or Neutral) and Criteria Weighting (Selection and Confidence) Selected by a Water Utility Research Manager in NSW, Australia.

	Criteria Description	Type of Influence	Weighting	Weighting Confidence
1	Whether the contaminant has been (or is it likely to be) regulated by a relevant regulatory agency to the organization	Positive	Moderately important	High
2	Whether the contaminant is known or suspected to cause acute or chronic health risks	Positive	Moderately important	High
3	Whether there is a lack of information regarding health risks	Neutral	Not applicable	Not applicable
4	Whether there is evidence for widespread or emerging public concern regarding this contaminant	Positive	Relatively unimportant	Medium
5	Whether the contaminant is known to be present (occasionally or consistently) in water the organization supplies or discharges	Positive	Very important	High
6	Whether the contaminant is known or suspected to be produced during drinking water treatment	Positive	Very important	High
7	Whether the contaminant is known or suspected to be produced during wastewater treatment	Neutral	Not applicable	Not applicable
8	Whether the contaminant is expected to present (somewhat) unique challenges to the organization	Positive	Very important	High
9	Whether there are existing analytical techniques available with suitable limits of detection	Positive	Moderately important	High
10	Whether the contaminant appears to be difficult to manage by existing or conventional treatment processes	Positive	Very important	High
11	Whether there is information available regarding removal by existing or conventional treatment processes	Negative	Moderately important	High

Since the research manager did not have a readily available list of candidate CECs for research prioritization, a list was adopted from the US Environmental Protection Agency Screening Document for the Fourth Preliminary Contaminant Candidate List (PCCL 4) (U.S. EPA 2016). This produced a list of 42 candidate CECs as presented in Table 7-2.

Table 7-2. Candidate CECs Selected Water Utility Research Manager, Based on U.S. EPA 2016.

Number	Candidate CEC
1	3-chloro-4- dichloromethyl-5- hydroxy-2(5H)- furanone
2	alpha-Hexachlorocyclohexane
3	Azinphos-methy
4	Bentazon
5	Bisphenol A (BPA)
6	Bromoxynil
7	Butyl benzyl phthalate
8	Carbaryl
9	Chlorothalonil
10	Chlorpyrifos
11	Dibutyl phthalate
12	Dicofol
13	Dicyclohexyl phthalate
14	Diethyl phthalate
15	Di-isononyl phthalate
16	Dimethyl phthalate
17	Di-n-octyl phthalate
18	Endosulfan
19	Fluometuron
20	Linuron
21	Malathion
22	Manganese
23	Methyl parathion
24	Methyl tert-butyl ether
25	Microcystin-LR
26	Nonylphenol
27	Nonylphenol ethoxylate
28	Octylphenol
29	Octylphenol ethoxylate
30	Oxacillin
31	Penicillin
32	Perfluorooctanoic acid (PFOA)
33	Permethrin
34	Phosmet
35	Progesterone

Number	Candidate CEC
36	Saxitoxin
37	Testosterone
38	Trichlorfon
39	Triclocarban
40	Triclosan
41	Tylosin
42	Virginiamycin

The Water Utility Research Manager was responsible for applying each of the chemical-specific criteria scores (selection and degree of confidence). While this information can be acquired from any source, in this case some information was adapted from the PCCL 4 document (U.S. EPA 2016). To do this, rules were adopted to translate PCCL4 Screening Notes to Criteria 1 responses ("Whether the contaminant has been (or is it likely to be) regulated by a relevant regulatory agency to the organization") as shown in Table 7-3. Similarly, rules were adopted to translate PCCL4 Screening Notes to Criteria 2 responses ("Whether the contaminant is known or suspected to cause acute or chronic health risks") as shown in Table 7-4.

Table 7-3. Rules Adopted to Translate PCCL4 Screening Notes to Criteria 1 "Whether the Contaminant Has Been (or is it likely to be) Regulated by a Relevant Regulatory Agency to the Organization"

PCCL4 Screening Notes	Criteria 1	Confidence
Incomplete data for screening/ remains in CCL 4 Universe	2. There may be regulations in the future	High
Makes PCCL 4	3. There are regulations in place or under development	High
Fails Screen/ remains in CCL 4 Universe	1. Future regulations are unlikely	High

Table 7-4. Rules Adopted to Translate PCCL4 Screening Notes to Criteria 2 "Whether the Contaminant is Known or Suspected to Cause Acute or Chronic Health Risks"

Toxicity Screening Category	Criteria 2	Confidence
Toxicity Category 1	3. Yes, significant health risks are anticipated	High
Toxicity Category 2	3. Yes, significant health risks are anticipated	Medium
Toxicity Category 3	2. Yes, but the significance of health risks appears low	Medium
Toxicity Category 4	1. Health risks are anticipated to be very low or negligible	Medium
Toxicity Category 5	1. Health risks are anticipated to be very low or negligible	High
Insufficient data	1. Health risks are anticipated to be very low or negligible	Low

The remaining nine criteria were filled on the basis of knowledge by the Water Utility Research Manager. The completed spreadsheet of responses was saved as a .CSV file and uploaded to the website for processing, as described in Section 6.2 of this report. After processing, the Calculated Combined Priority Indicator for 42 Candidate Contaminants was produced as presented in Table 7-5.

Table 7-5. Calculated Combined Priority Indicator for 42 Candidate Contaminants.

Chemical	CPI Mean	CPI Standard Deviation	Most important Criterion	Second Most Important Criterion
Perfluorooctanoic acid (PFOA)	1.88	0.74	10. Management by conventional treatment	1. Regulations
Microcystin-LR	1.74	0.79	1. Regulations	2. Health risks
Chlorothalonil	1.73	0.80	1. Regulations	2. Health risks
alpha-Hexachlorocyclohexane	1.73	0.80	1. Regulations	2. Health risks
Saxitoxin	1.72	0.79	1. Regulations	2. Health risks
Bisphenol A (BPA)	1.70	0.80	1. Regulations	9. Analytical techniques
Phosmet	1.69	0.80	1. Regulations	9. Analytical techniques
Dicofol	1.69	0.80	1. Regulations	9. Analytical techniques
Endosulfan	1.69	0.81	1. Regulations	9. Analytical techniques
Linuron	1.68	0.81	1. Regulations	9. Analytical techniques
Azinphos-methy	1.68	0.81	1. Regulations	9. Analytical techniques
Butyl benzyl phthalate	1.68	0.80	1. Regulations	9. Analytical techniques
Carbaryl	1.68	0.80	1. Regulations	9. Analytical techniques
Nonylphenol	1.67	0.81	1. Regulations	9. Analytical techniques
Malathion	1.67	0.81	1. Regulations	9. Analytical techniques
Diethyl phthalate	1.62	0.81	5. Present by supplies or discharges	6. Produced during water treatment
Chlorpyrifos	1.57	0.83	9. Analytical techniques	5. Present by supplies or discharges
Bentazon	1.57	0.83	1. Regulations	9. Analytical techniques
Permethrin	1.57	0.82	1. Regulations	9. Analytical techniques
Methyl tert-butyl ether	1.57	0.83	1. Regulations	9. Analytical techniques

Chemical	CPI Mean	CPI Standard Deviation	Most important Criterion	Second Most Important Criterion
Fluometuron	1.56	0.82	1. Regulations	9. Analytical techniques
Manganese	1.53	0.85	1. Regulations	5. Present by supplies or discharges
Methyl parathion	1.47	0.82	9. Analytical techniques	10. Management by conventional treatment
Dibutyl phthalate	1.42	0.83	5. Present by supplies or discharges	9. Analytical techniques
3-chloro-4- dichloromethyl-5-hydroxy-2(5H)- furanone	1.38	0.82	9. Analytical techniques	10. Management by conventional treatment
Progesterone	1.36	0.81	9. Analytical techniques	10. Management by conventional treatment
Trichlorfon	1.34	0.81	9. Analytical techniques	10. Management by conventional treatment
Dicyclohexyl phthalate	1.34	0.80	9. Analytical techniques	10. Management by conventional treatment
Bromoxynil	1.34	0.80	9. Analytical techniques	10. Management by conventional treatment
Di-n-octyl phthalate	1.34	0.80	9. Analytical techniques	10. Management by conventional treatment
Octylphenol	1.34	0.80	9. Analytical techniques	10. Management by conventional treatment
Virginiamycin	1.34	0.80	9. Analytical techniques	10. Management by conventional treatment
Testosterone	1.34	0.81	9. Analytical techniques	10. Management by conventional treatment
Penicillin	1.34	0.80	9. Analytical techniques	10. Management by conventional treatment
Oxacillin	1.32	0.80	9. Analytical techniques	10. Management by conventional treatment
Nonylphenol ethoxylate	1.31	0.80	9. Analytical techniques	10. Management by conventional treatment

Chemical	CPI Mean	CPI Standard Deviation	Most important Criterion	Second Most Important Criterion
Di-isononyl phthalate	1.31	0.80	9. Analytical techniques	10. Management by conventional treatment
Triclosan	1.30	0.80	9. Analytical techniques	10. Management by conventional treatment
Triclocarban	1.30	0.80	9. Analytical techniques	10. Management by conventional treatment
Tylosin	1.30	0.80	9. Analytical techniques	10. Management by conventional treatment
Octylphenol ethoxylate	1.30	0.79	9. Analytical techniques	10. Management by conventional treatment
Dimethyl phthalate	1.29	0.79	9. Analytical techniques	10. Management by conventional treatment

The key conclusion for the Research Manager, having completed this analysis is that the highest ranked CEC for research priority is Perfluorooctanoic acid (PFOA). Further insights can be gained by observing that the two criteria that led to this high prioritization were number 10 and 1:

- Whether the contaminant appears to be difficult to manage by existing/conventional treatment processes.
- Whether the contaminant has been (or is it likely to be) regulated by a relevant regulatory agency to the organization.

The first of these (concerning existing treatment processes) was ranked as “very important” with a “high” degree of confidence. The second (concerning likely regulation) was ranked as “moderately important”, also with a high degree of confidence. PFOA scored highly against both of these criteria, with assessments including that “existing treatment processes are insufficient (medium confidence) and that “there are regulations in place or under development” (high confidence).

These outcomes provide an indication that further research on PFOA is warranted due to the fact that it is known to be difficult for the organization to treat and future regulations are in place or likely in the future.

Other criteria deemed to be “very important” in this assessment included:

- Whether the contaminant is known to be present (occasionally or consistently) in water the organization supplies or discharges.
- Whether the contaminant is known or suspected to be produced during drinking water treatment.
- Whether the contaminant is expected to present (somewhat) unique challenges to the organization.

For the first of these, PFOA was assessed to be “Known to be occasionally present”, resulting in a moderate ranking for this criteria. However, PFOA did not score highly for either of the other two criteria.

The second most highly ranked chemical was Microcystin-LR, however, this was only ranked very slightly above a few others including Chlorothalonil, alpha-Hexachlorocyclohexane, and Saxitoxin. In each of these cases, the dominating criteria were as follows:

- Whether the contaminant has been (or is it likely to be) regulated by a relevant regulatory agency to the organization.
- Whether the contaminant is known or suspected to cause acute or chronic health risks.

Each of these contaminants was assessed as having “regulations in place or under development” with a “high” degree of confidence. Furthermore, each was ranked as “significant health risks are anticipated” with a “high” degree of confidence.

Follow-up discussions with the water utility Research Manager confirmed that the outcomes produced by the tool are consistent with logical decision making regarding research priorities for the organization. Feedback from this Research Manager indicates that the utility now intends to further refine the modelling outcomes, by undertaking wider consultation with the water utility organization. Once that is complete, the utility expects to apply the process of having used the prioritization tool in communications with Stakeholders including the governing Board of Directors.

CHAPTER 8

Conclusions

The need to prioritize research efforts was highlighted at a workshop conducted by GWRC on "Emerging Contaminants and Pathogens" in 2015. Key questions to be asked include:

- Which CECs are most worthy (or most urgent) for investment in research?
- What are the criteria by which we should judge the research need or urgency for CECs?
- What is the relative importance of each of these criteria?

The answers to these questions are dependent upon who is asking them. That is, different individuals or organizations will have different priorities, reflecting their individual corporate missions and responsibilities, as well as their individual circumstances. Consequently, there are no strictly or universally 'correct' answers to any of the above questions.

The process and tools presented in this work require decision makers to formally assess their own criteria for prioritizing research on CECs. A list of 11 default criteria were derived from a survey of water industry organizations for whom research is a component of their organizational activities. These 11 default criteria may now be considered and weighted in terms of their relative importance an individual organization. Some may be expected to be "very important", "moderately important", "relatively unimportant", or not applicable at all. By distinguishing among these, the decision maker can produce a prioritization weighting with the greatest emphasis given to consideration of criteria of greatest relevance to that decision maker. Given that many such considerations will be made without a high or uniform degree of confidence, it is important that the degree of confidence is also captured in the process.

The most time-consuming and challenging aspect of the overall process is the assessment of individual CECs in terms of their performance against each of the identified criteria. In most cases, it will likely prove impossible to collect complete information regarding such things as health risks, community concerns or the availability of analytical methods. However, this is process should be used to capture the decision maker's 'knowledge' regarding such concerns or the availability of such information. The degree of 'confidence' associated with each of these chemical-specific criteria scores tracks sources of imperfect knowledge and carries that uncertainty through to the final result.

The tool produced from this work is designed to be as user-friendly as possible. Key features include the use of downloadable/uploadable spreadsheets, which facilitate data collation in a familiar and non-time sensitive environment. As far as the authors are aware, this type of decision analysis has not previously been widely applied in the water research field. As such, it may be considered a prototype, which can be assessed for its usefulness. Facilities such as a discussion board have been incorporated to encourage and facilitate discussion regarding future developments and evolution of the tool. The authors remain engaged and willing to take on suggestions for improvement and further development.

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Emerging Contaminant Research Prioritisation Decision Making Framework

Background

The Global Water Research Coalition (GWRC) held a workshop on "Emerging Contaminants and Pathogens" in Karlsruhe, Germany in June 2015. An objective of that workshop was to identify and highlight research needs regarding emerging water quality contaminants. While numerous specific issues were identified, it was broadly acknowledged that the ability for water utilities to do so is hindered by the lack of the clear framework for prioritisation. Such a framework would assist utilities in identifying appropriate criteria for prioritisation, techniques for 'weighting' of balancing those criteria, techniques for assessing options against the criteria and techniques for drawing conclusions on research prioritisation. The availability of such a framework was considered to have a number of potential advantages. These included:

- An improved basis for research priority decision making.
- Improved decision making justification to stakeholders (including the community).
- Informed policy making.

Objectives

The objective of this project is to develop a transparent and efficient decision making framework to be used in making and communicating decisions around the prioritisation of research efforts on emerging water contaminants.

This survey

This survey has been developed as an initial means of gathering information regarding current practice and further industry needs. Following the survey, a summary report will be prepared as a 'discussion paper' (May 2017). This discussion paper will be circulated among GWRC members for feedback. A final report will present a finalised decision-making framework (October 2017).

1. Please provide contact details for any follow-up to this survey (all details will remain confidential)

Name

Company

City/Town

State/Province

Country

Email Address

2. How many customers does your organisation serve?

3. How significant are the following activities among the services provided by your organisation?

	This is a major activity of my organisation	This is a minor activity of my organisation	This service not provided by my organisation
Drinking water catchment management	○	○	○
Drinking water treatment	○	○	○
Drinking water distribution	○	○	○
Wastewater source control	○	○	○
Wastewater treatment	○	○	○
Wastewater discharge	○	○	○
Urban stormwater source control/catchment management	○	○	○
Urban stormwater treatment	○	○	○
Urban stormwater reuse	○	○	○
Reclaimed water non-potable reuse	○	○	○
Reclaimed water potable reuse	○	○	○
Water quality research	○	○	○
Water quality regulation	○	○	○
Water quality analysis	○	○	○
Environmental impact assessment related to water contaminants	○	○	○
Health risk assessment related to water contaminants	○	○	○

Comments or clarification

4. Select which statement best describes your current practice regarding prioritisation frameworks for emerging contaminants research.

- ◯ My organisation has a formal internal framework for prioritising research needs (note: a "formal" framework would be outlined in an existing document).
- ◯ My organisation has an informal internal framework for prioritising research needs (note: an "informal" framework may not be described in any document, but is nonetheless accepted practice).
- ◯ My organisation uses an externally developed framework for prioritising research needs.
- ◯ I am not aware of any formal or informal framework used by my organisation for emerging contaminant research prioritisation.
- ◯ Other

Please elaborate on your answer above. Titles of any formal or informal documents would be helpful and appreciated.

5. Assuming you are responsible for prioritising research on emerging water contaminants, how would you rate the importance of each of the following criteria?

	Very important	Moderately important	Relatively unimportant	Not important at all
Whether there is evidence for widespread public concern	◯	◯	◯	◯
Whether there is evidence for emerging public concern	◯	◯	◯	◯
Whether there is evidence of interest from regulatory organisations	◯	◯	◯	◯
Whether the contaminant is a (known or suspected) human carcinogen	◯	◯	◯	◯
Whether the contaminant is a (known or suspected) endrocrine disruptor	◯	◯	◯	◯
Whether the contaminant is (known or suspected) to cause acute health risks	◯	◯	◯	◯
Whether the contaminant is (known or suspected) to cause chronic health risks	◯	◯	◯	◯
Whether there is a lack of available information regarding health risks	◯	◯	◯	◯

	Very important	Moderately important	Relatively unimportant	Not important at all
Whether the contaminant is (known or suspected) to be produced during drinking water treatment	○	○	○	○
Whether the contaminant is (known or suspected) to be produced during wastewater treatment	○	○	○	○
Whether the contaminant appears to be difficult to manage by existing/conventional treatment processes	○	○	○	○
Whether there is a lack of information regarding removal by existing/conventional treatment processes	○	○	○	○
Whether customers have indicated that the contaminant should be prioritised	○	○	○	○
Whether other organisations are prioritising research for this contaminant	○	○	○	○
Whether other organisations have indicated a need for research on this contaminant	○	○	○	○
Whether this contaminant is believed to present (somewhat) unique challenges to my organisation	○	○	○	○
Whether the contaminant has been confirmed to be present (occasionally or consistently) in water my organisation supplies or discharges.	○	○	○	○
Whether existing analytical techniques are available with suitable limits of detection	○	○	○	○

	Very important	Moderately important	Relatively unimportant	Not important at all
Whether the contaminant has been regulated by a relevant regulatory agency to my organisation	○	○	○	○
Whether there is a perception or belief that the contaminant may be regulated (or regulations tightened) in the future	○	○	○	○

Comments or clarification

6. Please indicate any other criteria, which may be important and were not effectively described in the previous question

Additional criteria: Whether...

Additional criteria: Whether...

Additional criteria: Whether...

Additional criteria: Whether...

Additional criteria: Whether...

Additional criteria: Whether...

Additional criteria: Whether...

7. Does your organisation apply a process for screening chemicals of concern based on expected environmental fate? If so, please describe the basic concepts and/or intrinsic parameters (Kow, water solubility, molecular charge, etc….) that are used.

8. In addition to the answer provided in Question 4, are you aware of any existing frameworks for emerging contaminant research prioritisation? If so, please provide details.

9. Are you aware of any other current or previous research on the prioritisation of emerging contaminant needs?

10. Can you propose a suitable methodology (in general terms) that could be adopted for the prioritisation of emerging contaminant research needs?

11. How important or useful do you consider it will be to develop a broadly available framework for prioritisation of emerging contaminant research needs?

12. How interested do you think you (or other members of your organisation) will be to use a prioritisation framework that might be developed from this research project?

13. Describe any particular features of a research prioritisation framework that would be important to you or your organisation

14. A discussion paper will be produced on the development of an emerging contaminant research prioritisation decision making framework. Please enter any email addresses that you would like to be included on communications regarding the availability of that discussion paper when it becomes available in May 2017.

Email address 1

Email address 2

Email address 3

Email address 4

Email address 5

15. Please provide any further information that you consider to be important or useful.

Thank you very much for the time that you have taken to complete this survey!

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