Converting Hindsight into Foresight

Evidence Prepared for Water New Zealand

for submission to
Government Inquiry into Havelock North Drinking-Water

by

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Mr. John Pfahlert
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Re: Evidence for the Government Inquiry into North Havelock Drinking Water

Dear Mr. Pfahlert:

With full understanding of the importance of the North Havelock Inquiry to ensure the future safety of drinking water in New Zealand, I am grateful for the opportunity to share the evidence about underlying causes of drinking water outbreaks that I have gathered over the past 16 years. My involvement in providing advice to Justice Dennis O'Connor, Commissioner of the Walkerton Inquiry set me on a path of gathering and analyzing reports of drinking waterborne outbreaks in nations that clearly have the economic resources to ensure that drinking water should be safe. That evidence has now been captured in two books, co-authored with my wife, Elizabeth J. Hrudey and published by International Water Association publishing in 2004 and the American Water Works Association in 2014.

Thank you for providing this opportunity to assist. Please do not hesitate to seek clarification from me about any element of the attached evidence.

Yours sincerely,

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Table of Contents

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1. OUTLINE OF RELEVANT QUALIFICATIONS FOR AUTHORING THIS BRIEF

Dr. Steve E. Hrudey, FRSC, FSRA, IWAF, FCAE, FEC, FGC(Hon), PhD, DSc(Eng), PEng, is Professor Emeritus, Analytical and Environmental Toxicology, Faculty of Medicine and Dentistry, University of Alberta. He has been engaged in environmental health sciences research and practice for 46 years. While working with the Australian National Health and Medical Research Council (NHMRC) working group to develop a Framework for the Management of Drinking Water Quality from 1999 to 2002, he also served on the Research Advisory Panel (RAP) to the Canadian Walkerton Inquiry (WI) from 2000 to 2002. This inquiry was conducted by Justice Dennis R. O'Connor into a drinking water outbreak in Ontario, Canada's largest and wealthiest province, that caused 7 fatalities and over 2,300 cases of illness because livestock manure carrying *E. coli* O157:H7 and *Campylobacter* spp contaminated a groundwater supply. In serving the RAP of the WI, he was asked to prepare a report to guide Part 2 of the WI aimed at preventing a future re-occurrence by analyzing relevant drinking waterborne outbreaks that had occurred elsewhere. After the completion of the WI, Dr. Hrudey and his wife Elizabeth, a microbiological technologist and technical writer, expanded on the report for the WI to publish a book of case studies of drinking water outbreaks.[1] This 500+ page book published in 2004 by International Water Association Publishing provides analyses of over 70 reported drinking water outbreaks in 15 affluent countries (including New Zealand) over the previous 30 years. Since then they have published a follow-up book of detailed case studies of drinking water contamination specifically written to promote experiential learning for front-line personnel.[2]

In 2006, Dr. Hrudey served on a three-member expert panel addressing safe drinking water for First Nations (aboriginals) in Canada that was tabled in Parliament and ultimately formed the basis for the Canadian Safe Drinking Water Act for First Nations. In 2011, he presented the opening keynote address to Ozwater 2011, the annual meeting of the Australian Water Association (AWA) in Adelaide and he chaired an international workshop for AWA that resulted in the 2012 International Water Association Publishing book "*Disinfection By-Products and Human Health*". The American Water Works Association awarded him its highest research award, the A.P. Black Award in 2012. In 2014 he chaired an international expert panel in Washington for the Water Research Foundation (WRF) resulting in the 2015 WRF Report Evidence for Association of Human Bladder Cancer with Chlorination Disinfection By-Products, the first independent, comprehensive review of this topic in decades.

Since 2000 and his engagement in the Walkerton Inquiry, Dr. Hrudey has published 4 books, 16 book chapters, 63 refereed journal articles and participated in 12 expert panels all specifically addressing drinking water quality and safety. Since 2013 he has conducted training workshops for front line drinking water personnel (operators, managers and regulators) in Australia (11), Canada (8) and the USA (2). He has testified 6 times before Parliamentary Committees in Canada and once before the Legislative Council of Western Australia.

2. OVERVIEW SUMMARY OF EVIDENCE

The evidence for this analysis is based on a review of international experience relevant to the provision of safe drinking water in New Zealand. The evidence includes 38 outbreaks of serious drinking waterborne disease occurring in 13 affluent countries (9 in the USA, 7 in Canada, 6 in England, 3 in Finland, 2 each in Denmark, Norway, Sweden, Switzerland and 1 each in Australia, Ireland, Japan, New Zealand, and Scotland). These resulted in a total of 77 fatalities in 9 fatal outbreaks and they caused over 460,000 cases of gastrointestinal illness in the 38 outbreaks considered. All these outbreaks were preventable if the threat posed by microbial pathogens in drinking water had been recognized and suitable preventive measures had been implemented and consistently maintained.

The experience captured in this review goes intentionally beyond the specific details of the North Havelock outbreak in order to serve the purpose of Part 2 of the Inquiry. The 38 case studies were chosen on the basis of relevance to the provision of safe drinking water anywhere in New Zealand, a country with substantial agricultural activity, generally low population density and many small to medium size communities.

This review of international experience is organized according to 6 well-established principles for ensuring safe drinking water that were first developed in 2001 at an expert meeting in Adelaide, South Australia between the World Health Organization microbial pathogens expert group and the National Health and Medical Research Council of Australia working group on revising the Australian Drinking Water Guidelines. These principles are used for this document because they have stood the test of time and continuing experience.

The first and by far the most important of these principles is: "*The greatest risks to consumers of drinking water are pathogenic microorganisms. Protection of water sources and treatment are of paramount importance and must never be compromised.*" Unfortunately, an initial review of evidence from Part 1 of this Inquiry clearly indicates that those responsible for the safety of the North Havelock drinking water supply and hence the health of the community's consumers apparently had not embraced any of these guiding principles for ensuring safe drinking water. In particular, there was remarkable urgency demonstrated in ceasing chlorination after the minimum time allowed for attaining clear results after the 2015 *E. coli* contamination incident, yet there was no apparent urgency in obtaining results for an investigation to explain what had caused the microbiological contamination in the first place. This circumstance makes it difficult to avoid a conclusion that chlorination was seen as a greater concern than microbial contamination. If chlorination is regarded as untenable for consumers, for whatever reasons, then water purveyors and public health officials are obliged to require investment in alternative disinfection technologies with all of the attendant costs, treatment and reticulation system maintenance obligations that may be associated with those technologies.

The North Havelock outbreak was severe in its consequences, but the vulnerability that allowed it to occur could have resulted in an even more severe outcome. In particular, if livestock faecal contamination had included the pathogen *E. coli* O157:H7, the pathogenic strain of *E. coli* that was involved in the fatal Walkerton outbreak and in fatal outbreaks in Cabool, USA, Saitama, Japan and Washington County, USA, fatalities and severe illness among young children could have occurred in North Havelock.

Drinking water contamination events causing human illness are inevitably complex, but the root causes are remarkably common and simple – risk assessment needs to be tiered with global common cause issues understood first before greater detail on contributory causal factors is pursued and elaborated. While detail is ultimately important, the complexity arising from site specific details must not be allowed to interfere with achieving a thorough understanding of whether the overriding principles are being respected.

Ultimately, providing safe drinking water is an exercise in risk management. The Walkerton Inquiry into the fatal outbreak in Ontario, Canada in May 2000 described some essential characteristics of risk management as:

- Being preventive rather than reactive.
- Distinguishing greater risks from lesser ones and dealing first with the former.
- Taking time to learn from experience.
- Investing resources in risk management that are proportional to the danger posed.

International best practice for achieving risk management has been developed around the water safety plan approach. That approach, which is intended to be inherently preventive, can only be as effective as the care and commitment invested in preparing and continuously updating it allows. A water safety plan must be conscientiously developed and truly owned by those who must use it, not by an external third party. If a water safety plan is not owned by those running the water system it may become just another document taking up space on an office shelf.

Systemic problems that are evident in many of the international outbreaks reviewed and are certainly evident in North Havelock and likely elsewhere in New Zealand are the resource limitations and inadequate capabilities of small water purveyors. Although providing drinking water of adequate quality can often be comparatively routine, provision of high quality, safe drinking water 24 hour a day, 7 days a week, 365 days a year is a challenging interdisciplinary responsibility. Ensuring safe drinking water in the face of the pervasive challenge posed by microbial pathogens and the countless ways that pathogen contamination can occur is a daunting technical challenge. Allowing a fragmented system of drinking water supply by many small jurisdictions is a common problem worldwide that inevitably contributes to vulnerability for contamination. Some jurisdictions including England and the states of South Australia, Victoria and Western Australia have addressed this risk by creating larger, capable, regional or statewide water authorities to provide the critical mass of expertise for ensuring safe drinking water. Such measures are politically difficult to implement, but they can be remarkably effective.

Ultimately, a drinking water purveyor can only be relied upon to consistently provide safe drinking water if those responsible for delivering public drinking water take personal ownership of the considerable public health responsibility that providing drinking water entails. There should be no room for complacency among those who must accept this responsibility.

In closing, the common theme across all of the international outbreak evidence is one of complacency. Our affluent societies have known for many decades how to prevent outbreaks yet we continue to allow them to happen by failing to do what we know needs to be done. In this sense, an analogy may be drawn with recurring outbreaks of communicable diseases like measles and mumps that occur because of a failure to maintain adequate immunization. These circumstance reveal the inevitable tension between individual rights and societal benefit. In the case of drinking water, individual biases about water disinfection and treatment should not be allowed to endanger innocent consumers, especially when such biases are based on urban myths and are not founded on authentic public health evidence.

3. INTRODUCTION

Safe drinking water is essential for human life. We have known since the 1850s, decades before microorganisms were isolated and identified, that drinking water contaminated with faecal matter caused serious human disease and death. We have known for almost a century how to manage and treat drinking water to reduce the risk of drinking water disease transmission to almost negligible levels. Despite these advances, which must rank among the greatest public health measures in human history for improving quality of life and overall life expectancy, the World Health Organization (WHO) estimates that hundreds of thousands of deaths still occur every year around the world caused by diarrheal diseases attributed to contaminated drinking water, poor sanitation and hygiene. Almost half of these deaths are among children under 5 and they are preventable with relatively low cost intervention. This toll of disease and death is caused by microbial pathogens of faecal origin.

For humans fortunate enough to live in affluent nations, the disease and death toll from contaminated drinking water is much lower, but drinking water disease outbreaks continue to happen in all the richest countries of the world. Our advanced technological societies know the narrow, direct cause of these outbreaks; drinking water becomes contaminated through one or more pathways by microbial pathogens from human or animal faecal matter in sufficient numbers to infect human consumers and cause disease. We have refined and expanded the details of our knowledge of this basic, direct cause over many decades. We also have an enormous research knowledge base about how to treat drinking water to prevent this cause of disease. Our knowledge makes it feasible to treat even pathogen-contaminated sewage to a level that poses negligible risk of causing disease, provided the advanced treatment measures are rigorously maintained. Direct potable water reuse is expensive, but it can be done. Yet, despite all of our knowledge and technology, drinking water disease outbreaks remain a public health threat everywhere.

Why?

The harsh reality is that our advanced societies keep demonstrating an inability to learn from our continuing experience with the failure of management systems. Overall, we know what needs to be done, but we keep making avoidable mistakes. The underlying reason is a failure to focus on the key principle that protecting public health must be the paramount objective for managing drinking water systems. That core objective must not be compromised for any other objective. Of course, as the North Havelock Inquiry has clearly demonstrated, there is considerable complexity involved in the specifics of any particular drinking water system and the many ways that it can fail. There are countless thousands of pages of detailed information about various technical issues relevant to allowing failure. Pursuing a narrow focus on some of these details of a specific incident while losing sight of the paramount objective to protect public health will inevitably allow slightly different failure scenarios to occur in the future. An appreciation of this reality led to the genesis of the water safety plan rationale that was reflected in the 3rd Edition (2004) of the WHO Drinking Water Guidelines. This approach intended to focus on water purveyors and their operational staff taking ownership of their responsibilities for providing safe drinking water to their consumers. They can do so by thoroughly knowing their own systems, the threats these systems face and the capabilities they have for meeting those threats. They must know what measures (multiple barriers) their systems provide to deal with those threats to public health, how capable those measures are functioning on a continuing basis and how well do our management systems ensure that all of this knowledge is generated and continuously updated and applied.

The genesis of this preventive vs. reactive approach to ensuring safe drinking water can be traced to efforts, parallel to the WHO, by a working group of the Australian National Health and Medical Research Council (NHMRC) starting in 1999 to restructure the Australian Drinking Water Guidelines (ADWG) by placing them within the *Framework for Management of Drinking Water Quality.* In May 2001, the NHMRC Working Group met in Adelaide, South Australia with the microbial pathogen working group of the WHO to exchange views on dealing with this challenge. Thereafter, NHMRC published drafts for consultation and seconded one of its senior officials to WHO in Geneva that ultimately led to much of the NHMRC document being used, essentially verbatim, in the WHO description of the Water Safety Plan approach.

At the May 2001 Adelaide meeting,[a] a working session of the gathered international water safety experts was dedicated to generating a short list of key principles[b] that could be treated as "***read me first***" principles to aid with the interpretation of the otherwise inevitably large and complex drinking water guidelines.

3.1 Guiding Principles for Assuring Safe Drinking Water - ADWG[3]

1. ***The greatest risks to consumers of drinking water are pathogenic microorganisms. Protection of water sources and treatment are of paramount importance and must never be compromised***
   Pathogens clearly pose the greatest tangible human health risk from drinking water, in part because we keep providing proof of this principle by failing to prevent drinking water disease outbreaks.
   a) Faecal sources of pathogens are pervasive – they are found anywhere there are people, pets, livestock or wildlife, i.e., everywhere.
   b) There is no uncertainty about ability of waterborne pathogens to cause human illness via drinking water exposure.
   c) Extremely small quantities of faecal matter have demonstrated a remarkable capacity to contaminate drinking water to levels capable of causing disease because of the extremely large number of microbial pathogens per unit mass of faecal matter.

2. ***The drinking water system must have, and continuously maintain, robust multiple barriers appropriate to the level of potential contamination facing the raw water supply.***

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[a] New Zealand was effectively represented in Adelaide in 2001 by Dr. Michael Taylor on behalf of the New Zealand Ministry of Health.

[b] These Principles were developed from a joint meeting between Australian drinking water leaders and the Drinking Water Guidelines Group of the WHO held in Adelaide, South Australia, May 2001. These principles were generated by having the assembled experts work in smaller breakout groups to answer the question: "*If you could only tell someone responsible for drinking water 2 things what would they be?*". The collected wisdom of these international experts was ultimately distilled down to the 6 principles shown by the NHMRC Working Group.

Robust multiple barriers are essential to ensure the paramount objective of preventing the occurrence of drinking waterborne disease from affecting consumers.

a) Any individual water treatment barrier can fail.
b) Treatment barriers must be operationally monitored in real time to verify their effective function.
c) Individual barriers must be maintained otherwise multiple barriers can be reduced to a single remaining barrier thereby defeating the intended precautionary purpose of having multiple barriers.

3. ***Any sudden or extreme change in water quality, flow or environmental conditions (e.g. extreme rainfall or flooding) should arouse suspicion that drinking water might become contaminated.***

   Trouble is inevitably preceded by some kind of change.

   a) Change does not necessarily guarantee trouble, serious trouble is often rare, however changes must not be ignored.
   b) Operators must understand what is normal for their own system to be capable of recognizing and interpreting whether any change is important.
   c) Hindsight makes changes that were ignored appear obvious and incriminating.

4. ***System operators must be able to respond quickly and effectively to adverse monitoring signals.***

   Operators must be capable and responsive.

   a) Knowledgeable, committed operators provide the best assurance of safe drinking water for any system.
   b) Operators need training in the public health consequences of failure, not just mechanical issues of operating a system.
   c) When trouble does happen, operators are often unfairly blamed when management systems have been clearly deficient.

5. ***System operators must maintain a personal sense of responsibility and dedication to providing consumers with safe water, and should never ignore a consumer complaint about water quality.***

   Drinking water professionals, ranging from frontline personnel to managers and regulators must be accountable to consumers. This responsibility to consumers applies not only to operators.

   a) Consumer water quality complaints must trigger rapid and effective responses.
   b) Management, regulators and public health personnel must all be engaged and be accountable for ensuring safe drinking water.

6. ***Ensuring drinking water safety and quality requires the application of a considered risk management approach.***

   Risk management requires sensible decision-making in the face of uncertainty.

   a) After incidents happen it is often difficult to obtain conclusive evidence about the specific details causing the failure
   b) Critical decisions need to be made in real time facing uncertainty, so that sensible, defensible precaution in decision-making is necessary
   c) Reactive measures, such as boil water advisories, can only limit but not normally prevent public health consequences and often to a very limited degree; risk management must be focused on being preventive

d) Treated water monitoring for contaminants is mainly a reactive measure unless it includes effective early warning indicators that lead to system improvements

3.2 Context of the Inquiry Part 1 - Key Findings Concerning North Havelock Outbreak

An overview consideration of the evidence from Part 1 of this Inquiry appears to indicate that those responsible for the safety of the North Havelock drinking water supply and hence the health of the community's consumers failed to embrace any of the foregoing well-established guiding principles for ensuring safe drinking water. While knowledge of these principles in the form presented depends on being familiar with the Australian Drinking Water Guidelines, the underlying experience from which these principles were derived is engrained in good practice, worldwide. Failure to reflect any of these fundamental approaches in the management of the North Havelock drinking water system is profoundly troubling.

4.0 INTERNATIONAL OUTBREAK EXPERIENCE RELEVANT TO NEW ZEALAND

4.1 Evidence for Guiding Principles Applicable to New Zealand

The following analysis will be organized according to the insights captured in the Guiding Principles for ensuring safe drinking water outlined in Section 3.1. Documented drinking water disease outbreaks in affluent nations over the past 40 years will provide the evidence base for this analysis. These 38 outbreaks are summarized in Appendix 1.

4.1.1 *The greatest risks to consumers of drinking water are pathogenic microorganisms.*

Overwhelming evidence and experience shows that human consumers of drinking water will become ill if they consume drinking water that delivers an infective dose of a human microbial pathogen. There is essentially no uncertainty about this basic premise, only about the details of what constitutes an infective dose and what circumstances of population exposure and individual immunity will dictate the numbers of consumers who will fall ill.

There are several factors that create challenges in recognizing and responding to pathogens:[4]

"Faecal (human or animal) contamination can be found wherever humans, their domestic animals or wildlife reside; although exposure is reduced as sanitation and waste management are improved, complete elimination of potential exposure to faecal contamination is not possible.

Loading of pathogens into a drinking water system sufficient to cause outbreaks of disease will not be consistent; rather it will be intermittent and infrequent when higher levels of sanitation are achieved. As a result, extended periods without apparent problems do not guarantee future safety.

Pathogens are likely to be heterogeneously distributed in water because of their origin in faecal particles that will not be totally dispersed in receiving waters and because of clumping promoted in treatment processes.

Some pathogens have high infectivity, which, combined with a likelihood of pathogens clumping into fine particles, makes inconsistent and non-uniform consumer exposure to infective doses a likely mode of infection.

Some pathogens (e.g., Cryptosporidium*) are resistant to chemical disinfection, making fine particle removal and alternative disinfection processes, such as UV, critical elements of a multiple-barrier approach.*

Conditions that create a pathogen challenge to the treatment process are often event-driven (e.g., extreme weather, unusual operating conditions), meaning that such events should be recognized as potential triggers of trouble.

Multiple failures in a system must usually combine for disaster to occur, particularly as more barriers are made effective in seeking higher degrees of safety. This reality also means that one or more barriers can be failing and ineffective without an outbreak occurring. This makes the independent evaluation of treatment performance by measures such as turbidity or chlorine residual monitoring a necessary activity to assure that all of the multiple barriers are effective."

Because the common source of pathogens shown to be capable of causing human enteric illness transmitted via drinking water is faecal material from humans and animals (pets, livestock and wildlife, including birds) the risk of any drinking water supply becoming contaminated by microbial pathogens of faecal origin is pervasive. What drinking water source on earth is absolutely protected from exposure to faecal matter from humans, pets, livestock or wildlife all the way from source to the consumer's tap? This is a pervasive public health risk facing any drinking water system. Such a pervasive risk demands an inherently comprehensive and reliable response to reduce the risk to consumers. International best practice is to provide disinfection of drinking water delivered to consumers regardless of beliefs about the security of the raw water source. There are some important exceptions to this generalization, such as the exhaustively managed groundwater supply of Berlin, Germany, that uses chlorination only sparingly for disinfection.[5]

Opposition to chlorination of drinking water is a worldwide phenomenon, mainly in affluent nations, that likely has its origins in a campaign launched by Greenpeace in the 1980s to ban chlorine from all industrial uses. Initially, it was primarily focused on chlorine bleaching in the pulp and paper industry because of its contribution to formation of polychlorinated dibenzo(p)dioxins (dioxins). The publications in 1974 demonstrating that drinking water chlorination of water containing trace natural organic matter (NOM) led to the formation of trihalomethanes (THMs, chloroform, etc.) followed by identification of countless other halogenated disinfection byproducts (DBPs) in chlorinated drinking water, lead to a variety of health concerns with these trace chemicals.[6]

Opposition to chlorination or failure to recognize that disinfection is essential has been a factor in a number of drinking water outbreaks because inadequate or non-existent disinfection allowed microbial pathogens to reach consumers via drinking water.[7] The following cases of this phenomenon will be summarized as they may be relevant to circumstances in New Zealand. The 19 outbreaks to be discussed will be presented from the oldest (1980) to most recent (2008), except that the May 2000 Walkerton outbreak will be presented first because of the detail available and its relevance to the North Havelock outbreak.

A summary of outbreak cases that demonstrate this principle are provided in Appendix 2. These 19 outbreaks of serious disease occurring in 10 affluent countries (5 in the USA, 3 in Canada, 2 in Finland, 2 in Norway, 2 in Denmark, 1 each in Australia, England, Japan, Sweden, and Switzerland) included a total of 23 fatalities and over 35,000 cases of disease that were all preventable if the threat posed by microbial pathogens in drinking water had been recognized and suitable preventive measures had been implemented. The common theme among these cases is a failure to implement chlorination or a suitable alternative disinfection process. Although details were not generally available in the published sources, opposition to chlorination in the community and even among water operators was a common factor. This feature combined with a failure to appreciate the public health risks of delivering drinking water without any form of disinfection has allowed these disasters to occur. The number of events reported is only the tip of the iceberg because reporting of drinking water outbreaks is uneven and our data review was limited to English language publications in the open scientific literature. There were many more outbreaks which had insufficient documentation published in an accessible manner to allow inclusion in our reviews. **The resulting public health message should surely be compelling: drinking water must be disinfected regardless of the source water supply**.

A critical reality of recognizing the pre-eminent threat to human health posed by microbial pathogens is that chemical contaminants in drinking water are neither as conclusively a risk for causing human illness nor as pervasive a source of risk to drinking water. Credible chemical risks to human health such as arsenic and lead are not risks for every drinking water supply. Certainly, the number of cases where the concentrations of these chemical contaminants are high enough to deliver a dose capable of causing an adverse human health effect are rare compared with the large number of drinking water outbreaks caused by pathogens. Disinfection by-products (DBPs) create a more pervasive risk because most drinking water utilities in affluent countries recognize the compelling need for disinfection that inevitably results in some DBP exposure for consumers. However, the confidence we can place in whether any DBP causes adverse human health effects at levels that DBPs are normally allowed to occur is vastly lower than is generally recognized. Certainly, the fear of chlorination because of perceived health risks from the formation of DBPs such as THMs has become a widely believed urban myth [see DBP references provided in endnote 6]. In contrast, consumer dislike of chlorine taste and odour is usually authentic and must be recognized as such by water providers.[8]

4.1.2 *The drinking water system must have, and continuously maintain, robust multiple barriers appropriate to the level of potential contamination facing the raw water supply.*

The paramount objective for ensuring safe drinking water should be to prevent drinking waterborne disease from affecting consumers by preventing or limiting exposure to waterborne pathogens. This paramount objective can be and often is a technically challenging undertaking to ensure that safe water is delivered directly to residential household taps 24 hours a day, 7 days a week, 365 days a year. While economists, or those who are persuaded by economists, may see the concept of multiple barriers for water security as being inherently redundant and not cost effective, the technical realities of meeting the paramount objective to protect public health make multiple barriers necessary. Economists are often more influential with politicians than public health experts, but political leaders need to decide that public health protection is indeed the paramount objective of drinking water policy.

The multiple barrier concept has been regarded as international best practice for ensuring safe drinking water for more than 60 years. The challenge for any system is to determine what level of potential contamination exists so that barriers with appropriate capabilities are implemented. Those capabilities are based on each barrier functioning as expected. Any technology can fail or operate below specifications. Operators need to know that each barrier is functioning as intended, so real time, or at least regular, operational monitoring is necessary to provide the assurance that water will be kept safe. A focus on operational knowledge and monitoring is fundamental to a preventive approach for ensuring safe drinking water.[9] The all too common emphasis on compliance monitoring of treated water quality against water quality guideline numbers is inherently a reactive approach because the monitoring results are generally not available until or after the treated water has reached consumers. Recognition of this misunderstanding about a numerical focus on compliance monitoring is a worldwide misinterpretation that largely motivated the efforts from 1999 to 2004 to restructure the ADWG and the WHO DWG towards an operationally-oriented water safety plan, risk management approach to ensuring safe drinking water.

Which features can be regarded as barriers to be credited for the multiple barrier approach has been a matter of some debate and interpretation. The Walkerton Inquiry outlined 5 key elements to providing a multiple barrier approach:[10]

"1. Source protection
2. Effective treatment
3. Secure distribution
4. Effective monitoring
5. Effective responses to adverse signals."

While source water protection has been accepted as a barrier, verifying how well source water is truly protected is far more demanding than many water purveyors are willing to acknowledge. There must be rigorous and continued evidence gathering to support any claims of source water being "protected" from contamination.

There must be acknowledgement that:

1. Any water treatment barrier can fail
2. Treatment barriers must be operationally monitored in real time to verify their function
3. Individual barriers must be maintained otherwise multiple barriers can become a sole barrier and defeat the purpose of having multiple barriers.

Implementing an effective multiple barrier approach requires a comprehensive understanding of the system being operated, including: the nature of all major threats to system safety, capabilities of all the barriers, what monitoring signals mean or do not mean, what response actions are able to achieve and which are appropriate and knowing / understanding when you do not know enough and when to call for help. These all require a sound, fundamental understanding of water quality.

The multiple barrier approach is a long established premise for ensuring safe drinking water. Unfortunately, understanding of this approach in a manner that achieves the objective has proven more difficult. Failures have often included an inaccurate or even naïve characterization of the level of risk posed by source water quality leading to an underestimation of the capability of barriers necessary to protect consumers. There has also been a failure to understand that all barriers must be fully functional for this approach to succeed. Clearly if one or more barriers are non-functional or functioning below necessary levels of performance, the entire premise of water security will be undermined.

4.1.3 *Any sudden or extreme change in water quality, flow or environmental conditions should arouse suspicion that drinking water might become contaminated.*

Trouble is inevitably preceded by change. Too often in outbreaks, the critical change(s) that could have provided a warning are not recognized until the outbreak is being reviewed in retrospect. Hindsight is generally 20:20 vision making missed signals appear all the more obvious.

Not all change, often very few cases of change, necessarily signal trouble. That is the challenge of taking ownership of protecting public health. Constant vigilance is necessary, meaning the management systems must be robust and responsive (see subsequent principles). Changes to be wary of must include process and operational changes that could affect contamination and / or treatment efficiency.

The ability to detect important change signals for any water system demands that those running the system know and are able to recognize what is normal. The need for these subtle strengths in the capabilities of system operators are not recognized as widely as they should be.

4.1.4 *System operators must be able to respond quickly and effectively to adverse monitoring signals*.

Operators must be capable and responsive. They must understand what constitutes adverse monitoring results, how to interpret their meaning and what are effective responses to deal with the monitoring signals. This capability requires a total commitment to vigilance which can only be achieved with an appropriate organizational culture, one that promotes and rewards vigilance. Pride in keeping drinking water safe must be continuously reinforced.

Operators need to accept and understand that contamination can strike any drinking water system. Anyone responsible for a drinking water system who believes otherwise is inherently vulnerable to failure. Promoting and maintaining a meaningful and thorough understanding of the entire water system from source to consumers tap, its challenges and limitations is essential and is the underlying rationale for the water safety plan approach. This approach also needs to adopt real time process control (e.g., monitoring and maintaining an adequate chlorine residual and low turbidity) as the basic operating approach in every possible way. Viewing operations this way allows development of an effective response plan for abnormal conditions should they arise. An important element for this is to have operators being willing to acknowledge those occasions when they do not understand what is happening when unusual signals are received. In such circumstances, operators must be willing to call for assistance.

4.1.5 *System operators must maintain a personal sense of responsibility and dedication to providing consumers with safe water, and should never ignore a consumer complaint about water quality.*

Drinking water professionals, ranging from frontline operating personnel to managers and regulators must be accountable to consumers. A critical aspect of that accountability is for everyone who should know the system to recognize vulnerabilities in the system that demand improvement. By taking ownership of all problems, operators need to make certain managers and decision-makers (i.e. politicians) cannot claim that that were not aware of the problems that may threaten public health.

Another element of taking ownership of problems is make sure that all close call (problem) incidents are fully investigated and that such incidents are effectively used for training purposes. This kind of commitment to institutional learning can be effective to ensure that emerging problems are recognized early and effective solutions are implemented.

The nature of drinking water supply to large numbers of consumers makes very serious the public health consequences of a serious failure. Effectively, those engaged in all responsible aspects of providing drinking water must see themselves as being public health professionals because of the serious responsibility they carry. The public's health can only be protected if those in responsible positions take ownership of their responsibility to keep consumers safe.

4.1.6 *Ensuring drinking water safety and quality requires the application of a considered risk management approach.*

Risk management inevitably requires sensible decision-making in face of uncertainty because full information is not known at the time that events are unfolding. Sensible decision-making under these circumstances requires as much advance preparation as possible. The concepts underlying the water safety plan approach is designed to anticipate what problems could occur with any water system. Clearly, the water safety plan approach must also promote healthy skepticism about possible explanations that are inevitably based on incomplete information.

Water safety plans must be developed by the operational staff who need to know and understand their own water system. Consultants can be helpful to facilitate development of a water safety plan, but if a consultant is tasked with writing a water safety plan, the people who need this plan to avoid trouble will not be adequately engaged and will likely not take ownership of the knowledge that must be present in such a water safety plan.

A preventive risk management mindset is required. The case studies presented provide compelling arguments for a preventive, rather than a reactive, approach to ensuring safe drinking water. The toolbox of reactive measures for water utilities once contamination has occurred (flushing, boil water advisories) is clearly limited in their ability to prevent harm to consumers. This makes a strong case for a thoughtful risk management approach. The Walkerton Inquiry Part 2[11] described some essential characteristics of risk management as:

- Being preventive rather than reactive.
- Distinguishing greater risks from lesser ones and dealing first with the former.
- Taking time to learn from experience.
- Investing resources in risk management that are proportional to the danger posed.

4.2 Recurring Themes Evident from an Analysis of International Outbreak Experience

4.2.1 *Complacency*

- Outbreaks are comparatively rare and not front of mind for public health officials or frontline operational personnel and regulators
- Most regulators are unlikely to have experienced a waterborne disease outbreak
- Our collective success at reducing waterborne disease over the last century effectively sets us up for complacency by consumers and among drinking water personnel

4.2.2 *Lessons that should have been learned and widely known are too often forgotten*

- Documentation of failures and close calls within the drinking water industry is not widely done or adopted as mandatory basic training for drinking water personnel.
- Training of operating personnel is too often focused on technical details of keeping the system running and insufficient attention to the consequences of failure, especially with regard to public health risks.

4.2.3 *Groundwater is a common source in outbreaks if mistakenly trusted as secure*

- The subsurface is heterogeneous, but judgments about the subsurface are necessarily made by evidence from a limited numbers of boreholes
- Once groundwater is accepted as “secure”, ongoing attention and validation can be very limited to essentially negligible

4.2.4 *Politicians and “responsible” officials are often skeptical about possible contamination*

- If valid concerns are raised about threats, the absence of documented illness is cited as grounds to ignore the threats
- There is generally little understanding about what is needed for ensuring safe drinking water among those who control funding
- Regulators and public health officials who cannot be bothered to investigate or who simply look the other way when they encounter poor practice are just as, if not more, culpable than those carrying out the poor practices.

4.2.5 *There is a common myth about water being pristine which reduces vigilance*

- A prevailing societal view that "natural" is inherently good overlooks the harsh reality that microbial pathogens are "natural" and unless drinking water is disinfected, illness occurring in consumers is not a question of "*if*", but "*when*" and "*how many*".
- Water systems that are operated without any disinfection, even if the source water is of high quality, must still be distributed to consumers and many cases of dangerous contamination have occurred in the distribution system that caused serious illness among consumers.
- A single infected animal or human can excrete hundreds of millions of pathogens, which can impact even a large municipal system
- There are practical limitations to the ability of source protection alone to ensure a safe drinking water supply.

4.2.6 *Safety does not require stricter water quality numbers – better practice is needed*

- The severe consequences for Walkerton could have been avoided if the quantitative requirement for achieving a chlorine residual of 0.5 mg/L after 15 minutes had been maintained
- Even if the high level of contamination had precluded achieving the specified chlorine residual with the chlorination equipment available, recognizing that inability would have provided real time warning of the contamination

4.2.7 *Misplaced fear of chemicals has interfered with adequate management of pathogens*

- Drinking water guidelines are dominated by long lists of chemical contaminants creating an inaccurate impression that such chemical contaminants pose the most serious risk to safe drinking water while microbial contamination from faecal contamination continues to cause water borne illness in consumers.
- Consumer concerns with chlorine off-flavors and, more recently, with unsubstantiated fears about health effects from disinfection by-products can produce pressure to reduce disinfection by chlorine or chloramines, sometimes causing disastrous consequences.
- Public health officials and environmental organizations often do not understand the real limits and uncertainty of the evidence concerning adverse human health effects from disinfection by-products that has led to widespread opposition to disinfection.

4.2.8 *Public health monitoring is generally unable to detect small outbreaks*

- Failure to show demonstrable evidence of health effects is often used as an argument to avoid action when contamination is highly likely.

- Evidence of disease typically is not clear until long after contamination happens because most gastrointestinal diseases have an incubation period before symptoms occur and there is an inevitable time lag between some consumers becoming ill and widespread recognition that an outbreak is occurring.

4.2.9 *Miscommunication occurs among individuals who are relied on to ensure safety*

- Those engaged in drinking water come from diverse and often remotely related backgrounds making miscommunication of critical issues more likely
- Rarity of severe incidents makes it unlikely that individuals will understand the consequences of allowing a serious failure
- The drinking water industry is dispersed in many jurisdictions with only limited interaction and communication making dissemination of knowledge fragmented
- A compelling need exists for routine and effective communication with the public health agency because drinking water personnel will need to work closely with the public health agency if a problem does arise.[12]
- An emergency is a poor time to try to establish a relationship with all parties working under stress.

4.2.10 *Even high quality systems can fail*

- Source water protection to minimize risk is important.
- Source water protection alone is not sufficient, safe community water must be disinfected because of the pervasive risk of microbial pathogen contamination.
- A commitment to continuous improvement with the paramount objective of protecting public health is necessary.

4.2.11 *Chance / luck is often a factor in avoiding or driving an incident*

- Outbreaks generally require a combination of multiple factors occurring simultaneously
- Weird occurrences, coincidences, and multiple concurrent failures do happen,
- Strange, unexpected occurrences may hide a real cause of problems and lead to incorrect responses. Operators need to be careful about adopting the first explanation of trouble that may be suggested.
- Problem-solving needs to beware of “group think” (rapid and uncritical consensus). Assumptions should be challenged when uncertainty is high. Problem-solving should be viewed as peeling back layers to uncover the core cause of a problem.
- The 2000 Walkerton (Appendix 1) water source was vulnerable for 22 years.
- North Battleford (Appendix 1) inevitably experienced source water contamination from the upstream sewage effluent outfall, but the detectable outbreak in 2001 required a combination of factors.
- The 2007 Nokia (Appendix 1) disaster involved coincidental failures at the water treatment plant and the sewage treatment plant to unfold as it did without recognition of the cause and with such serious consequences.

4.2.12 *Investigations into the causes of an outbreak will often find multiple causes*

- In many cases, investigations after an outbreak occurs will reveal multiple potential problems that could have caused the incident, but only one or more will be judged to be the primary causes.
- However, under different circumstances, the other indentified potential problems could also have been responsible, so they are important to fix.
- Drinking Water Safety Plans are intended to reveal such potential problems *before* a serious incident, rather than after something serious has happened.
- Finding the detailed causes of a waterborne disease outbreak after it has occurred is very difficult, and in some cases impossible, even with dedicated resources and sophisticated monitoring techniques.
- Turning back the clock to capture a slug of contamination that happened days before is not possible no matter how powerful the sampling techniques might be; so rational and logical inference must be applied to the evidence.
- Achieving a criminal legal standard of proof - beyond a reasonable doubt - is usually not possible, but the civil legal standard of proof - on a balance of probabilities (i.e., more likely than not) - may be achieved in some cases with sufficient commitment to evidence gathering.
- Investigation that uncovers multiple flaws capable of causing failure can reach diminishing returns in trying to establish a single or dominant cause for the failure

4.2.13 *Blaming failures on human error generally misrepresents the underlying problems*

- Humans are constantly making mistakes; it is the normal state of human affairs. If a simple human mistake in a given system can cause disaster, then the system is unacceptably vulnerable to failure because mistakes are inevitable.
- Those at the front line when problems occur do not have the luxury of calling a time-out or the benefit of all the knowledge that can be gained in hindsight when a failure is thoroughly investigated afterwards
- Training is essential at all levels from operations to management, oversight, and regulation.
- Necessary training must move beyond just the skills needed to keep the system running to a meaningful appreciation of the major responsibilities of all concerned to protect the public's health.
- Training is a continuous, ongoing requirement for all parties.

4.2.14 *Preventing failure requires learning from experience*

- Close calls must be investigated to document what happened and how the system can be improved to prevent future incidents from slipping into disaster.
- Water utilities need to recognize the value of such evidence and find ways to collect this experience internally and ultimately to share such experiences across the industry.
- Many examples exist of people engaged in the water business who seriously underestimate the capability of concentrated sources of microbial pathogens like human sewage (or one infected rabbit in Northampton –Appendix 1) to contaminate huge quantities of drinking water sufficiently to cause large numbers of cases of illness.

4.2.15 *<u>Risk-based approaches like Water Safety Plans cannot work if identification and understanding of risk is inadequate.</u>*

- Water safety planning is all about prevention. Relying on compliance monitoring or, worse yet, waiting for signals of problems in the community is inherently reactive. The international move to a water safety planning approach is founded on the basic truth that prevention is a better approach than simply waiting for trouble and trying to react quickly enough to avoid disaster.
- Water utilities must not blindly perform procedures to meet regulatory requirements; rather they must seek to fully understand why these requirements are specified and what must be achieved.
- Water utilities must encourage appropriate curiosity by staff to fully understand how things work. They should hold regular meetings to involve staff in discussions about facility performance and discuss examples of how small flaws can grow into large problems if not resolved when first recognized.
- Having even an excellent Drinking Water Safety Plan will be of no value if it is not understood and used by operational personnel on a regular basis as they seek to learn all the subtleties and surprises that can be hidden in their system.
- Effective water safety plans require engagement of front line operating personnel. Documents prepared by third parties such as consultants are very unlikely to be “owned” by those who need to understand and implement the water safety plan.
- An international expert panel was convened by the Canadian Water Network to consider and explicitly report on what needs to be understood by water utilities to effectively manage risk given the inevitable uncertainties that are routinely encountered.[13] This panel explained that not all risks are created equally and drinking water risks must be analyzed in a rational manner that can be used to set priorities

Appendix 1 Summary of 38 International Drinking Water Borne Disease Outbreaks

Year of Outbreak	Location	Source Water	Treatment	Major Failures	Pathogens	Cases Confirmed	Total Cases Estimated	Hospital Admissions	Deaths	Comments
1980	Georgetown, TX, USA	ground	chlorination	heavy rains; porous aquifer with fault lines; manual chlorination – no backup	Coxsackievirus B3; hepatitis A	Hepatitis A (36 cases)	~7,900	not reported	–	Heavy rain with surface contamination along fault line; leaking sewer lines, septic systems; limited contact time.
1980	Bramham, England	ground	chlorination	inadequate to no chlorination; sanitary sewer leak	not identified	–	3,000	not reported	–	Confounding of investigation by poor monitoring practices; fissures in limestone; faulty sewer connections; sewer line blockage; low chlorine.
1981	Eagle Vail, CO, USA	surface, river	pressure filtration, chlorination	chlorination failure; raw water contaminated with sanitary sewage	not identified; rotaviral infection in 5 of 7 patients	–	81	not reported	–	Chlorination failure alarm was shut off without any other action.
1982–83	Edmonton, AB, Canada	surface, river	softening, coagulation, filtration, chloramine	sanitary sewage contamination of upstream storm sewer, poor filtration and inadequate contact for chloramines	*Giardia lamblia*	895	2,200-29,000	not reported	–	This was the second largest outbreak ever of laboratory-confirmed giardiasis, but waterborne cause was not evident until months after the outbreak.
1983	Drumheller, AB, Canada	surface, river	filtration, chlorination	sanitary sewage spill upstream; inadequate disinfection	not identified	1326	3,000	not reported	**2**	Sanitary sewage spill not reported to water treatment plant or to health authorities.
1984	Alsvåg, Norway	surface, lake	none	heavy spring rain, sheep grazing near reservoir, likely manure contamination	*Campylobacter jejuni*	22	680	not reported	–	Outbreaks prevalent in N. Norway; low water temperatures aid survival; 1 case of reactive arthritis developed, 22 strains of *C. jejuni* in patients.
1985	Orangeville, ON, Canada	ground	none	heavy spring runoff and rainfall carried livestock contamination into bores	*Campylobacter jejuni*	57	>241	not reported	–	Low water temperatures aid *C. jejuni* survival; lack of chlorination with no maintenance of an adequate chlorine residual was responsible.
1988	Sunbury, Vic, Australia	surface, reservoirs creeks	none	one creek source found to be faecally-contaminated and outbreak preceded by heavy rain	not identified	–	6,600	not reported	–	Heavy rains fell 24-48 hours before outbreak; complaints of "*foul quality of the water*"; faecal contamination of water at one weir site; boil water order.
1988	Skjervøy, Norway	surface, reservoir	chlorination	chlorination system off for repairs; water delivered with no disinfection for 4 weeks	*Campylobacter jejuni / coli*	10	330	not reported	–	15% of exposed population became ill, 2 cases of reactive arthritis, lower attack rate possibly due to some immunity in community.

Year of Outbreak	**Location**	**Source Water**	**Treatment**	**Major Failures**	**Pathogens**	**Cases Confirmed**	**Total Cases Estimated**	**Hospital Admissions**	**Deaths**	**Comments**
1988–89	Swindon & Oxfordshire, England	surface, river	coagulation, filtration	change in water supplied to Swindon; inconsistent fine particle removal and recycling of filter backwash water	*Cryptosporidium*	516	–	41	–	First major waterborne outbreak of cryptosporidiosis in England. Heavy rain in Nov – higher levels of oocysts in raw water; filtration insufficient to remove oocysts; no specific faults found in existing treatment.
1989	Sedona, Oakcreek Canyon, AZ, USA	ground	no chlorination	sewage infiltration of groundwater aquifer through underground fractures in sandstone, limestone	possibly Norwalk virus	3	900	not reported	–	Resort sewage system had mechanical problems, causing flooding. Dye tracer from septic leach fields reached well in 3 to 11 days.
1989–90	Cabool, MO, USA	ground	none	sewage infiltration believed to have contaminated distribution system during mains repair and/or water meter replacements	*Escherichia coli* O157:H7	243	–	32	**4**	Contamination occurred during unseasonably cold weather causing water mains breaks and repairs under difficult circumstances with no disinfection after repair; 4 deaths, 63% cases–female.
1990	Creston - Erickson, BC, Canada	surface	none	beavers contaminated water supply with no treatment barriers	*Giardia lamblia*	124	–	not reported	–	Strong evidence was gathered linking cause to beavers, community had experienced a previous outbreak in 1985, yet Erickson continued to oppose chlorination for more than another decade.
1990	Saitama, Japan	ground	none reported	contamination of the bore supply was not explained	*Escherichia coli* O157: H7	42	186	20 HUS	**2**	Although few details are given about cause, this is a serious waterborne outbreak because the median age of HUS cases was 3.9 years and the 2 deaths were children aged 5 and 4.
1991	Naas, Ireland	ground	chlorinated	sanitary sewage contaminated the aquifer; overwhelmed the chlorine disinfection	not determined but isolates of entero-toxigenic *E. coli, Giardia lamblia* found	340	5,600–6,800	not reported	–	Massive contamination with *E. coli* at 15,000,000 per 100 mL. First sign of contamination was consumer complaints of foul odour, possibly as early as October 5 at the beginning of the outbreak.
1991–92	Uggelose, Denmark	ground	aeration filtration, no disinfection	heavy rain, sanitary sewer blockage led to back up of sewage, short circuiting of pump – sewage level rose, contaminating bore	not identified	–	1,600	10	–	Connection through old drainage pipe had been questioned, but no response was reported from the waterworks personnel; several periods of heavy rain followed by increased illness.
1992	Bradford, England	surface, reservoir	slow sand filtration, chlorination	no specific cause confirmed but heavy rains, poor quality finished water, slow sand filter recommissioned	*Cryptosporidium*	125	–	9	–	Increased turbidity was measured after heavy rain; filters not at peak efficiency following maintenance work, oocysts detected in treated water.
1992–93	Warrington, England	ground	chlorination	heavy rainfall washed livestock pasture drainage into groundwater collection system; cross-connection	*Cryptosporidium*	47	–	5	–	Extremely high turbidity at reservoir on one occasion was an indication of problems.

Year of Outbreak	**Location**	**Source Water**	**Treatment**	**Major Failures**	**Pathogens**	**Cases Confirmed**	**Total Cases Estimated**	**Hospital Admissions**	**Deaths**	**Comments**
				with a sewage leak to one bore shaft						
1993	Milwaukee, WI, USA	surface, large lake	chlorination, $KMnO_4$, coagulation, filtration, chloramine	sanitary sewage contaminated lake water intake, combined with sub-optimal filtration performance	*Cryptosporidium*	285	up to ~400,000	not reported	**~50** increased chronic deaths over 2 yrs	Speculation early on included livestock runoff, but genotyping of oocysts has pointed to the human genotype and human sewage contamination as the cause.
1993	Gideon, MO, USA	ground	none	bird faeces likely contaminated water storage tanks; flushing of system drew tank water into service	*Salmonella typhimirium*	31	650	15	**7**	Claimed to be the largest number of deaths in waterborne outbreak in 50 years, but likely did not consider Milwaukee
1994	Noormarkku, Finland	ground, river bank infiltration bores	pH adjustment, no disinfection	heavy spring melt, ice dam flooded wells with river water combined with upstream flooding of sewage treatment plant	likely Norwalk or other virus	5	1,500–3,000	not reported	–	Forgotten drainage pipe connected 1 bore to river, upstream discharge of sewage (50% untreated) due to flooding.
1994–95	Victoria, BC, Canada	surface, series of reservoirs	chloramines	specific contamination source not found but most likely feces from cougars or feral cats in the watershed	*Toxoplasma gondii*	>100	2,900–7,800	not reported	–	This was the first documented case of a waterborne outbreak of toxoplasmosis in a developed country.
1995	Freuchie, Scotland	ground	chlorination	backflow of contaminated water due to local plant pumping water from stream below sewage outflow	*Escherichia coli* O157:H7, *Campylobacter* spp.	6 (E) 8 (C)	633	5	–	Consumer complaints of discolored water reported before illness; increased pressure from plant pumps reversed flow, contaminated village water.
1995	South Devon, (Torbay & District), England	surface, river and reservoir riverbank infiltration	coagulation, filtration, chlorination	no clear single flaw but less than optimum fine particle removal; likely sewage contamination of river or riverbank infiltration sources; oocysts detected in treated water	*Cryptosporidium parvum*	575	–	25	–	Changes in treatment process included using small volumes of backwash water to wash magnetite from flocculation; spring flooding with high turbidity levels; *Cryptosporidium* oocysts detected in some source water, also in upstream sewage effluent.
1995–96	Klarup, Denmark	ground	none	waterworks testing for nitrate drilled ~25m from the source bore, damaging a sewer line at ~3m depth which leaked into the aquifer via the exploration borehole	*Campylobacter jejuni*	110	~2,400	13	–	An exploratory bore, drilled to monitor for nitrate contamination of the aquifer, damaged a sewage pipe which leaked into the groundwater reservoir for over 1 month. Second water system became contaminated when valve between both systems was opened for routine check..

Year of Outbreak	**Location**	**Source Water**	**Treatment**	**Major Failures**	**Pathogens**	**Cases Confirmed**	**Total Cases Estimated**	**Hospital Admissions**	**Deaths**	**Comments**
1998	Brushy Creek, TX, USA	ground	none	deep, encased bores contaminated through underground fissures by a raw sewage spill into a surface creek	*Cryptosporidium parvum*	89	1,300–1,500	not reported	–	Spill of raw sewage 0.4 km distant contaminated deep groundwater source through fissures in bedrock following period of drought, extreme heat; vulnerability of aquifer was known.
1998	La Neuveville, Switzerland	ground	iron and manganese oxidation, no disinfection	pump failure in sanitary sewage system caused back-up and over-flow into the ground water aquifer; physician suggested illness due to contaminated drinking water	multiple: *C. jejuni,* *S. sonnei,* *E. coli*, NLV	–	~2,400	not reported	–	An earlier outbreak the previous fall was not subjected to an epidemiologic investigation; an alarm fitted on the sewage pump had been shut off because of too frequent false alarms. Ultraviolet and continuous chlorination treatment operative since June 1999.
1999	Washington County Fair, NY, USA	ground, shallow bore	no treatment	some vendors used unchlorinated well water for beverages and ice; shallow wells were located ~11 m from dormitory septic tank seepage pit with rapid hydraulic connection to the bore	*Escherichia coli* O157:H7, *Campylobacter jejuni*	161 primary, 10 secondary	2,800–5,000	71 (14 with HUS)	**2**	Two deaths, 3 year-old-child and 79-year-old due to HUS complications. Source of the *E. coli* O157:H7 in the septic tank seepage was not determined, but faecal contamination from this source occurred with heavy rain after a drought.
2000	Walkerton, ON, Canada	ground, shallow	chlorination	inadequate chlorination to cope with influx of cattle manure-contaminated water to a shallow bore following heavy rains	*Escherichia coli* O157:H7, *Campylobacter* spp.	163 (E) 105 (C) 12 both	2,300	65, 27 HUS	**7**	A litany of underlying failures contributed to the events of May 2000. Inadequately trained operators, failure to monitor chlorine residual, disinterested regulators - no follow through, highly vulnerable system and complacency all around.
2000–01	Asikkala, Finland	3 ground water systems	no chlorination	3 outbreaks in groundwater systems, all without chlorination, all due to *C. jejuni*	*Campylobacter jejuni*	A: 10; B: 5; C: 56	A ~400 B ~50 C ~1,000	not reported	–	Outbreaks A and C due to surface water contamination of bores following heavy rains, source of contamination of B was not determined.
2001	North Battleford, SK, Canada	surface, river	coagulation, filtration, chlorination	poor fine-particle removal performance; intake located 3.5 km downstream of sewage effluent discharge	*Cryptosporidium parvum* type 1 (human)	375	5,800–7,100	50	–	Raw water quality problems caused by the sewage discharge were overlooked for years. In March 2001, maintenance to an up-flow clarifier was followed by poor turbidity removal.
2001	Te Aute, College, Hawkes Bay, New Zealand	surface, spring	pressure sand filter, cartridge filter, UV	cattle grazing in a swampy area where the springs arose, causing manure contamination of the raw water supply	*Campylobacter jejuni*	few stool samples taken	95–185	not reported	–	Although UV treatment was provided, the source water was allowed to become seriously contaminated and the treatment process was not operated effectively, UV lamp burned out.

Year of Outbreak	**Location**	**Source Water**	**Treatment**	**Major Failures**	**Pathogens**	**Cases Confirmed**	**Total Cases Estimated**	**Hospital Admissions**	**Deaths**	**Comments**
2002	Transtrand, Sweden	ground	no treatment	cracked sewer located ~10 m from one bore supplying the system responsible	Norwalk-like virus	4	~500	not reported	–	This outbreak was noteworthy because ~1/3 of cases could have been avoided by effective implementation of boil water advisory. The community opposed chemical disinfection and refused to believe waterborne transmission until the sewer damage was discovered.
2007	Nokia, Finland	ground & lake infiltration	pH adjust, aeration, chlorination, sand filtration	cross-connection at sewage treatment plant without proper backflow prevention, slow response	*Campylobacter* spp., Norovirus, *Giardia*, *Salmonella* spp. *Clostridium difficile*, Rotavirus	-	6,500	not reported	**2**	Nokia had a water safety plan but it failed to identify the cross-connection vulnerability. Because of a coincidence water treatment staff thought consumer complaints were caused by change in water source, responded only with flushing and allowed consumers to receive drinking water contaminated with 400 m^3 of sewage effluent for 2 days
2008	Adliswil, Switzerland	ground	no treatment	cross-connection at sewage treatment plant without proper backflow prevention, rapid response	pathogens not identified	-	180	not reported	-	This failure was very similar to Nokia and it happened only a few months after Nokia. According to media reports, wastewater officials did not expect serious consequences because the wastewater was "treated", reflecting a dangerous misunderstanding about the health risk of microbial pathogens and their presence in sewage
2008	Alamosa, CO, USA	"*secure*" ground water	no treatment	vermin contamination of a poorly maintained above-ground water storage led to high quality supply being contaminated in distribution	*Salmonella*	124	1300	20	**1**	Alamosa was operating under a State agency approved waiver to provide drinking water that was not chlorinated or disinfected in any way because the "*secure*" groundwater supply from artesian bores had not shown any signals of contamination based on total coliform monitoring
2008	Northampton, England	surface reservoir	ozone pre-oxidation, coagulation, clarification, granular multi-media filtration, ozonation, GAC	A rabbit gained access to a GAC backwash tank and it was drowned and found in the chlorine contact chamber. This single animal contaminated the entire reticulation system with oocysts affecting 258,000 consumers	*Cryptosporidium cuniculus*	22	422	not reported	-	This water utility would, by any objective measure be rated as excellent. The outbreak was only detected as quickly as it was because of extraordinary continuous monitoring of treated water for *Cryptosporidium* oocysts and the rapid precautionary measures taken by the water utility in calling an immediate boil water advisory without waiting for confirmation of the cause of the problem. The total cost of this event to this private, investor-owned water utility was estimated at £4.9 million
2010	Õstersund, Sweden	surface lake	ozone pre-oxidation, sand filtration, chlorination	An apartment building sewer was cross-connected to a storm drain that discharged to a small creek <500m up-current from the drinking water treatment plant intake. An	*Cryptosporidium*	>29, final number not reported	27,000	57 reported, 270 est.	-	This outbreak is the largest reported outbreak of cryptosporidiosis in European history. The underlying cause was evident naiveté on the part of water authorities about their belief in the pristine status of the raw water source. The lake source was actually subject to many inputs of human

Year of Outbreak	**Location**	**Source Water**	**Treatment**	**Major Failures**	**Pathogens**	**Cases Confirmed**	**Total Cases Estimated**	**Hospital Admissions**	**Deaths**	**Comments**
				infected family resided in the apartment building. The water treatment processes were not operated at an efficiency level capable of removing *Cryptosporidium* oocysts						sewage and the water treatment plant and its operating processes were not adequate to deal with a serious challenge of Cryptosporidium oocysts such as occurred. A UV-disinfection system was installed as a result of this outbreak. Direct costs to the community were estimated at 6.2 million kroner and indirect costs of 220 million kroner.

Appendix 2
Outbreaks Relevant to Principle 1

1. ***The greatest risks to consumers of drinking water are pathogenic microorganisms. Protection of water sources and treatment are of paramount importance and must never be compromised***

Walkerton, Ontario, Canada[14] in May of 2000 was a community of about 4,800 residents that was relying on groundwater supplies from three bores, Wells #5, #6 and #7. This outbreak resulted in 7 deaths and over 2,300 cases of illness attributed to *E. coli* O157:H7 and *Campylobacter* spp. The relevant details in the context of chlorination is that Well #5, the oldest of the operating bores was shown to be subject to faecal contamination on its pump test in 1978, ultimately leading to a requirement for water entering the reticulation system to have a chlorine residual of 0.5 mg/L measured after 15-min contact time. Walkerton operators were required to check this chlorine residual requirement daily to verify that it was being met. In reality, likely in part because they failed to understand why this requirement was necessary, the operators were not measuring chlorine residual and, instead, were entering fictitious values into the daily log. In May 2000, Well #5 became heavily contaminated by cattle manure from a nearby farm paddock, so much so that the chlorination equipment would likely have not been able to provide a sufficient dose of chlorine to overcome the demand caused by the manure contamination. The failure of the operators to measure chlorine residual daily, which most likely would have shown a zero residual because of the excessive chlorine demand, created a missed opportunity to recognize that the water supply was contaminated. As a result, seriously contaminated water was delivered to Walkerton residents for 9 days before a boil water advisory was called, only after the emergence of widespread illness in Walkerton. This failure to measure chlorine residual was most likely a factor in the number of consumers who became ill and possibly in the severity of illness leading to 7 deaths. Knowledge that measuring the chlorine residual provides a real time indicator of contamination by chlorine-demanding substances was not apparent even among the regulators who required this measurement.

The cavalier attitude of the Walkerton operators to the need for disinfection and the monitoring role of measuring chlorine residual was born of ignorance about the public health consequences of contaminated drinking water. They continued to drink the water during the outbreak and the Operator Foreman had routinely consumed raw water from the bores because he disliked the taste of chlorine. He had also operated Well #7 without a functional chlorinator for the week during which contaminated water was being delivered to the community. The General Manager mistakenly believed that Well #7 was the problem when he became aware of microbial contamination from an incidental sample taken during a water main repair and he learned of public health official concerns once illness was occurring.

Bramham, England[15] was in a group of small communities serviced by four bores. Bore #4 was the newest bore in service, but it was ultimately identified as the most likely source of the contaminated water in an outbreak of gastrointestinal illness (pathogen not identified) affecting 3,000 of 12,000 exposed residents. The water from these bores was chlorinated but because the bores were located within Bramham village and there was no treated water storage, consumers complained about the taste of the freshly chlorinated water. Accordingly, operators kept the total chlorine residual as low as possible, typically providing chlorine residuals of less than 0.01 mg/L at the sampling point 100 m downstream.

Recent water monitoring for bacterial indicators had revealed treated water contamination, indicating a need to increase the chlorine dosage. The operating staff sent to deal with the problem had no means of measuring chlorine residual so they relied instead on estimating the chlorine dose by means of the rate of depletion of the reservoir of hypochlorite solution. Only after the outbreak, when the whole system was investigated, was it revealed that although the chlorine solution was being drawn from the reservoir, it was not being injected into the bore water, but rather was bypassing the bore water and running to the drain. This failure mode had been reported at other sites experiencing chlorination problems and cases of this failure mode going undetected for long periods were also noted. The overall investigation indicated that the most likely source of contamination was a leaking sanitary sewer that contaminated the fractured limestone aquifer feeding bore #4.

Alsvåg, Norway,[16] in 1984, was a remote coastal community of about 1,000 people that experienced an outbreak of campylobacteriosis affecting about 680 residents in June and July of 1984. Clear evidence of the cause of the Alsvåg outbreak was not reported, but sheep had been grazing along the water reservoir for a period of 2 to 3 weeks before the outbreak. Because no treatment, including no disinfection, was provided for this surface water supply, there was no barrier for faecal pathogens contaminating the reservoir.

Orangeville, ON, Canada,[17] was, in 1985, a rural community of less than 20,000 population with its water being supplied without any treatment from six bores ranging in depth from 18 to 80 m. Orangeville experienced an outbreak of camplylobacteriosis with 57 lab-confirmed cases and at least 241 residents seeking medical treatment. The source of the contamination was not explicitly identified, but because of the timing of this outbreak, in late winter with the ground still frozen and livestock not being pastured for feeding, frozen manure was judged to be the most likely source. The lack of chlorination allowed this vulnerable groundwater supply to cause the outbreak.

Sunbury, VIC, Australia[18] was, in 1988, a suburban/rural region of approximately 19,000 population that experienced an outbreak of gastroenteritis affecting an estimated 6,600 residents. The surface water sources from two creek supplies were at substantial risk of contamination from livestock grazing near the creeks. A watershed sample from one creek contained 45 *E. coli* per 100 mL. No specific source of contamination was confirmed as the cause of the outbreak, but heavy rainfall preceded the outbreak by 24 to 48 hours.

Australia had a history of supplying drinking water without treatment from surface waters in "protected" catchments, but the supply for Sunbury was clearly not up to the expected high source water quality standards that has been maintained, for example, for Melbourne. The use of higher risk supplies without any effective barriers possibly reflects an older Australian perspective on pathogens reflected in an interview with a former president of the Australian Water and Wastewater Association who answered a question of whether there were any problems concerning waterborne disease in Australia:[19] "*For many years the isolation of Australia made this an almost germ-free continent, and the level of waterborne pathogenic organisms was not significant."* This statement from a leader of the Australian Water and Wastewater Association, albeit from 34 years ago, reflects an extremely naïve perspective about waterborne disease that could only undermine the recognition of the need for securing drinking water supplies from contamination that must be required anywhere in the world.

Skjervøy, Norway[20] in 1988, was a remote coastal community with a population of about 3,000 that experienced an outbreak with an estimated 330 cases of gastroenteritis including 9 cases who were lab-confirmed to have been infected by *C. jejuni*. Community drinking water was supplied from a reservoir created by a dam on a nearby river and was normally chlorinated, but the chlorination system was being replaced and water was delivered without chlorination for four weeks during the outbreak. The likely source of pathogens was not reported, but *C. jejuni* is found in birds and other wildlife. Because this pathogen is exquisitely sensitive to chlorine, maintaining chlorination would likely have prevented this outbreak.

Oakcreek Canyon, Sedona, Arizona,[21] was in 1989, was home to a rapidly growing number of tourist resorts. An estimated 900 individuals who visited a resort in this region suffered from gastroenteritis most likely caused by Norwalk virus. The resort's water supply was used without chlorination and it was found that the treated (chlorinated, but no indication of disinfection efficiency was reported) sewage effluent disposal via seepage fields was able to pass through 60 to 80m of fractured sandstone in 3 to 11 days. Both the security of the groundwater supply and the adequacy of relying on wastewater disinfection were found to be deficient leading to the outbreak.

Kindergarten / Nursery School, Saitama, Japan[22] in 1990 experienced an outbreak of infection with *E. coli* O157:H7 because the bore water supply to the nursery school in Saitama, a prefecture northeast of Tokyo, was contaminated. Diarrhea occurred in 106 children (aged 3 to 6) and 80 family members. There were 42 laboratory-confirmed cases of *E. coli* O157:H7 and 20 developed HUS, 11 with neurological symptoms and two children died. No details were provided about the water supply for this school beyond indicating that drinking water was drawn from a bore and no details were reported about how the bore water became contaminated. There was no mention of any treatment or disinfection in either report of this incident.

Cabool, Missouri, USA,[23] was in 1990, a town of about 2,100 population within a rural township with a population of about 3,100. On January 4, 1990, the local health department learned of ten cases of severe gastroenteritis exhibiting bloody diarrhea and abdominal cramps. A total of 243 cases were identified, 82 with bloody diarrhea; 32 cases were hospitalized, 2 developed hemolytic uremic syndrome (HUS) and 4 died. Drinking water was supplied by two bores (Wells #5 and #6) when the outbreak occurred. Monitoring data for these bores from November 1981 to January 1990 showed that no coliforms had ever been detected in any source water sample, suggesting that the groundwater source was not the source of the outbreak.

The Cabool water system distributed water without treatment or disinfection. The reticulation system was in poor repair and vulnerable to sewage contamination at several locations. The sewer system was in worse condition and was unable to cope with the sewage loading, causing regular sewage back-ups and overflows, particularly during precipitation events. The occurrence of 45 water meter replacements and two major water main repairs in the period immediately before the outbreak strongly suggests contamination during these repairs. The absence of any chlorination made incidental contamination by pathogens the likely cause of this fatal outbreak.

Creston - Erickson, BC, Canada[24] was in 1990, a town (Creston) with a population of about 4,200 and the surrounding agricultural region (Erickson) with a population of about 2,000. Creston and Erickson were supplied by unfiltered, unchlorinated surface water from a mountain stream originally from an undeveloped mountain watershed that was subsequently permitted for logging. Over a 4 month period in early 1990, 124 laboratory-confirmed cases of giardiasis occurred among residents of these communities. This followed an earlier outbreak of 83 laboratory-confirmed cases of giardiasis in late 1985. The contamination of the untreated water supply in 1990 was ultimately traced to an infected beaver living on the stream.

This outbreak also demonstrated the risks of using surface water that was not disinfected for a drinking water supply. Contrary to common belief, residents were apparently able to acquire long-lasting (at least 5 years) immunity to giardiasis, making the risk greatest for new residents and visitors such as tourists. Community opposition to chlorination was evident when the responsible Medical Officer of Health obtained a court order to implement chlorination - only to be met by a blockade of the road to the water intake that lasted for 55 days with the support of 200 local volunteers. Opponents to disinfection erected a sign at the entrance to town declaring "*Welcome to Erickson CHLORINE FREE ZONE*".

Uggelose, Denmark,[25] in 1991-92, was a small rural-suburban community. The discovery of sewage contamination of the local water supply ultimately led to a series of actions, including an outbreak investigation that revealed approximately 1,600 individuals having experienced gastroenteritis. Although the investigation showed strong links of gastroenteritis to drinking water exposure in the community, no pathogenic agent was identified in this outbreak. The drinking water system relied upon groundwater derived from two bores that were used alternately. Well #2 was a deep bore (86 m) with its well-head located about 8 m south of a municipal sewer and 14 m east of an old waterworks building. Water was treated by aeration and filtration, but was distributed without chlorination.

Following heavy rains in December 1991 and January 1992, flooding was discovered in an old waterworks building that was connected by means of a drain to the well-head of one drinking water supply bore. The head-works for Well #2 was located in an installation pit that had a drain to a sump in the old waterworks building. The old waterworks building in turn had a pipe draining to a nearby sewer. The outbreak was likely caused by blockage of the sewer, creating a backup and overflow of sewage into the old waterworks building. When the flooding of the building was deep enough, the drainage pipe to the installation pit for Well #2 back-flowed with sewage and contaminated the water supply being provided by Well #2 because the gasket seal on the well-head was also defective. A water sample from this system was taken the next day, but not reported to health authorities until 4 days later. This sample had thermo-tolerant coliforms at 920 per 100 mL, resulting in an immediate boil water order being issued. The offending connection between Well #2 and the sump in the old waterworks building had been recognized by both the local authorities and the waterworks management. In 1990, the local authorities had asked the waterworks personnel if there was a danger posed by this connection, but they received no answer.

Gideon, Missouri, USA[26] was, in 1993, a town of about 1,100. After a taste and odour episode in early November 1993, the water system was subjected to extensive flushing that preceded an outbreak of salmonellosis affecting more than about 650 people and causing 7 deaths. The municipal water system for Gideon was constructed in the 1930s and provided groundwater from two deep (396m) artesian bores to the reticulation system without disinfection or treatment under the belief that the bores were geologically isolated and secure from surface contamination. Ironically, the bore water was not the source of contamination.

A municipal storage tank in disrepair commonly had pigeons roosting on its roof. The most plausible explanation of the contamination was judged to be bird droppings entering this water storage. Extremely low temperatures were believed to have caused a thermally-induced turnover that mixed the stored water leading to the taste and odour complaints that triggered a massive flushing program. This flushing drew more of the contaminated, stored water into the reticulation system. Ultimately, this outbreak was caused by a poorly maintained and operated water system with no disinfection, despite having access to a high quality "secure" groundwater supply.

Noormarkku, Finland[27] was, in 1994, a municipality of about 6,300 in southwestern Finland. In April, 1,500 to 3,000 residents experienced acute gastroenteritis that was attributed to viral pathogens. The municipal water supply was drawn from two bores situated on the banks of the Noormarkku River in a largely agricultural region with grazing livestock. The river also received treated, but not disinfected, sewage effluent from four upstream communities. The water was pH-adjusted, but received no other treatment or disinfection. Coliform monitoring of the distributed water had consistently reflected good water quality before the outbreak.

The municipal water supply was not protected by any source protection zone around the bores. The winter of 1994 had double the normal snowfall and rapid melting occurred at the beginning of April. An ice dam formed downstream of the bores, causing river flooding back to the bores. A drainage pipe from one bore had been neglected and provided a route for the river water to contaminate the bore. This situation was exacerbated by the heavy flows to the upstream sewage treatment plants that caused about half of the sewage to be discharged to the river untreated. Furthermore, livestock manure from upstream pastures was washed into the river during the flood conditions. Thus, many features contributed to contamination but the common cause of the failure was the lack of treatment for pathogens, particularly lack of disinfection.

Klarup, Denmark[28] was, in 1996, a rural town of about 4,000 residents. A private water company supplied the community from two bores with water that was neither filtered nor chlorinated. One bore that became contaminated produced water from an aquifer at least 80 m deep. Between mid-December 1995 and early March 1996, 110 cases of laboratory-confirmed campylobacteriosis (total estimated cases of illness was 2,400) were attributed to contamination of the drinking water. Investigations revealed that an exploratory bore to evaluate nitrate contamination of the aquifer was drilled about 25 m from the contaminated bore. During the drilling, a sewer, at about 3 m depth, was damaged and sewage was allowed to leak from this damaged sewer into the aquifer supplying the bore. The absence of any disinfection of this groundwater supply readily allowed the sewage contamination to infect the community.

La Neuveville, Switzerland[29] was, in 1998, a township of over 3,300 residents on the shores of Lake Bienne in Switzerland. More than 2,200 cases of gastroenteritis were estimated to have occurred among residents with at least another 200 or more cases occurring among visitors or temporary residents. Analyses of stool samples revealed two strains of *C. jejuni* and two strains of small round structured viruses, a common strain of *Shigella sonnei*, and possibly a strain of enteropathogenic *E. coli*. The drinking water system was supplied by two groundwater bores with the pump stations located near the lakeside sewage pump station. The drinking water system had no disinfection, only an aeration oxidation process for precipitating iron and manganese. An outbreak of gastroenteritis with at least 30 cases had occurred 11 months previously. A pump failed at the sewage pump station causing a sewage overflow that contaminated the drinking water aquifer. Local politicians were reluctant to acknowledge the drinking water contamination. Ultimately, 10 months after the large outbreak, the system adopted continuous chlorination and ultraviolet (UV) disinfection.

Washington County Fair, NY, USA[30] near Albany, the state capital, was attended in 1999 by 108,000 persons. An estimated 2,800 to 5,000 individuals developed gastrointestinal illness, with 781 confirmed or suspected cases. Of these, 127 cases of *Escherichia coli* O157:H7 and 45 cases of *C. jejuni* were lab-confirmed, 71 individuals were hospitalized and 2 died: a 3-year-old girl and a 79-year-old man.

Water for the fair was supplied by bores that were typically 7 m deep beneath soil overburden described as gravelly sand with coarse fragments. The local district office of the state Department of Health (DOH) learned in the fall of 1997 that fair officials had installed three unchlorinated drinking water supply bores, but determined that the duration of use for the fair was too short to regulate them as a public water supply. Two chlorinated bores had been expected to provide potable water for the Fair, but the drought of the 1999 summer severely reduced the yield of one of these resulting in a decision to use supplementary supply for food concessions from unchlorinated bores.

The outbreak investigation studied seepage from a septic system serving a dormitory building. The septic tank seepage area was located only about 11 m from the suspect unchlorinated bore. Dye flushed down a toilet in the dormitory began to appear in the bore after 9.5 hours travel time, peaking at 21.3 hours, demonstrating a rapid flow path from the dormitory sewer. The combination of poor decisions had fatal consequences. This public health disaster occurred 9 months before and 600 km distant from Walkerton. The findings of the investigation into the cause were made public less than 2 months before Walkerton but had no impact there.

Asikkala, Finland,[31] was, in 2000, a community of about 5,500 residents experienced an outbreak of campylobacteriosis affecting about 400 residents in August 2000 because drinking water was supplied by bores without chlorination or other treatment. Several possible sites where contamination could have entered the system were acknowledged but contamination was likely associated with surface runoff following heavy rains. Other cases of unchlorinated drinking water supplies causing outbreaks were reported shortly thereafter. A smaller community in eastern Finland with 600 to 800 consumers, served by a communal system, experienced an outbreak of campylobacteriosis in about 50 consumers in August 2001. Finally, from October through November 2001, approximately 1,000 cases of campylobacteriosis occurred among 18,000 residents of an unnamed town in southern Finland.

Transtrand, Sweden[32] in 2002 had a base population of 605 and was a popular tourist destination during the ski season. At that time an outbreak of gastroenteritis caused by Norwalk-like virus infected some 500 people. No details were published, but the water supply was not chlorinated. In mid-April, the environmental regulators revealed a substantial crack in a sewer located 10 m from one of the bores supplying the contaminated water system. The community and local authorities only agreed to having this water supply chlorinated after this discovery. Opposition to chlorination was based on the local authorities not believing the relationships of the field epidemiological investigation that attributed the outbreak to contaminated water and "*the general reluctance of the population to regular chemical treatment of the water supplies*"[33]

Alamosa, CO, USA,[34] was in 2008, a community of about 8,900 population. The water system at that time consisted of seven deep (275 to 550 m) seasonally artesian bores, two elevated storage towers, one ground-level reservoir storage and about 80 km of reticulation serving the City and another 1,000 consumers outside of Alamosa. An outbreak resulted in 124 lab-confirmed cases of salmonellosis, an estimated 1,300 cases of gastrointestinal disease, with 20 hospitalizations and 1 death. At the time of the outbreak, the system had no treatment process and distributed water without chlorination under a 1974 waiver from the State regulator based on the apparent security of the groundwater aquifer. Ironically, Alamosa was planning a water treatment plant to deal with identified natural arsenic contamination of the ground water supply. Microbiological monitoring of bore water quality was only performed for total coliforms and there were no consistent indications of adverse water quality. Overall, the most plausible explanation for *Salmonella* contamination was the entry of faecal contamination carried by rain or snowmelt through cracks in the roof and sides of the storage. Small animals or birds may also have entered this ground-level reservoir storage through one or more of the larger holes, but no bird or animal carcasses were located. There was bird faecal material on the roof of the reservoir.

Appendix 3
Outbreaks Relevant to Principle 2

2. ***The drinking water system must have, and continuously maintain, robust multiple barriers appropriate to the level of potential contamination facing the raw water supply.***

Edmonton, AB, Canada,[35] was in 1982-83, a city of of about 580,000 when it was providing treated drinking water via a city centre water treatment plant drawing from the North Saskatchewan River by means of a full conventional water treatment system (chemical coagulation, granular media filtration and chloramine disinfection, plus lime soda softening). The intake for this plant was located downstream from 85 storm drain outfalls, many of which had intentional sanitary sewer cross connections for residential sewer back up prevention, providing seriously challenged raw water quality conditions at times of storm drain discharge. The outbreak, that was denied by the water utility and the regulator was likely the world's largest reported outbreak of giardiasis to that time. *Giardia* was still a relatively recently recognized protozoan pathogen then. *Giardia* cyst ability to bypass conventional water treatment unless turbidity removal and chemical disinfection was optimized was not widely recognized across the water industry. Neither process had been achieved at the water treatment plant because the filtration barrier was performing at a sub-optimal level and disinfection was dependent on chloramines that required a high combination of dose and contact time to inactivate the *Giardia* parasite. As a result, Edmonton experienced an outbreak of giardiasis that ultimately caused a total of 895 laboratory-confirmed cases at a time when this disease was not yet reportable in Alberta. This giardiasis outbreak had the second highest number of lab-confirmed cases of waterborne giardiasis documented to that date in the open scientific literature and likely corresponded to an outbreak of at least 10 times the number of lab-confirmed cases.

The Edmonton outbreak occurred because the multiple barriers, of which there were several, were ultimately found to be seriously inadequate to deal with the actual microbial pathogen challenge that the City of Edmonton faced with its drinking water system.

Swindon & Oxfordshire, England,[36] in 1988-89, experienced the first major outbreak of cryptosporidiosis that involved 516 symptom-defined cases in the rapidly growing city of Swindon and surrounding regions of Oxfordshire and Wiltshire. The water was drawn from the upper regions of the River Thames and subjected to treatment by coagulation with polyaluminum chloride, rapid sand filtration and chlorine disinfection ("conventional treatment") so the disease outbreak was completely unforeseen, resulting in the Badenoch Commission of Inquiry which defined the body of knowledge for preventing drinking water outbreaks of cryptosporidiosis 3 years before the massive outbreak in Milwaukee.[37]

The Badenoch Inquiry identified that the practice of recycling filter backwash to the headworks of a treatment plant, without off-stream treatment, led to a massive concentration of the oocyst loading on granular media filters (up to 1,000,000,000 oocysts per filter per day) such that previously "acceptable" fine particle removal of 99% would be inadequate to limit the concentration of oocysts in treated water. This provides a classic case of where multiple barriers are needed, but because of a failure to ensure that every barrier, or the combination of barriers, is performing effectively, an outbreak can still occur.

Milwaukee, WI, USA,[38] was, in 1993, a city of 600,000, in a metropolitan area with a regional population of about 1,600,000. In early spring, Milwaukee experienced a massive outbreak of gastrointestinal disease attributed to *Cryptosporidium* oocyst contamination of its surface filtered water supply with the first published estimates attributing more than 400,000 cases to this outbreak. These cases included an estimated 4,400 hospitalizations and possibly 50 deaths primarily among immunocompromised individuals over the following year, mainly AIDS patients. The implicated treatment plant provided full conventional treatment (chemical coagulation, granular media filtration and chlorine disinfection) for raw water drawn from Lake Michigan. Although the source of the *Cryptosporidium* oocyst contamination was not clearly established, it was demonstrated to have come from a sewage origin (human strains were responsible, not cattle). *Cryptosporidium* is resistant to chlorine inactivation making it necessary for other barriers to protect consumers. In this case, fine particle removal by means of optimized turbidity removal was necessary, but the filtration practices were not sufficiently efficient to deal with the oocyst challenge. Although *Cryptosporidium* had caused outbreaks at full conventional treatment plants in the U.S. (Carrollton, Georgia, 1987) and in the U.K. (Saltcoats/ Stevenston, Scotland 1988 and Swindon / Oxfordshire, England 1989) that led to major investigations and recommendations for water utilities to avoid such outbreaks, Milwaukee was unaware of that prior experience. The magnitude of this outbreak did lead to major regulatory reforms in the U.S. that have shaped the requirements for water utilities drawing from surface water sources.

Victoria, BC, Canada,[39] in 1994-95, had a regional population of about 322,000. Between October 1994 and May 1995, at least 100 acute, non-congenital cases of toxoplasmosis were judged to have been outbreak-related (Bell et al., 1995; Bowie et al., 1997) and between 2,900 and 7,700 individuals may have been infected by *Toxoplasma gondii* during this outbreak. The regional water system relied upon drawing surface water from reservoirs in a forested catchment protected from development with limited human activities. Water was treated with chloramine disinfection, but no filtration before delivery to the regional reticulation system. In March, 1995, the B.C. Centre for Disease Control (BCCDC) learned of 15 acute *Toxoplasma gondii* infections, identified by serological analyses, over the previous three months in the Greater Victoria area, compared with 1 to 4 diagnoses per year typically observed in this region. A resulting detailed investigation revealed the 100 acute, non-congenital cases of toxoplasmosis. The epidemiologic curve of cases aligned with weather and water quality data to show that the two main peaks of disease onset arose after heavy rainfall events in November 1994 and February 1995. The source of *T. gondii* is normally the feces of cats. Cougars frequent this watershed. Although none could be trapped, a study of cougars 100 km north found 5 to be serologically positive for *T. gondii*. A single animal may shed 200 million oocysts in feces. A follow-up study the next year found ~1,250,000 oocysts per g of fresh cougar feces. A sample of feces found on the ground near the Humpback reservoir showed ~25,000 oocysts per g.

The only treatment barrier was chloramine disinfection dosed at 1 mg/L. Although the susceptibility of *T. gondii* to disinfection is not known, it was believed to be similar to resistant protozoan pathogens like *Cryptosporidium*, meaning that the chloramine disinfection provided would have been inadequate to prevent an infection risk for consumers. This case provides an example of an unexpected contamination source (wildlife faeces) defeating the barriers expected from the presumed protected catchment and chloramine disinfection.

North Battleford, SK, Canada,[40] was, in 2001, was a community of about 15,000 in the Battlefords district adjacent to the Town of Battleford, with a population of about 4,000. The main water treatment plant drew raw water from the North Saskatchewan River, about 3.5 km downstream from the City's sewage treatment plant outfall. There was some, but not very insightful, recognition that such a water withdrawal location required a full conventional water treatment process including potassium permanganate raw water oxidation (during taste and odour episodes); polyaluminum chloride and polymer chemical coagulation, upflow gravity clarification, pH adjustment with lime and granular media filtration. Chlorine was the sole disinfectant.

North Battleford experienced a 6-week long outbreak of cryptosporidiosis with an estimated 5,800 to 7,100 cases. Because this outbreak occurred only 11 months after Walkerton, a public inquiry was called by the Government of Saskatchewan to determine its cause. The inquiry revealed a complex situation of infighting among water utility staff, resignation of the water supervisor months before the outbreak and a failure of political leadership to take ownership of its responsibility to provide its citizens with safe drinking water. The detailed technical cause was a badly timed and poorly performed maintenance operation on the up-flow clarifiers that eliminated any effective turbidity removal in this multiple barrier treatment train leaving chlorine disinfection as the only barrier for dealing with *Cryptosporidium*. This outbreak provides an excellent demonstration that chlorine is ineffective for *Cryptosporidium* and that a failure to keep all barriers operating effectively can result in a major disease outbreak.

Te Aute College, Hawkes Bay, New Zealand,[41] in May 2001 an outbreak of campylobacteriosis occurred among students and staff of a boarding school located among hills in a rural setting about 20 km inland from Hastings and Havelock North, affecting between 95 and 185 people, some of whom were confirmed to be infected with camplyobacteriosis. The water for the school was drawn from a source that originated at springs arising in the fractured limestone hills high above the school. The springs fed a swampy region that drained through an outlet stream. The raw water intake for the school was located in the bed of this outlet stream. Water was treated by pressure sand filter, softener, filtration cartridge (1 µm nominal pore size) and UV disinfection. An environmental investigation was undertaken that showed heavy contamination of both the untreated water supply (460 to 980 *E. coli* per 100 mL) and the treated water supply (22 to 59 *E. coli* per 100 mL). The source water intake area was inspected to reveal that this was open to grazing cattle because fences protecting the source area were in disrepair, allowing the cattle direct access.

In addition to allowing source water contamination, this outbreak was caused by treatment failure. There was evidence that the UV treatment system was not performing adequately prior to the outbreak. The UV bulb was being replaced annually; the UV bulb sleeve was cleaned at the same frequency. The manufacturer's specifications for this system called for bulb replacement approximately every 9 months, based on decline in light output to 65–70% of that of a new bulb, normally expected after 4,500 hours of continuous operation. The bulb sleeves should have been cleaned every 3 months, according to the manufacturer's specifications. These hazardous circumstances were further endangered when the UV bulb failed altogether and was not replaced for 3 to 4 days, meaning that this faecally-contaminated raw water received filtration but no disinfection. An outbreak occurred because the raw water source was not protected and the critical disinfection treatment barrier was allowed to become non-functional.

Östersund, Sweden,[42] was in 2010, a city of 60,000, about 560 km northwest of Stockholm. The water works drawing raw water from a large lake provided treatment of pH adjustment, pre-ozonation, rapid gravity filtration and chlorine disinfection. The local authorities regarded this lake as a pristine water supply (one official described the lake as the "cleanest lake in Europe") that posed minimal contamination risk even though it received storm water discharges from the urban area, as well as treated sewage and had recently experienced a major raw sewage spill when an underwater sewer leaked.

Östersund experienced the largest outbreak of cryptosporidiosis in European history with 27,000 cases, almost half the population. Ultimately the cause was traced back to a sanitary sewer from an apartment building that was cross-connected with a storm drain that fed a very small creek that discharged into the lake water supply up-current from the drinking water plant intake. Despite having at least 3 treatment barriers, 2 of them (ozonation and filtration) were not operated at a level of efficiency capable of inactivating / removing *Cryptosporidium* oocysts leaving only chlorination which is not capable for this purpose. This massive outbreak was allowed to happen by a classic failure to anticipate the level of threats to drinking water safety that were posed by the "pristine" water supply. Experience also showed how little faecal contamination is needed to cause a massive outbreak.

Appendix 4
Outbreaks Relevant to Principle 3

3. ***Any sudden or extreme change in water quality, flow or environmental conditions (e.g. extreme rainfall or flooding) should arouse suspicion that drinking water might become contaminated.***

Georgetown, TX, USA,[43] was in 1980, a small city of about 13,000. A large outbreak likely caused thousands of cases of gastroenteritis among about 10,000 persons served. The Georgetown region was supplied by seven bores, four of which (Wells 1 to 4) were located in the city centre. The outbreaks were clearly associated with contamination of the bores in the city centre. Bore water samples, after the largest peak of illness, showed faecal coliforms ranging from 150 to 1,500 per 100 mL. The water being distributed was heavily chlorinated and a boil water advisory was in effect by the time these monitoring data were revealed. The exact source of contamination was not identified with nearby sewers and an abandoned bore which did not show leakage or a hydraulic connection to the aquifer. A large region with homes on septic tank systems might have contributed. The aquifer in use was exposed to the surface through a fault line near the bores and the outbreak was judged to be associated with heavy rainfall events.

This outbreak, occurring after an outbreak one year earlier under similar circumstances, suggests a serious lack of responsiveness by the water utility and public health officials. The problems signaled by the first outbreak did not drive the actions necessary to prevent the 1980 outbreak. This system relied on groundwater with limited treatment (chlorination) and under such conditions, meaningful source protection, at minimum, is necessary, but was apparently not pursued in this case.

Skjervøy, Norway (1988). This outbreak was previously described in Appendix 2. The drinking water was normally chlorinated, but the chlorination system was being replaced and water was delivered without chlorination for four weeks during the outbreak. This obvious and dramatic change in the water management system should have been a serious warning, such that even if no treatment alternative was possible, a boil water advisory should have been called.

Bradford, England,[44] was in 1992, a city of about 300,000 and it experienced 125 lab-confirmed cases of cryptosporidiosis. As had occurred in outbreak experience elsewhere with cryptosporidiosis in particular and waterborne gastroenteritis in general, many more cases of illness occurred in the community than were evident from the total of lab-confirmed cases. Microbiological investigations at the water treatment plant revealed low concentrations of *Cryptosporidium* oocysts in the treated water during the outbreak.

One of the slow sand filters had been re-commissioned and heavy rainfalls in the region had produced higher than normal turbidity in the treated water supply. No specific source of *Cryptosporidium* contamination was reported. The outbreak was likely a result of the combination of heavy rainfalls creating a raw water treatment challenge of *Cryptosporidium* oocysts and poor performance of one slow sand filter being impaired by its recent re-commissioning. The first Badenoch Inquiry report had warned against prematurely re-commissioning slow sand filters after they had been cleaned because a ripening period was recognized to be essential. Likewise, the severe weather, which was documented to have affected raw water quality (increased colour), offered a warning against the premature return of this slow sand filter into delivery of potable water. The risk posed by unusual conditions coinciding with treatment process changes is a recurring theme in a number of outbreaks.

Warrington, England,[45] in 1992-93 experienced an outbreak of cryptosporidiosis with 47 lab-confirmed cases occurred, primarily in one water-supply region serving a population of about 38,000. During exceptionally heavy rains in January, 1993, drainage from a flooded field with grazing livestock was observed in shaft 3 of the Houghton Green groundwater supply. Review of meteorological records revealed several days of heavy rainfall. These earlier rainfall periods would have explained the onset of disease first reported in December 1992. Inspection inside shaft 3 showed evidence of water ingress, but there was also cross-connection between a septic tank and chambers adjacent to shaft 1. The concrete lining of shaft 1 had exposed aggregate indicative of corrosion by aggressive water with possible contaminated seepage occurring.

This outbreak provides another instance of a normally high-quality groundwater source that became contaminated by surface contamination. This supply should have been subject to routine monitoring of raw water and to periodic inspections seeking to identify hazards that could place the otherwise high quality water at risk. The high turbidity reading at the service reservoir, while within the allowable limits for turbidity in force at that time, was unusual for this water supply. Such unusual results, in relation to normal results expected for any water source, should trigger an investigation of the water supply to determine the cause of the change.

Milwaukee, WI, USA (1993). This fatal outbreak was summarized in Appendix 3. The raw water supply from Lake Michigan was subject to high turbidity during winter storms. Although there were several water treatment plants that suffered from high turbidity raw water at the time of the Milwaukee outbreak and only one water treatment plant experienced an outbreak. That reality likely reflects the coincidental occurrence of unusually high raw water turbidity with a strong source of *Cryptosporidium* oocysts near the water intake of the affected water treatment plant.

South Devon (Torbay & District), England[46] in 1995 had an urban and surrounding rural area population of over 300,000. This region, was served by a water treatment plant which provided a clarification process, granular media filtration, flotation-filtration units and chlorination. An outbreak of cryptosporidiosis emerged over a period of several weeks and ultimately about 500 cases occurred, leading to a major outbreak investigation. An earlier outbreak of cryptosporidiosis involving 200 confirmed cases had occurred in this same region 1992. An epidemiological investigation at that time had concluded that water was the most likely mode of transmission for the outbreak, but no oocysts were found in the treated water at that time. There had also been a small outbreak in June 1991 without any cause determined.

There was no obvious, single flaw identified to explain this outbreak, but it was evident that the water company was under pressure to maximize water production to meet the local demand during a hot, dry summer. A power failure caused by a thunderstorm knocked out a pumping station for 5 hours at one of the remote supplies. This circumstance required an increase in water withdrawal from the river supply at the time when this river source was experiencing sudden flood conditions. A sewage treatment plant was located 8 km upstream of the drinking water intake on the River Dart. The fine particle removal efficiency was reduced during this period, leaving ineffective chlorine as the only barrier to *Cryptosporidium*. Despite a major investigation, the details of how this outbreak occurred were not established, but it should be clear that there were several signals of unusual conditions that coincided with the outbreak.

Brushy Creek, TX, USA,[47] was in 1998, a district with about 10,000 residents served by the municipal utility. This community experienced an outbreak of cryptosporidiosis affecting 1,300 to 1,500 people. This community is just 20 km south of Georgetown, a community that experienced major waterborne outbreaks with a groundwater supply in 1979 and 1980 (reviewed earlier in this section). The contaminated supply was a set of bores to about 30 m depth drawing on a local aquifer. A lightning strike caused a raw sewage spill of 635,000 L from the nearby City of Austin pumping station into Brushy Creek. The chlorinated water supply samples were consistently negative for faecal coliforms but the state regulator requested testing of bore water before chlorination which revealed that four out of five bores were contaminated with faecal coliforms. The utility was ordered to take these bores out of service and to purchase the necessary drinking water supply from another nearby city.

The contaminated bores were approximately 400 m from Brushy Creek so they were not regarded as a high risk for contamination from Brushy Creek. However, Brushy Creek is normally fed by springs that were dry at that time because of extended drought conditions. The sewage spill appeared to have gained access to the aquifer by means of the hydrogeological connections that fed the springs or similar geological fractures. These conditions were believed to have been exacerbated by a hot period with heavy water demand and no rainfall to recharge the aquifer before the sewage spill. Of course, any aquifer that relies on recent rainfall for recharge is also subject to recent surface contamination. The unusual weather conditions and the sewage spill were changes that should have triggered investigation and limited the impact of this outbreak. However, the signals were likely not recognized as efficiently as they could have been.

Walkerton, ON, Canada (2000). This fatal outbreak was previously described in Appendix 2. The heavy rainfall that occurred during the week preceding the manure contamination of Well #5 resulted in extensive flooding and power outages in the Town. Such events should always be taken as a signal to anticipate potential source water contamination.

Washington County Fair, NY, USA (1999). This fatal outbreak was previously described in Appendix 2. The outbreak was preceded by a long drought that led to the unchlorinated bore being used for potable purposes, then during the Fair, heavy rains occurred. The combination of protracted drought followed by heavy rain should always be taken as a signal to anticipate potential source water contamination.

North Battleford, SK, Canada. (2001). This large outbreak of cryptosporidiosis was previously described in Appendix 3. The ill-timed maintenance performed on an upflow clarifier caused almost total loss of the turbidity removal capability of the treatment plant. A major process change like this demands careful operational attention.

Appendix 5
Outbreaks Relevant to Principle 4

4. ***System operators must be able to respond quickly and effectively to adverse monitoring signals.***

Eagle-Vail, CO, USA,[48] was in 1981, an unincorporated communities with a combined population (with the adjacent community of Avon) of about 3,500 population. These communities experienced an outbreak of viral gastroenteritis with over 80 cases reported among 168 persons interviewed by telephone, but no estimate of total illness was reported. Raw water was usually drawn from a small creek in the mountains immediately south of Eagle-Vail; but at the time of the outbreak, an alternate intake in the Eagle River had been in use for months because the primary source could not supply the community demand because of warm, dry weather. The water treatment plant used a dual-media, direct-pressure filtration process without any chemical coagulation, followed by chlorine disinfection. The outbreak was attributed to rotavirus.

Three coincident factors were among those implicated as major contributing causes of this outbreak. An upstream sewage treatment plant for the large resort community of Vail was overloaded and was discharging sludge solids to a tributary of the Eagle River upstream of the raw water intake. The pressure filter media beds revealed severe channeling and separation of the media from the filter walls, thereby providing hydraulic bypass for the feed water into the filtered supply. Finally, and likely most critically, the gas chlorinator failed for up to 24 hours before the outbreak. An automatic alarm was sounded in the community fire house, but was apparently turned off without any investigation of cause. This outbreak revealed a dangerous combination of environmental and process changes that failed to elicit any appropriate response from operational staff.

Edmonton, AB, Canada (1982-83). This large outbreak of giardiasis was previously described in Appendix 3 and it lasted over an extended period of months. Despite considerable concern being expressed in the community about illness possibly being caused by water contamination. The water utility denial of the possible importance of the most critical kind of monitoring results (illness in the community) allowed the ineffective treatment conditions to continue, thereby allowing the outbreak to last longer.

Milwaukee, WI, USA (1993). This massive outbreak of cryptosporidiosis was previously described in Appendix 3. The operators did not recognize the meaning of turbidity spikes in the treated water that were ultimately found to coincide with initiation of the outbreak. The main fault underlying this lack of problem recognition was the failure of Milwaukee drinking water managers to stay in touch with research in other jurisdictions. Specifically, the findings of the English Badenoch Inquiry if they had been applied in Milwaukee could have allowed earlier recognition of treatment vulnerabilities when facing a *Cryptosporidium* challenge.

Walkerton, ON, Canada (2000). This fatal outbreak was previously described in Appendix 2. The operators did not understand the importance of chlorine disinfection nor the importance of monitoring chlorine residual as a real time measure of water contamination. That failure prevented them from detecting the contamination by accurately measuring chlorine residual and correctly interpreting the inability to find a residual when chlorine was being dosed to demonstrate the water contamination within 24 hours of it occurring. The General Manager did not understand the serious implications of ignoring a failed bacteriology result on a reticulation sample.

North Battleford, SK, Canada. (2001). This large outbreak of cryptosporidiosis was previously described in Appendix 3. The operators failed to understand the serious implications of allowing negligible clarification prior to granular media filtration for a water source that was drawn downstream of a sewage discharge and was clearly at risk of *Cryptosporidium* oocyst contamination. Such an oversight might have been understandable in the early 1990s, but not in 2001.

Northampton, England,[49] in 2008, was served along with 258,000 regional residents by the Pitsford Water Treatment Works. This advanced water treatment facility undertook more detailed monitoring than required, specifically by continuously monitoring treated water for *Cryptosporidium* oocysts. Early one weekday evening, the regional laboratory informed the water operators that it had detected 6 oocysts in a sample of 11,848 L of water (equivalent to 0.0005 oocysts per L vs. the regulatory requirement to be below 0.1 oocysts per L). Because this was the first time an oocyst had ever been detected in treated water over years of continuous monitoring, a decision was made to remove and send the current sampling cartridge to the lab for analysis. At 8:00 PM, that cartridge was sent to the regional lab 70 km away and early the following morning, the lab reported 418 oocysts in 5,064 L (0.08 oocysts per L). At 3:30 AM, the decision was made to call a boil water advisory affecting all 258,000 customers. Many other extraordinary measures were taken to protect public health, but a relatively small cryptosporidiosis outbreak (22 lab confirmed cases, 422 total estimated cases) still occurred. Ultimately, the oocyst contamination was traced to a single infected rabbit that gained access to a treatment unit and was drowned there. Despite this tiny source, the entire system was contaminated with oocysts. Likewise, despite the rapid actions taken hundreds were made ill. This makes a strong case of the need for prevention because even very rapid and effective reaction did not prevent this outbreak.

Appendix 6
Outbreaks Relevant to Principle 5

5. ***System operators must maintain a personal sense of responsibility and dedication to providing consumers with safe water, and should never ignore a consumer complaint about water quality.***

Naas, Ireland,[50] was in 1991, a rural town with a population of more than 11,000. Sewage contaminated the groundwater supply distributed to about half of the population, leading to an outbreak of gastroenteritis that may have affected several thousand residents. A single consumer complained that the domestic water supply smelled foul, leading to sampling for bacteriological analyses. Although no further complaints were received that day, complaints the next day led to an inspection of the borehole, revealing visual evidence of sewage contamination. This supply was closed and the distribution system flushed and super-chlorinated. Samples taken during the inspection of the contaminated source revealed an *E. coli* count of 15,000,000 per 100 mL, levels that would be expected in raw sewage and which indicated that massive sewage contamination of the water supply had occurred. This massive contamination may explain why the chlorination of this groundwater supply failed to prevent the outbreak, likely because a normal chlorine dose to such contamination would be consumed by the massive chlorine demand that would be exerted. In Naas, action taken in response to the consumer complaints at least limited the magnitude of this outbreak.

Gideon, MO, USA (1993). This fatal outbreak was previously described in Appendix 2. Odour complaints from consumers led to flushing of the reticulation system before the causes of the problem was understood. Retroactive analysis of the outbreak suggested that the flushing response likely made the problem worse by drawing more contaminated water into the reticulation system and increasing exposure of consumers. Flushing has been a typical response to aesthetic complaints, but there is evidence in several of these outbreaks that there needs to be some understanding of the causes of a problem before extensive flushing is pursued.

Milwaukee, WI, USA (1993). This fatal outbreak was previously described in Appendix 3. There was evidence that consumer complaints rose dramatically during the contamination episode, but there was not documentation available to indicate that these complaints had any influence on the operational response to this issue.

Freuchie, Scotland,[51] was in 1995, a village of about 1,100 population and was served by a regional water system providing surface water that was chlorinated only. An outbreak of gastroenteritis caused by drinking water contamination with *Camplyobacter* and *E. coli* O157:H7 made 711 people ill. The contamination was detected by consumer complaints of discoloured water with an odour that ultimately revealed a cross-connection within a vegetable washing operation that contaminated the village water supply. That facility had stopped using the village supply after it commissioned its own bore. When the pump on their bore failed, the company used raw water from a nearby creek for the initial wash and returned to using the village water supply for their final wash. Unfortunately, since they had last used the village water for washing, the raw water supply from the creek was now downstream from the village sewage treatment plant, there was now an interconnection between the initial wash and final wash piping and the pressure in the raw wash system was higher than the village water supply. As a result, for 5 days, sewage contaminated raw water was allowed into the village water supply, leading to this outbreak. The water utility staff responded rapidly and traced the problem in under 12 hours from receiving the first consumer complaint. There were fortunately no deaths in this outbreak, an outcome that can probably be credited to the rapid determination of the problem and resolution, followed by a well-notified boil water advisory.

Nokia, Finland,[52] was in 2007, a community of about 32,000, 15 km west of Tampere, the second largest urban area in Finland. Nokia's raw water was normally drawn from an urban lake that was treated by pH adjustment, oxidation for iron and manganese removal, sand filtration and chlorination. Nokia experienced a major outbreak in which 1,200 people sought medical care and over 8,450 were ill with gastroenteritis with 6,500 of these cases directly attributed to the water contamination. Water samples revealed at least six microbial pathogens (*Campylobacter* sp., Norovirus, *Giardia*, *Salmonella* sp., *Clostiridium difficile* and Rotavirus). Two women (52 and 81 years of age), suffering from other health conditions, died in hospital after seeking care for gastrointestinal illness. These cases were investigated to determine whether water contamination had contributed to the fatalities (Anon 2007). A waterworks employee was charged in 2010 with two counts of involuntary manslaughter, but he ultimately received a seven month suspended prison sentence. This outbreak involved an extremely unfortunate coincidence. The water treatment plant was under maintenance and operators were not able to restart it, so a pipeline from Tampere was activated to supply Nokia's drinking water. Simultaneously a cleaning operation at the sewage treatment plant that normally used treated sewage effluent was unable to do so, leading to use of treated drinking water. When completed, the valve connecting the drinking water system to the recycled sewage effluent was left open and its higher pressure led to substantial contamination of the drinking water system (400,000 L of sewage effluent) over two days.

When the water treatment operators began receiving complaints about the drinking water being discoloured and odorous, they assumed that this had been caused by switching to the Tampere water system. They began flushing the reticulation system which only had the effect of drawing more sewage effluent in. Two days passed before the cross connection was found and closed. In this case, the Nokia operators were responding to consumer complaints by flushing but they were inadequately curious about the inconsistencies in their assumed explanation cause for the aesthetic water problems.

Adliswil, Switzerland,[53] was in 2008 a suburban municipality with a population of about 16,000 about 7 km southwest from the center of the City of Zurich. Adliswil experienced an outbreak of about 180 cases in an incident remarkably similar to that in Nokia only months earlier. A cross connection at the sewage treatment plant allowed treated sewage effluent into the drinking water system, but unlike Nokia, a consumer complaint about odour led to discovery of the cause within a few hours and a rapid boil water advisory was called immediately. The number of cases of illness that occurred demonstrates the limitations of reactive measures in these circumstances. While credit for rapid response is warranted, media reports quoted wastewater officials as suggesting this incident posed a low risk to consumers because it was "*treated*" sewage effluent that had contaminated the drinking water.[54] The apparent lack of understanding that normally "treated" sewage effluent carries a serious, pathogen risk for drinking water consumers suggests a wider problem in the water industry of public health risk being misunderstood.

A 2009 survey of 77 Swiss sewage treatment plants for the SVGW (Swiss Gas and Water Industry Association) found that 62 had a pipe network for high pressure, treated wastewater that was used onsite for cleaning purposes.[55] Of these 30 had the possibility of cross-connection with the potable water system and 23 of these had a proper air gap pressure-break back-flow preventer as well as a contract for annual inspection and maintenance of the device. The other 7 had a backflow valve intended to prevent treated sewage backflow into the potable water system, but this valve was not labeled nor was there an understanding that it had to be maintained. An analysis of 10 drinking water outbreaks in France between 1998 and 2006 found that 3 of these were summarized as wastewater treatment plant effluent backflow and one was industrial wastewater (contaminated with microbial pathogens) that was cross-connected and had backflow, suggesting that these kind of incidents are surprisingly common.[56]

Östersund, Sweden (2010). This massive outbreak of cryptosporidiosis was summarized in Section 4.1.2. The rapid and committed response to this incident by public health officials was able to convince skeptical water treatment officials to mount a major investigation into the likely cause(s). This work revealed that the belief by water officials that the source water was immune to contamination because the lake was “pristine”. Likewise, discovery of the most plausible cause demonstrated how remarkably little faecal contamination was able to cause Europe’s largest recorded outbreak of cryptosporidiosis.

Appendix 7
Outbreaks Relevant to Principle 6

6. ***Ensuring drinking water safety and quality requires the application of a considered risk management approach.***

Drumheller, AB, Canada,[57] was in 1983, a town of about 6,500 population, experienced an intense, short-duration outbreak of gastroenteritis that affected 3,000 people, including 2 deaths that winter. The municipal water treatment plant drew water from the Red Deer River and provided sedimentation, filtration, without chemical coagulation (in winter) and chlorine disinfection before distribution. The levels of free chlorine leaving the treatment plant had been consistently recorded at approximately 0.6 mg/L, but routine monitoring of chlorine residuals in the distribution system was not being performed. After the outbreak, chemical coagulation was reinstated, chlorine dosage was stepped up to achieve a residual of 2 mg/L at the treatment plant and the water towers were super-chlorinated. Even so, detectable chlorine residuals were often not achievable in the middle of the distribution system, suggesting that substantial chlorine demand was occurring within the distribution system.

A raw sewage overflow 4.5 km upstream of the drinking treatment plant water intake on the same bank of the river before the outbreak came to light six weeks after the epidemic. Apparently, overflows at this location were common (occurring 6 to 10 times per year) during heavy storm flow conditions, but this winter the failure occurred because a pump failed, spilling raw sanitary sewage into the river. The municipal employees responsible for the sewage pumping station apparently did not notify water treatment operators. The local public health unit laid charges when the drinking water regulator declined to charge the community for this incident. The court case failed on the grounds of “reasonable doubt” for the judge because there was no witness to establish that the sewage spill on the river bank reached the river. This incident happened 20 years before the international adoption of the water safety plan approach, but this kind of risk is exactly what a valid water safety plan needs to identify.

Uggelose, Denmark (1991-92). This outbreak was previously described in Appendix 2. There was a failure to respond to an obvious identified risk of sewage contamination of this groundwater supply that had no disinfection. Such obvious vulnerabilities are the kind of risk that a meaningful water safety plan must be able to identify so that remedial measures can be taken before disaster strikes.

Walkerton, ON, Canada (2000). This fatal outbreak was previously described in Appendix 2. This tragic incident likely qualifies as an extensive case study on how to fail to manage risk.

North Battleford, SK, Canada (2001). This major outbreak was previously described in Appendix 3. This outbreak, while not having consequences as severe as Walkerton, may provide an even more serious case study on institutional failures in risk management.

Nokia, Finland (2007). This fatal outbreak was previously described in Appendix 6. Nokia had a water safety plan because it participated in a pilot test for the water safety plan concept when the WHO guidelines were being developed. The failure of Nokia’s water safety plan to identify the cross connection set-up at the sewage treatment plant indicates that input to the development of this plan were woefully inadequate for managing risk to public health.

Adliswil, Switzerland (2008). This recent outbreak was previously described in Appendix 6. Because this incident was so similar to Nokia, similar criticisms must apply. The apparent failure of senior wastewater personnel to understand that normally “treated” sewage effluent is a serious source of microbial pathogens is also a failure of public health risk management.

Northampton, England (2008). This recent outbreak was previously described in Appendix 5. The extraordinary measures taken by the water utility to detect and respond to this outbreak, with costs totaling £4.9 million, are exemplary for a risk management program. However, the failure to have a regular inspection of process units for vulnerability to invasion by vermin illustrates the need for a strong commitment to continuous improvement.

Appendix 8
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