CANADIAN WATER NETWORK
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MANAGING UNCERTAINTY IN THE PROVISION OF SAFE DRINKING WATER

June 2012

Managing Uncertainty in the Provision of Safe Drinking Water

A report prepared for the Canadian Water Network

by

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Preface

The Canadian Water Network (CWN), Alberta Innovates-Energy and Environmental Solutions (AI-EES) (formerly the Alberta Water Research Institute), and the Ontario Centres of Excellence (OCE) initiated a collaborative effort to create the Canadian Municipal Water Consortium (CMWC) (formerly known as the Canadian Municipal Water Management Research Consortium (CMWMRC), a new initiative to engage those involved in the management and regulation of municipal water systems and allow them to access research capacity to tackle shared critical issues. In 2009, the challenges of managing uncertainty in the provision of safe drinking water were selected for focus by the CMWC. An international expert panel with scientists from Australia, Canada, the USA and Europe was assembled to work with a steering committee of municipal water providers and drinking water regulators to address this topic (Hrudey *et al*. 2011). This working group consisted of five invited expert panel members:

Steve E. Hrudey, Chair of Expert Panel, Faculty of Medicine & Dentistry, University of Alberta, Edmonton, Alberta, Canada

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William Leiss, McLaughlin Centre, University of Ottawa, Ottawa, Ontario, Canada

Joan B. Rose, Homer Nowlin Chair in Water Research, Michigan State University, East Lansing, Michigan, USA

Martha Sinclair, Department of Epidemiology & Preventive Medicine, Monash University, Melbourne, Australia

Three CMWC Project Steering Committee Members (Ian Douglas,[1] Ted Gillespie[2] and Donald Reid[3]) and five project sponsors and invited guests (Bernadette Conant,[4] David Hill,[5]

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[1] Water Quality Engineer and Plant Manager, Drinking Water Services, City of Ottawa, Ottawa, Ontario, Canada
[2] City Manager at City of Wetaskiwin, Wetaskiwin, Alberta, Canada
[3] Drinking Water Specialist, Drinking Water Branch, Alberta Environment, Edmonton, Alberta, Canada
[4] Executive Director, Canadian Water Network, Waterloo, Ontario, Canada
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Grahame Farquhar,[6] Laura D'Costa,[7] John Cooper[8] and Val Mellesmoen[9]) also provided input to the expert panel during the project.

This group was presented with a framing document outlining some key challenges before attending a two-day workshop in Banff, Alberta in July 2009. The following report was developed after that workshop through several drafts, and taking into account comments provided by all parties, including drinking water regulators. The document was revised after a follow-up project meeting in Ottawa, Ontario in January 2010 leading to the final draft. A summary paper (Hrudey *et al*., 2011) was produced as a consensus paper for presentation at the IWA World Water Congress in Montreal in September 2010. In addition to the foregoing presentation, these concepts were presented by Ted Gillespie at the Canadian National Conference on Drinking Water in Saskatoon, Saskatchewan in October 2010 and by Ian Douglas at the Water Quality Technology Conference of the American Water Works Association in Savannah, Georgia in November 2010. Subsequently, major aspects of the framing document have been presented by Steve Hrudey for the opening keynote address at *Ozwater11*, the Annual Convention of the Australian Water Association in Adelaide, Australia in May 2011, for the Annual Lorch Lecture, Prestige Lecture Series, at Cranfield University, Cranfield, UK in December 2011 and for the opening keynote address to the professional program of ACE12, the Annual Conference and Exhibition of the American Water Works Association in Dallas, Texas in June 2012.

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Managing Uncertainty in the Provision of Safe Drinking Water

Statement of Problem and Intent

Numerous and complex issues face drinking water providers and regulators who share the goal and responsibility for safeguarding public drinking water supplies. Our regulatory and management systems for drinking water collectively focus on the best response to addressing the many challenges and managing the various unavoidable uncertainties inherent in the task of ensuring delivery of high-quality drinking water. A frequent result, if not intent, of recent research has been to highlight numerous gaps and limitations in the knowledge that underpins our decision-making with respect to drinking water management. This project deals with clarifying a common framework and approach to management options, one that can be used by providers and regulators to approach management choices and underpin their commitment to the central task of maintaining a vigilant focus on the following:

How best can drinking water providers and their regulators address risk and uncertainty to assure safe drinking water?

Inherent in this question is the commitment to recognizing among the uncertainties the true priorities in terms of risks to public health that require action and prioritizing those actions *that can most effectively address them.*

To avoid any misunderstanding, this project does not propose or in any way advocate abandoning numerical water quality guidelines or standards as a core element for assuring safe drinking water. Rather, this project simply recognizes that having numerical guidelines, no matter how soundly developed, cannot by itself assure that consumers will be delivered safe drinking water. The numerical criteria that were to be met in Walkerton would have been adequate to disinfect the water supply and prevent illness among consumers if those criteria had been achieved. The Walkerton disaster happened because many elements of the operational and regulatory system failed to do what was necessary to assure that Walkerton's system was able to cope with a severe pathogen challenge. The operational aspects of continuously providing consumers with safe drinking water are complex and challenging, making it necessary to invest in the knowledge and capacity of the entire operational system, including the personnel and their ongoing training.

This project starts from the basic premises that:

- a precautionary approach to preventing adverse health outcomes from drinking water exposure inevitably involves dealing with a substantial degree of uncertainty.
- safe drinking water does not mean zero risk.
- zero risk is unattainable in any public health risk management issue.
- all professionals involved in the provision of safe drinking water share a goal of collectively managing uncertainty appropriately.

This project provides an over-arching framework that embodies the challenge question to provide a common conceptual approach to dealing with the challenges. Most of the intended application of this framework is to guide internal development within organizations to better equip them for dealing with the inevitable challenges. There is no expectation that most of what is presented here will be effective for communications with the public at this time.

The purpose of this project is to neither promote nor thwart any comment or criticism of any particular standard or practice related to drinking water. Rather, this project seeks to improve the quality and relevance of internal deliberations and debates by providing:

- a better framing of the underlying principles of health risk to clarify those aspects of the science that are relevant, and
- a better understanding of how these principles relate to the intended end goal of protecting public health.

A common framework of these principles can help to reduce the occurrence of professionals *talking past one another* in the course of health risk discussions or debate about how to effectively implement drinking water standards. Informing decisions and deliberations concerning water supply management may provide an improved understanding for the conceptual underpinning of various practices, guidelines and actions related to health risk as well as an ability to put them in “context” when approaching management or regulatory decisions. Promoting better understanding of the conceptual foundations of these issues surely cannot be a bad thing if drinking water provision is to be based on knowledge of the relevant science.

Ultimately, dealing with the challenges posed by the issues of health risk and drinking water safety will be well served by greater adoption of a *know your own system better* approach, such as that embodied in the water safety plan approach advocated by the World Health Organization. This needs to start from a basic recognition that providing safe drinking water is an intensely knowledge-based activity that requires all stakeholders to invest in and promote a greater emphasis in developing the knowledge and skills of front-line personnel.

Drawing upon a synthesis of available scientific evidence on public health risks from drinking water and its implications for developing a rationale for analysis of evidence our project seeks to achieve tangible progress in managing risk issues. The framework is built on the foundational principle that tangible progress is best achieved by ensuring that drinking water providers and regulators are served in their various roles by sharing a common understanding about what is known about risks, what level of confidence applies to our knowledge and what remains mostly uncertain.

Ensuring safety of drinking water supplies is not a new challenge. But key drivers that contribute significantly to the increasing complexity of this task include:

- A large and expanding list of drinking water contaminants of potential concern that both drinking water regulators and water providers must address.
- Continuing advances in analytical techniques that lower detection limits such that contaminants will be detected in future where they were not detected in the past, and usually in advance of any ability to formulate individual contaminant guidelines or understand the health implications of the contaminants at concentrations near the new detection limit.
- Lack of clarity on public expectations for “safe” water, combined with more frequent detection of trace contaminants or exotic chemicals, which are likely to undermine public confidence in what is safe water.
- A need to assure that the aesthetic quality of drinking water does not undermine public confidence in the safety of their water.
- A recognition that source water quality is rarely under the control of the water utility, making it necessary to achieve effective collaborative efforts among stakeholders who can protect source water quality.

The first two key drivers do not derive directly from the actions or intent of any particular group of scientists or regulators. These drivers are simply the result of an evolution of knowledge driven by advances in analytical capability that cannot be matched by more limited advances or the restricted capacity of toxicology or epidemiology to adequately characterize the corresponding risks to public health, particularly when the projected risks are extremely small. As a result, it is often very difficult to identify and maintain a focus on the relative importance of “new” and “additional” concerns among the many existing ones when endeavouring to *address risk and uncertainty to assure safe drinking water*.

Addressing the problem question and finding a shared approach to best options relies upon first adopting some common understanding of terminology for some core risk concepts. The following proposed definitions seek to serve that purpose.

Definitions

Before proposing a working concept of what we mean by safe drinking water, we must stress that this is **not** intended to be a regulatory or a legally enforceable definition; it is intended to promote greater perspective and understanding of relevant issues.

Safe drinking water can be interpreted to mean:

> *water of such consistent quality, posing no significant health risk, that a reasonable, accurately informed consumer need have no health concerns sufficient to justify seeking alternatives.*

No current legislation in Canada, including the Ontario Safe Drinking Water Act and the Guidelines for Canadian Drinking Water Quality, defines “*safe drinking water.*” Likewise, there is no definition of safe drinking water in the U.S. Safe Drinking Water Act. The World Health Organization (WHO 2011) states: “*Safe drinking-water, as defined by the Guidelines, does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages*.” The definition provided for this project is adapted from Justice O’Connor’s Walkerton Inquiry Part 2 Report — A Strategy for Safe Drinking Water (O’Connor 2002, p.75): “*The goal of any drinking water system should be to deliver water with a level of risk that is so negligible that a reasonable and informed person would feel safe drinking it*.” Our working definition is also consistent with the internationally developed goal of the Bonn Charter (IWA 2004) to provide “*Good safe drinking water that has the trust of consumers*.”

The absence of legislative definitions of safe drinking water likely reflects the reality that the designation of “safe” remains an individual value judgement, but the importance of water being “safe” for consumers is beyond question. The definition of safe drinking water adapted for this project means that a water provider must satisfy Justice O’Connor’s goal of providing drinking water that poses a negligible risk while also providing and using the knowledge about negligible health risks to allow a reasonable consumer to be accurately informed.

Relevance of Understanding of “Safe Drinking Water”

Safety and risk are opposite dimensions of water quality. Water that is unsafe is relatively easy to define. There is not likely to be any disagreement that the drinking water that killed seven consumers in Walkerton in May 2000 was clearly ***unsafe***. The challenge for drinking water providers and regulators is in determining, once water quality is improved sufficiently to avoid water being indisputably unsafe, how much further must the health risk be lowered for a reasonable consumer to accept it as safe.[10] This has conventionally been pursued by setting drinking water guidelines or standards for individual parameters on a precautionary basis to assure negligible health risk over a lifetime of human consumption (WHO 2011). Reasonable, accurately informed consumers will generally accept as safe, water that achieves such negligible levels of risk.

Some critical issues that this working concept brings into focus are that there is not a sharp dividing line between safe and unsafe. So while *unsafe* can be obvious, *safe* is much more difficult to reach consensus about. The concept that water that is technically safe, *e.g.*, safe to the satisfaction of the health experts, does not assure that all members of the public will agree. There is certainly scope for fostering greater appreciation of the complexities and pitfalls surrounding the notion of safe drinking water. If consumers are not convinced that their water is safe, even if health professionals are satisfied about safety there is a danger that consumers will seek alternative water supplies that are either needlessly expensive or that may not be as safe as the water they distrust. Alternatively, consumers

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[10] The consideration of safe vs. unsafe may be discussed with a traffic safety analogy that non-specialists may find helpful. Most drivers understand, if they think about it, that driving through a green light is essentially safe, although it does not carry zero risk because someone could drive through the simultaneous red light and cause a collision.

Driving through an amber light is not as safe as driving through green, but it can be done occasionally without attracting intolerable risks and under some conditions, *e.g.*, on icy roads with tailgaters, proceeding through amber is arguably safer than stopping.

Driving through a red light does not guarantee a collision, but doing so certainly dramatically increases one’s chances of a collision and hopefully we can all agree that driving through red lights is clearly **unsafe**. With this imperfect analogy, the meaning and intent of the red, amber and green light system of signals can be equated with setting quantitative guidelines for drinking water. There is a need for a nationally recognized system of signals that is standardized in its meaning, but establishing that basic system by itself cannot assure effective traffic risk management given all of the differences and needs of local specific requirements for intersection design, timing of lights, levels and means of enforcement and driver education programs.

who do not trust their water may lobby their politicians to pursue ineffective water treatment investments.

One clear benefit of the proposed working concept of safe drinking water is that it sets out the long-term goal of developing consumer trust in their water. That goal will require, among other things, better comprehension of the issues among all health professionals, a group that is generally trusted by the public more than other opinion leaders.

A challenge for drinking water providers and regulators arises when specific water quality monitoring yields detections approaching or somewhat exceeding these precautionary guideline values, or where guideline values do not yet exist. These circumstances will often raise the need for comparing and judging competing and often ill-defined risks, making a better understanding of risk and uncertainty essential.

Risk has different meanings for different individuals and professionals. A common technical approach to assigning a quantitative value to a risk estimate has been to calculate the product of probability times consequences. This approach does not address the complexity that is usually inherent in discussions of risk. A more comprehensive notion of **risk** is a multidimensional prediction (necessary to allow prevention) of what can go wrong consisting of the following elements (Kaplan and Garrick 1981, Renn 1992, Hrudey 2000):

- **Hazard** — the potential to cause harm (intrinsic capacity to cause damage).
- **Probability** — the likelihood that specified harm will occur for a specified scenario.[11]
- **Consequences** — the nature of harm that occurs (illness, disability, death) in a specified scenario.
- **Time frame** — the duration over which the risk is quantified (immediate, short or long term) will influence the numerical estimate of probability (chance of harm in a day vs. a lifetime)**.**
- **Personal perspectives**[12] of those affected — regardless of the quantitative elements of risk, individual judgements about importance will differ for the same set of "facts"

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[11] There are three major classes of probability: classical, frequentist and subjective (Kleindorfer *et al*. 1993). The latter is a well-respected field of mathematics based on Bayes' theorem, which refers to an individual's estimate (belief) in the likelihood that something will happen that is based on an individual's interpretation of available evidence. This process of risk estimation is, in fact, what risk assessors must do. The key distinction is that being subjective (a process related to an individual's analysis of evidence) does not mean being emotional or inherently irrational, although that may be the approach for some individuals. The challenge in choosing among different subjective estimates of risk is not to find out who knows the real risk, which is an inherently unknowable entity that has yet to occur, but to determine who has used the most rational analysis of the most relevant evidence in developing an individual (subjective) estimate of risk.

[12] This aspect of risk is often dismissed as merely the "perception of risk", as opposed to "real risk." Kaplan, a mathematician, and Garrick, a nuclear engineer, observed (1981): *"risk is relative to the observer. It is a subjective thing — it depends upon who is looking. Some writers refer to this fact by using the phrase "perceived risk." The problem with the*

based upon what a particular individual values (*e.g.*, which is worse, premature death or long-term, painful and severely incapacitating disease?).

Risks relevant to drinking water providers can take various forms, with substantially different characteristics, including:

Primary Risk of Concern

- Public health or occupational health risks

Additional Relevant Types of Risk

- Regulatory compliance risk
- Economic risk
- Consumer confidence risk
- Political or management risk

For a **public health risk** any threat that may cause illness in the public represents a *hazard*. For example, *Cryptosporidium* is a pathogen that is a *hazard* for most surface water supplies. However, the *risk* posed by *Cryptosporidium* for a water provider is a prediction of the probability that sufficient numbers of viable, infective *Cryptosporidium* oocysts will challenge and breach the water treatment barriers to allow the likelihood of infection among drinking water consumers. Public health risk estimates may be quantified in terms of probability and number of cases of illness.

For a **regulatory compliance risk** all quantifiable limits represent *hazards*. The compliance *risk* for a water provider is a prediction of the probability that one or more numerical guideline(s) or standard(s) will be closely approached or exceeded. Regulatory compliance risks may be quantified in terms of probability and the number and/or degree of non-compliance.

For an **economic risk**, any failure mode that results in economic loss is a *hazard*. The economic *risk* is a prediction of the probability and magnitude of an economic loss. Economic risks may be quantified in terms of probability and the dollar value of loss.

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phrase is that it suggests the existence of some other kind of risk other than perceived. It suggests the existence of an "absolute risk." However, under attempts to pin it down, the notion of absolute risk always ends up being somebody else's perceived risk." The notion that risk is subjective is often profoundly uncomfortable for scientists and engineers, yet the inherent role of probability in any technical definition of risk makes it necessary to also confront the notion of subjective probability, which upon reflection will be found to be the most relevant class of probability for risk assessment.

For a **consumer confidence risk**, any circumstance that may undermine consumer confidence in the water supply is a *hazard*. The consumer confidence *risk* is a prediction of the probability and characteristics of a set of circumstances where consumer confidence is lost. Consumer confidence risk may be quantified by means of consumer confidence surveys.

For a **political or management risk**, anything that may undermine the confidence of political leaders or management regarding water operations is a *hazard*. The political or management *risk* is a prediction of the probability and characteristics of a set of circumstances where political or management confidence is lost. Political or management risk is difficult to quantify but is still a valid concern.

Any drinking water problem or scenario is likely to involve one or more of these classes of risk. Rational decision-making will need to make effective choices about which risks demand specific responses with an appropriate consideration of priority. Other than the inescapable pre-eminence of public health risk, no universal guidance can be given about dealing with the other types of risk. However, recognizing the nature and drivers for other forms of risk may lead to better understanding of such risks making possible more informed decisions.

The Challenge to Considering Complexities of Risks and Risk Comparisons

The multi-dimensional character of risk, in addition to providing complexity, precludes assured reliance only on a ranking of numerical risk estimates to address all the issues of concern. This caution results from there being no strictly objective (*e.g.*, absolutely free from individual judgement) way to weight the various elements contributing to a risk, let alone the comparative uncertainty in those estimates (Hrudey 2000). Even an assumption that all elements should be weighted equally is a judgement choice, it cannot follow uniquely from any scientific analysis of the problem.

Comparing the different classes of risks is fundamentally challenging because they can differ so completely in their characteristics and units of measure. However, even comparing risks within a single category is challenging. For example, consider the issues if we attempt to compare health risks of infection posed by inadequate disinfection of drinking water versus the formation of disinfection by-products with possible risks of cancer or adverse reproductive outcomes. A simple numerical comparison of probabilities of harm between these competing risks inevitably involves a comparison between different consequences (*e.g.*, gastrointestinal illness vs. cancer), not to mention the frequently overlooked, but substantially different levels of uncertainty about the ability of the contaminant to cause a specified adverse consequence as a result of plausible drinking water exposures. There have been attempts to address this comparison by finding a common metric (*e.g.*, disability adjusted life-years) for dissimilar outcomes (Havelaar *et al*. 2000, Ashbolt 2004), but the common metric necessarily incorporates value-driven weighting. The comparison also did not address the substantially differing certainty about drinking water being the cause of the adverse outcomes. There is comparative certainty that pathogens in drinking water can lead to gastrointestinal illness among consumers attributable to the direct causative mechanism of pathogen infection and consequent illness. This certainty stands in sharp contrast to the inherently uncertain epidemiological evidence and lack of direct toxicological evidence for elevated risks of bladder cancer or adverse reproductive effects from exposure to disinfection by-products. Consequently, any attempt to address drinking water safety and risks in context must confront uncertainty in its various forms.

Uncertainty

Uncertainty can usually be characterized as being some combination (Finkel 1990, Hoffman and Hammonds 1994) of knowledge uncertainty (sometimes called true uncertainty or ignorance) and variability (sometimes called heterogeneity).

Knowledge uncertainty is the inadequate understanding of a risk resulting from limited or no knowledge about one or more elements of the risk. **Variability** is uncertainty caused by the existence of multiple true values of relevant factors like degree of exposure, susceptibility, etc. In such cases of heterogeneity, risk will differ depending on which factors apply to a set of circumstances, but there is no certainty about which values should apply to specific circumstances.

Uncertainty is inherently involved in any health risk because of numerous factors, including:

- Uncertainty about the specific nature of a hazard (*e.g.*, What adverse effect(s) occur(s)? What levels of exposure are required?).
- Uncertainty about the ability of a hazard to cause relevant adverse outcomes at plausible drinking water exposure levels (*e.g.*, What is the evidence of causation?).
- Probability estimates that are invariably less than 100%, making occurrence for any particular time and place uncertain.
- Probability estimates that must be based on subjective probabilities, often with little frequency-based evidence making for necessarily high uncertainty in probability estimates.
- Uncertainty associated with analytical measurements. Are samples representative?

- Uncertainty about health effects from combinations of contaminants. Are effects additive or could there be synergistic or antagonistic effects?
- Variability in consequences because of individual differences in exposure (How much or does any individual drink the water?) or susceptibility (How susceptible is an individual to an adverse outcome?).
- Variability among individuals in their individual time windows (*e.g.*, visitors vs. long-term residents for short-term exposure; infants vs. seniors for lifetime exposure).
- Variability in perspectives of what is most important among different individuals (*e.g.*, How much is anyone willing to pay to reduce a very small risk even lower?)

These factors in uncertainty range from primarily technical issues to some that involve differing value judgments (*e.g.*, willingness to pay).

What can be done to address complex risks with dominant uncertainty?

Getting Beyond a Numbers Only Approach

Risk with its inevitable uncertainties is a much more complex matter than is immediately evident to professionals or the public. Faced with massive complexity, the natural human response is to simplify a problem to make it more manageable in terms of a response. While simplification is a rational response, simplification can be dangerous if it is based on a flawed understanding of reality (*e.g.*, ignoring or misunderstanding key drivers).

A good illustration of how a simplification of the problem may be driven by the best intentions and at first appear logical on the face of it was provided by a report prepared for the David Suzuki Foundation entitled "*The water we drink*" (Boyd 2006); see www.davidsuzuki.org/Publications/Water_we_drink.asp. This report compared the Guidelines for Canadian Drinking Water Quality with those of Australia, the European Union, the US EPA and the World Health Organization. Its finding is captured in its first recommendation:

"*The Canadian Guidelines for Drinking Water Quality should be replaced by a set of health-based long- term objectives for drinking water quality, and legally binding national standards for drinking water quality that are equal to or better than the highest standards provided in any other industrialized nation*."

This recommendation included a table of 53 parameters showing the current Canadian Maximum Acceptable Concentration (MAC) and a more stringent recommendation based on the lowest published number found in any of the other jurisdictions. This simplistic idea that setting standards at lower concentrations would increase drinking water safety missed the reality, among other things, that many of the lower numbers being proposed were not based on a thorough health risk assessment, but rather on an arbitrary detection limit. As an aside it is worth noting the paradox of the standard protocols for guideline derivation that substances that have been well characterized toxicologically will normally have fewer uncertainty/safety factors applied in deriving the guideline number. Those substances for which data are limited in quality or quantity will normally get more safety factors applied, which results in a lower, more stringent guideline value. This practical reality undermines the intrinsic meaning of comparing guideline numbers between parameters without considering the evidence that was used in deriving the guideline. For example, a jurisdiction that made greater use of the best evidence might conceivably develop a higher guideline number compared with another jurisdiction that made less use of available evidence, preferring to use larger or more uncertainty/safety factors instead.

A mature and careful analysis of the diverse nature of risks facing drinking water providers will reveal that focusing only on monitoring treated water samples against the final "numbers" generated by numerical drinking water guidelines or standards will not assure safe drinking water (IWA 2004, NHMRC 2011, WHO 2011). Of course, published health based guidelines and promulgated regulatory limits based on them play an essential role in setting targets and establishing and ensuring compliance in limiting contaminant exposures via drinking water. But, operating within the numerical parameter limits, considerable scope remains for regulators and providers to develop strategic monitoring programs and operational practices to assure that the drinking water delivered is truly safe.

The premise that simply monitoring for a long list of contaminants should be the first priority for improving drinking water safety does not accord with experience or public health evidence about illness caused by drinking water (Fawell & Niewenhuijsen 2003, Hrudey 2009, Hrudey & Hrudey 2004, Sinclair & Rizak 2004). Adding contaminants to a monitoring list certainly adds cost but, by itself, does not assure safety (Callan *et al*. 2002, Hrudey *et al.* 2006, Rizak & Hrudey 2007a, b). A focus only on monitoring of lists of contaminants can distract from managing important operational issues and becomes unmanageable for small- and medium-sized operators.

Even if resources were not an issue, there is an inescapable reality that monitoring for rare hazards encounters diminishing returns in the value of information obtained (Hrudey & Leiss 2003, Hrudey & Rizak 2004, Rizak & Hrudey 2006). The concept of diminishing returns is most readily demonstrated by the futility of calls for pursuing zero risk as a viable target or as a definition of safety (Hrudey & Krewski 1995).

Rather than pursuing a monitoring-against-numbers-only approach, recent international progress for assuring drinking water safety has been based upon a water safety plan or preventive risk management approach (IWA 2004, NZMOH 2005, Sinclair and Rizak 2004, WHO 2011, NHMRC 2011). These preventive approaches are directed towards knowing and fully understanding one's system, the contaminant challenges it faces and the capabilities and limitations of the water safety barriers that are in place to deal with the system's contaminant challenges. The water safety plan approach of the WHO and the Australian Drinking Water Guidelines advocates a comprehensive risk management approach that is essentially preventive rather than reactive in scope. Achieving the basic elements of the water safety plan approach promoting knowledge of one's own system should preclude allowing disastrous failures like the Walkerton outbreak that occurred primarily because of the absence of such knowledge.

In keeping with a water safety (preventive risk management) plan approach, our current knowledge about risk and comparative uncertainty can be used to propose a hierarchy of drinking water safety risks. The rationale for this approach is explained to provide individual water providers with the flexibility to adapt this risk hierarchy for local needs.

Making More of What We Know

While uncertainty can seem to be overwhelming at times, we ought not lose sight of all that we have learned about water quality and water treatment through decades of research and practice. For example, we can start with a characterization of water quality parameters (Figure 1).

Every water quality parameter has associated physical, chemical or biological characteristics that are inherent properties. These properties predict how a substance will behave in water (if suspended, it may settle; if volatile, it may vapourize from water; if biodegradable, it may biodegrade easily, etc.).

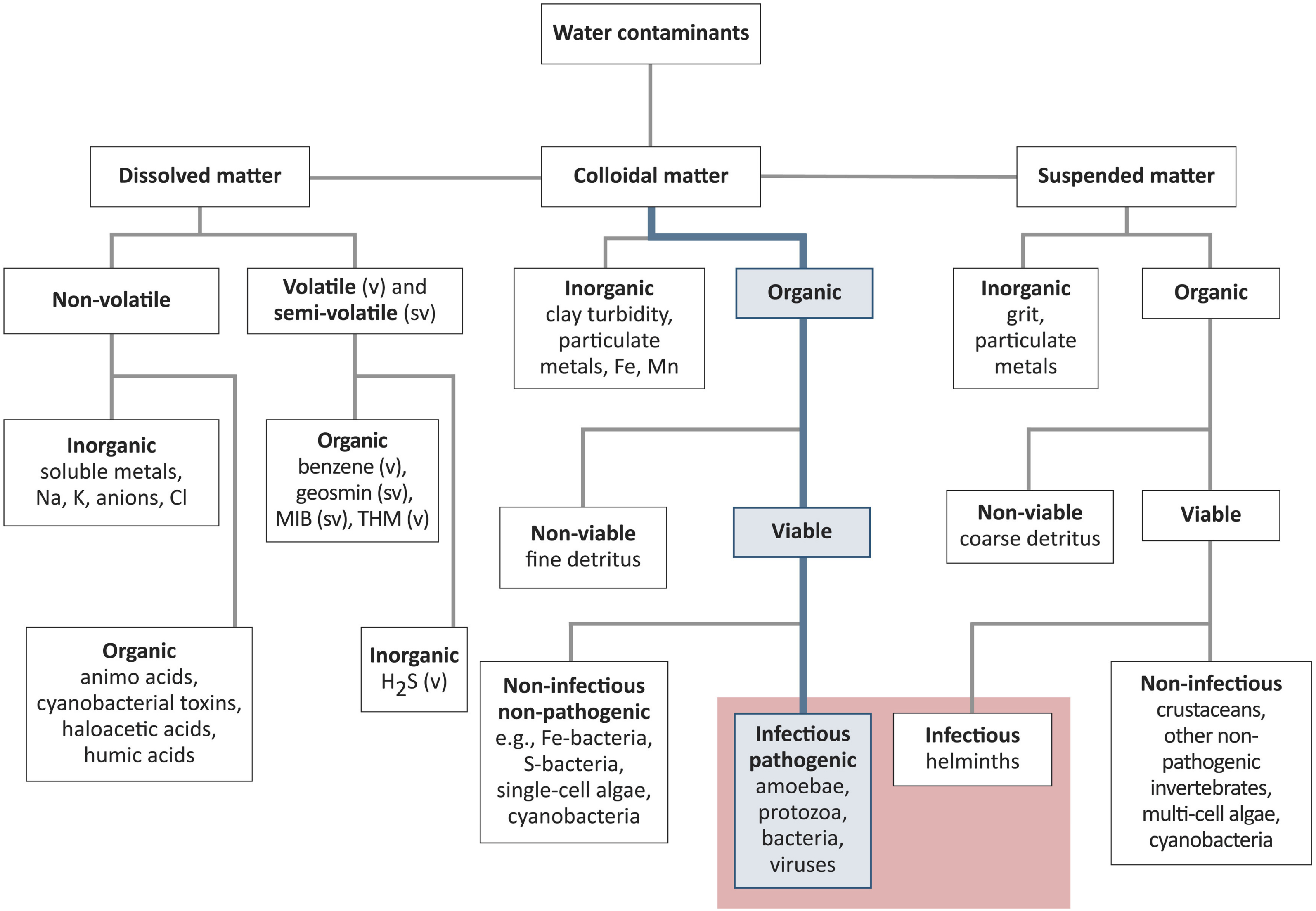
Likewise, our water treatment processes are designed to exploit the physical, chemical and biological properties of substances to remove, modify or destroy particular parameters. Because a process is aimed at removal of a particular parameter does not prevent that process from also removing other parameters with similar properties.

While it is not a simple task, and much information about the physical, chemical or biological properties of individual substances is likely missing, much can be estimated by general knowledge, by comparison with similar substances or by inferential processes like structure-activity relationships. There is likely much scope for making better use of how we look at the ability of existing or proposed treatment barriers at affecting the transmission of new or emerging contaminants through a water treatment process.

A Risk Hierarchy Approach to Incorporating Uncertainty

Any strategy to prevent harm arising from unsafe water necessitates a committed effort to harnessing the predictive value of risk assessments to assure that adequate water safety barriers are in place to address the specific challenges faced. The inevitable need to deal with assessed risks demands a rational way to deal with different types of risk. This approach must assure that the most critical risks receive the highest priority while less critical risks are given the less urgent level of attention they warrant. Simplistic numerical comparisons of risk estimates are fundamentally unreliable. Therefore, an effective framework that supports consensus judgements among operational personnel with concurrence from the regulator on relative magnitude and certainty of risks offers the best means for using available knowledge.

Figure 1. Classification of Water Quality Parameters (Hrudey & Hrudey 2004).



Among the types of risk that may arise, the following priorities are recommended. Local circumstances may justify some re-ordering in specific circumstance, but the pre-eminent position of health risk should always remain.

Pre-eminent Risk

1. Public health or occupational health risks

Additional Risks

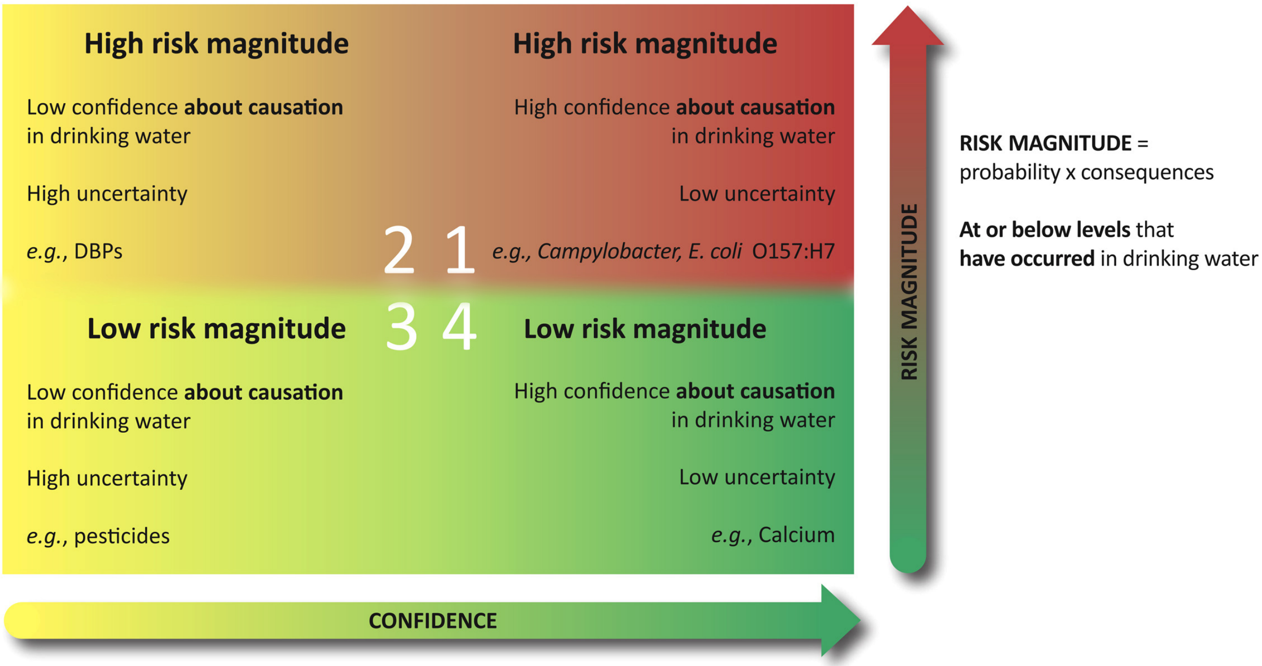
2. Regulatory compliance risk
3. Economic risk
4. Consumer confidence risk
5. Political or management risk

Recognizing a pre-eminent position for health risk, even if one or more other categories of risk may be relevant, suggests a priority need to further categorize health risks associated with drinking water quality in a rational manner. A risk hierarchy is proposed that can be adapted to fit local needs, based on a clear understanding of the hierarchy logic.

1. **Highly certain and pervasive risks**
    - **require action for any water system** — these are best represented by the microbial pathogens that are known to cause human disease via drinking water exposure and because of their fecal origin present a pervasive risk to all surface water systems, many groundwater sources and to all distribution systems.
2. **Reasonably certain but less pervasive risks (appearing in some drinking water systems)**
    - **should be identified and addressed as demonstrably necessary** — various parameters have provided essentially certain evidence of causing human illness (or adverse effect) via drinking water exposure at some time, somewhere in the world (*e.g.*, arsenic, fluoride, nitrates and lead — WHO 2007). These will be site-specific and only apply to some water providers.
3. **Common but comparatively uncertain risks (*e.g.*, produced in water treatment)**
    - **require a rational precautionary response** — various parameters (*e.g.*, DBPs, aluminum, water treatment chemicals) warrant scrutiny because they are produced or added in the water treatment process, are very common and may be amenable to reduction through process refinements.

4. **Site-specific contaminants with noteworthy toxic potential**
    - **require localized plans commensurate with risk** — various parameters (*e.g.*, pesticides, cyanobacterial toxins) with toxic potential relevant to drinking water exposure and that can be found in water need to be assessed to determine site-specific relevance and appropriate local action.
5. **Emerging contaminants**
    - **require research to characterize nature of problem** — advances in analytical chemistry guarantee that many contaminants will continue being identified in drinking water and these require research to characterize their nature to determine if they pose a drinking water health problem vs. a hypothetical problem. Once research has adequately characterized the risks, and the importance of drinking water relative to other sources of human exposure, such emerging contaminants may be classified into an appropriate category above. In the meantime, treatment barriers should not be altered unless there is reasonable certainty that such alterations will not simply create other, as yet uncharacterized risks.

The logic underlying these categories is captured in figure 2, based on scales of confidence (in the ability of a hazard to cause human illness via drinking water exposure) in the horizontal axis and risk magnitude (a product of probability times consequences occurring at exposure levels at or below levels that are known to have occurred in drinking water). Pervasive or highly prevalent risks will have higher probability for the risk magnitude estimation.



CONFIDENCE about **disease causation** must be specific to drinking water exposure

Figure 2. Categorization of Risks According to Risk Magnitude and Uncertainty.

The risk hierarchy deals mainly with risks that appear in quadrants 1 or 2 of figure 2. Well-characterized microbial pathogens (*e.g.*, *Campylobacter*, *Cryptosporidium*) would generally fit in quadrant 1. Disinfection by-products would fit in quadrant 2 because of their widespread population exposure and serious suspected outcomes and because of the major uncertainty associated with evidence that they have caused human disease via drinking water exposure. Most trace contaminants (*e.g.*, pesticides) would normally fit in quadrant 3 because the exposure level typically found in drinking water is very low and usually not widespread and the confidence that such low-level exposures can cause human health effects is low. Emerging contaminants may belong in quadrant 2 or 3 with research hopefully eventually reducing uncertainty to allow confident reassignment to quadrants 1 or 4. Substances with well-known but very limited toxic properties, *e.g.*, iron, calcium, would fit in quadrant 4. The latter risks are logically at the bottom of any risk comparison because of their characteristics of being low risk magnitude with a high degree of certainty.

Other Tools to Support Risk-Based Decision-Making

In addition to the background about risk and uncertainty and the primary logic of a risk hierarchy, this project will develop a number of other tools to support individual water providers and their regulators in their decision-making. These should include:

1. An explanation of the science underlying risk assessments and how scientific evidence is used to assess health risk for drinking water substances, including illustrations of key elements (*e.g.*, probability estimation) and default assumptions that must be relied upon that would allow water providers and front-line regulators to look beyond the numbers.
2. A toolkit of what would contribute to making an informed consumer.
3. A basic primer on water safety plans with appropriate references and web links and case studies.
4. Case studies to illustrate how the risk hierarchy logic could have been applied
5. An explanation of a rationale for strategic water quality monitoring
6. An outline for a public communication strategy about health risk

Other tools that would be desirable for this project include:

1. A summary table of MAC values that elaborates all the key elements that have contributed to their determination by risk assessment (*e.g.*, uncertainty factors, animal or human evidence, etc.)
2. An application of the hierarchy table applied to current MACs and parameters actively under consideration for MAC development to illustrate how it might apply.

3. An approach based on the application of physical, chemical and biological properties of substances to allow for a better mapping of contaminants against the capabilities of treatment barriers in place.
4. Recommendations on basic quality assurance requirements for water quality monitoring — guidance on interpreting analytical uncertainty (microbial and chemical) and particular advice on validating evidence for non-compliance and to aid decision-making if advisories may be necessary.

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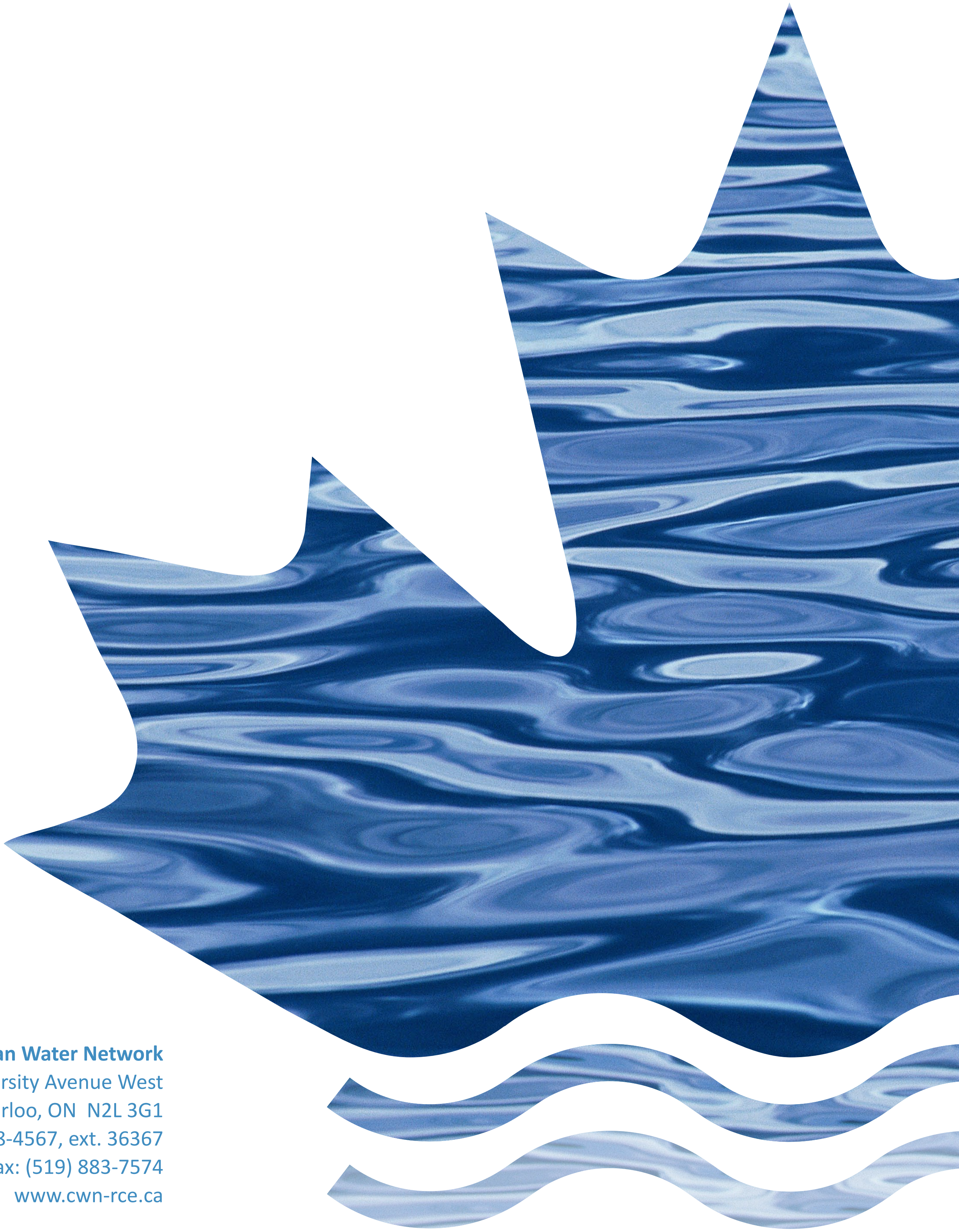

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