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Risk management for assuring safe drinking water

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Abstract

Millions of people die every year around the world from diarrheal diseases much of which is caused by contaminated drinking water. By contrast, drinking water safety is largely taken for granted by many citizens of affluent nations. The ability to drink water that is delivered into households without fear of becoming ill may be one of the key defining characteristics of developed nations in relation to the majority of the world. Yet there is well-documented evidence that disease outbreaks remain a risk that could be better managed and prevented even in affluent nations. A detailed retrospective analysis of more than 70 case studies of disease outbreaks in 15 affluent nations over the past 30 years provides the basis for much of our discussion (Hrudey & Hrudey, 2004). The insights provided can assist in developing a better understanding within the water industry of the causes of drinking water disease outbreaks, so that more effective preventive measures can be adopted by water systems that are vulnerable. This preventive feature lies at the core of risk management for the provision of safe drinking water.

1. Introduction

1.1. Risk management in the modern water utility business

Managing risk is an essential business requirement across the process and utility sectors. From embedding good corporate governance within organizations through to the management of individual projects and assets, the ability to understand and assess risk and to implement preventive measures to improve control of risk is a mainstream activity (Pollard et al., 2004). Many of the larger water utilities have connected their responsibilities for financial control with the risk management programmes that are implemented throughout their businesses, including the operational risk analysis and management activities at the process plant level. In the water industry, there is a need for a continued shift in the approach to risk management from one historically implicit to treatment plant design and operation to one increasingly explicit and better integrated within the core business of providing safe and wholesome drinking water that deserves the trust of consumers.

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The benefits of good corporate risk management should achieve the preventive management of risks throughout a business. One potential danger may be that the principal goal of assuring public health protection through safe drinking water may be viewed as only equivalent to many other priorities in the organization. With the focus increasingly on income, expenditure and whole-life costing under new institutional arrangements for the provision of drinking water, new facilities are being designed to refined and better-characterized margins of safety. Water utilities must seek not only to meet their legislative requirements but also maximize the availability, serviceability and life of their assets and minimize expenditure on energy, chemicals and processes. But whilst new arrangements undoubtedly offer greater management control and flexibility in decision-making, the drive for shareholder dividend or stakeholder value must be second to maintaining a secure and safe water supply system. We contend that an over-emphasis on the administration of risk management in isolation of practical knowledge on *what can go wrong* in practice, can itself be a hazard. Further, we note caution in an inappropriate use of risk management as the rationale for 'optimizing' infrastructure and process systems below what may inadvertently become inadequate margins of safety. In this paper, we discuss current advances in water quality risk management in the light of six case studies that aptly describe what can go wrong when risk management and specifically, public health risk management fails to be the primary focus.

On a continuing basis around the world an estimated 1.8 million people die every year from diarrheal diseases (including cholera). The majority of these deaths is among children in developing countries and up to 39% of diarrheal disease could be prevented by household water treatment by chlorination (WHO, 2004a). By contrast, drinking water safety is largely taken for granted by many citizens of affluent nations. The ability to drink water that is delivered into households without fear of becoming ill may be one of the key defining characteristics of developed nations in relation to the majority of the world. Valuing that enormous benefit appropriately must be a core value guiding risk management in the drinking water business.

1.1.2. A concept of safe drinking water

If the goal of risk management in the water utility sector is to assure safe drinking water, we need to consider what is *safe*. The concept of safety, while largely intuitive to the public, has confounded debates about risk management for decades. Perhaps these debates can be resolved by first considering what safe is not. Safe does not mean zero risk. To demand an absolute standard would guarantee that nothing could be considered safe, making safety a meaningless concept. There is no sharp line between safe and unsafe because safety has meaning on a relative basis. Finally, each person has an individual notion of safety that may vary from one risk to another. We propose a pragmatic notion of safety as "a level of risk so negligible that a reasonable, well-informed individual need not be concerned about it, nor find any rational basis to change his/her behaviour to avoid such a small, but non-zero risk". This notion was first articulated in the context of addressing whether there could be a safe dose for exposure to a carcinogen, an example that squarely confronts the distinction between safety and zero risk (Hrudey & Krewski, 1995). More recently, the issue of what constitutes safe drinking water was addressed for Part 2 of the Walkerton Inquiry (Canada) that was charged with recommending how a disaster like the Walkerton drinking water disease outbreak, which killed seven and made 2,300 ill, could be prevented from re-occurring in Ontario (O'Connor, 2002b). A similar notion of drinking water safety was adopted.

In the context of drinking water, and given our current capability for reducing risk, this notion of safe drinking water should mean that we do not expect to die or become seriously ill from drinking or using it. Assuring that drinking water is essentially free (to negligible levels) from the risk of infectious disease can be, and largely has been, achieved for most public water supplies in affluent nations. The challenge for drinking water risk management is to maintain and extend that remarkable achievement as widely as possible.

1.2. Characteristics of risk management for safe drinking water

The Walkerton Inquiry 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; and
- investing resources in risk management that are proportional to the danger posed." (O'Connor, 2002b).

Managing risk effectively requires making sensible decisions within the constraints of knowledge and resources. Risk management is an exercise of decision-making under uncertainty. Even if negligible scientific uncertainty could be achieved, the wide range of competing views for social priorities would still challenge decision-making, but at least the evidentiary basis for any decision would be clear. For drinking water disease outbreaks, cases with such clarity of scientific evidence are the exception rather than the rule. Because there is always some uncertainty in the evidence, errors in decisions can be of two main types (Hrudey & Leiss, 2003; Hrudey & Rizak, 2004):

(i) a decision could be made to act when there is truly no need - a false positive error;

(ii) a decision could be made not to act, when there *is* truly a need - a false negative error.

These types of errors can be illustrated by reference to some of the cases reviewed below. The 1998 Sydney water crisis has been described as a case of issuing a boil water alert for Sydney residents on the basis of erroneous monitoring results (Clancy, 2000), making that decision a false positive error. Walkerton was perhaps the most severe example of a false negative error. Warnings at Walkerton about drinking water quality had been ignored for over 20 years. Ultimately, tragedy ensued. Given these examples, a commitment to precaution for public health decisions demands a preference for false positive over false negative errors, because the consequences of the latter are usually more direct and potentially more severe. However, there are inevitably policy implications to false positive errors as well. In the Sydney case, tens of millions of dollars of public funds were spent on circumstances where investigation revealed that public health was not harmed. The merits of the decisions involved have remained a source of debate. However, given their access to and understanding of the evidence provided at the outset of this incident, the public inquiry found that health authorities chose correctly in deciding to issue a system-wide boil water alert in the first instance (McClellan, 1998). Although the merits of each case will differ, the general reality remains that frequent false positive errors eventually create a "cry wolf" response with the public such that important measures like boil water advisories may be ignored when they are truly needed to protect public health. Although the decision-making challenge for boil water advisories can be characterized in relatively stark terms after the fact, when outcomes are known (with the benefit of hindsight), the reality for any outbreak situation is that the evidence is usually not clear as the events are unfolding.

2. Learning from experience

2.1. The analysis of failure

The multiple barrier approach to assuring safe drinking water is founded on the maintenance of multiple unit processes and procedures to ensure that pathogens and undesirable chemicals do not reach the consumer's tap. Maintaining these barriers to exposure is critical because, by and large, each barrier in series can offer orders of magnitude (log) levels of protection to the drinking water supply. The level of barriers required must be a function of the level of challenge posed by the source water (Figure 1). Barriers are often thought of in terms of treatment technology but additional critical barriers involve source water protection, distribution security and monitoring/response capabilities. The failure, or bypass, of any single barrier must be a major concern for operators. The potential technical failures that might occur provide only part of the story because risks usually manifest themselves through a combination of technical, management and human errors (Figure 2). Undertaking a 'forensic analysis' of historic incidents can highlight the aspects of risk management that are often ignored.

Fig. 1. Drinking water risk management and the multiple barrier approach (Hrudey, 2001)

Fig. 2. Reasons for system failures (after Hurst, 1998).

We performed an analysis of the major factors contributing to drinking water disease outbreaks by searching electronically and through bibliographic cross-referencing the published English language literature over the past 30 years. We screened papers for those that discussed specific disease outbreaks in affluent nations and which described some of the failure modes contributing to the outbreak. We did not attempt to review all outbreaks. There was substantial variation in the quality and detail of the description of failure mechanisms among the papers that we retrieved. In all, over 70 case studies were prepared from this database and are analyzed in detail elsewhere (Hrudey & Hrudey, 2004). The case studies included six outbreaks where fatalities arose, causing a total of 22 deaths during or shortly after the outbreak and an estimated 50 to 70 deaths over the two years following the Milwaukee outbreak (Hrudey & Hrudey, 2004). These fatal outbreaks are summarized in Table 1. The risk management lessons are reviewed in the next section.

2.1. Recurring themes

The factors contributing to outbreak failures summarized in Table 1 included: sewage contamination of raw water, inadequate knowledge of source water hazards, inadequate disinfection, extreme weather (heavy precipitation, runoff), cross-connections and distribution failures, filtration failures, livestock or wildlife fecal contamination and process changes. More than one mechanism was involved in contributing to each outbreak and often vulnerable conditions had been in place for years, if not decades. In hindsight, all of these outbreaks were preventable. Although only fatal outbreaks from Hrudey and Hrudey (2004) are summarized below, these are reasonably representative of the features contributing to failure among the 70 case studies reviewed there.

The 1983 Drumheller outbreak was caused by a spill of raw sewage upstream of the drinking water intake. Sewage overflows were common at this location during heavy storm flow conditions but this spill occurred because of a pump failure. The contamination source was certainly foreseeable. Even though the sewage pump station was operated by the same municipality as the drinking water utility, no notice of the incident was provided. The lack of notice precluded implementation of any precautionary measures, such as additional treatment by the water utility. Likewise, water quality monitoring might have provided earlier warning to initiate a boil water advisory. In this case, the boil water advisory was issued almost five days after the first signs of illness.

The 1989 Cabool outbreak was caused by sewage contamination of drinking water in the distribution system during water main break repairs following unseasonably cold weather. The distribution system in this community was in poor repair and vulnerable to sewage contamination, while the sewer system was in worse condition experiencing regular sewer back-ups and overflows. The groundwater drinking water source for this community was of excellent quality and this water was distributed with no treatment and or real time warning system (e.g. chlorine residual monitoring). The combination of poorly maintained infrastructure, lack of any treatment or monitoring capacity and unusual weather events triggering upset conditions led to this fatal outbreak.

In 1993, Milwaukee experienced an enormous outbreak of cryptosporidiosis in a drinking water system that practiced full conventional water treatment and was meeting their treated water quality standards at the time of the outbreak. This outbreak has been the subject of numerous publications, but the early speculation that the source of contamination was from upstream agricultural runoff has later been discounted. The most likely source of contamination was sanitary sewage discharge from Milwaukee that impacted the drinking water intake for one of their treatment plants. This circumstance mirrored previous winter outbreaks in Milwaukee in 1916, 1936 and 1938. Despite having what appeared to be adequate water treatment to cope with raw water contamination, the demands for optimum filtration performance, as measured by maximum turbidity removal, and disinfection capable of handling the chlorine-resistant pathogen, *Cryptosporidium parvum*, left Milwaukee vulnerable.

In hindsight, Milwaukee had not learned from the experience of the 1989 Swindon – Oxfordshire outbreak in England which led to the Badenoch expert panel report documenting the measures needed to prevent *Cryptosporidium* outbreaks (Badenoch et al., 1990). Likewise, there was an inadequate response to both the turbidity spike in filtered water and a sharp rise in consumer phone complaints that corresponded with the contamination episode.

The 1993 Gideon fatal outbreak was caused by poor maintenance of water storage facilities that allowed bird fecal contamination that was flushed into the distribution system during an effort to flush the system because of water quality complaints. Like Cabool, this community had a high quality groundwater supply feeding into a poorly maintained distribution system without any treatment barrier.

The 1999 Washington County Fair fatal outbreak was caused by inadequate awareness of the risk of shallow well contamination from a nearby septic seepage field. The well in question was allowed to supply unchlorinated water during the Fair and this source was improperly used for food and beverage production with tragic consequences. The well in question had never produced adverse microbiological monitoring results in the intermittent, seasonal monitoring program, but a severe drought over the previous summer may have made this well more vulnerable to near-surface contamination.

The Walkerton outbreak in May 2000 involved a litany of failures from the operators, through management, the provincial regulator and the Government of Ontario (O'Connor, 2002a). The shallow well that became contaminated by cattle manure following heavy spring rainfall that caused widespread flooding, had been identified as vulnerable to agricultural contamination by the hydrogeologist who installed the well in 1978. His warnings were not fully heeded and over the years, adverse microbiological monitoring results were common without any remedial action. The operators were inadequately trained to recognize the risks or the need for requiring adequate chlorination. In particular, they were oblivious to the need for monitoring chlorine residual as a real time measure of disinfection performance for susceptible pathogens (Hrudey & Walker, 2005). The two year, $9 million public inquiry into this outbreak revealed the numerous failure at many levels (O'Connor, 2002a) and made over 100 recommendations for how drinking water safety might be assured in Ontario in the future (O'Connor, 2002a, b).

In every case above, the numerous failures are obvious in hindsight. Yet the case studies presented span almost 20 years and the total collection of cases these are drawn from spans 30 years (Hrudey & Hrudey, 2004). Risk management seeks to achieve a preventive approach and therefore effective risk management needs to demonstrate the ability to translate the enormous collection of hindsight available into effective foresight.

3. Drinking water risk management

3.1. Overall risk management for drinking water utilities

Over the past 25 years, the drinking water industry has faced rising consumer expectations and substantially more stringent regulatory requirements while experiencing dramatic changes from privatization, sector globalization, increased competition, emerging technologies and trends towards financial self-sufficiency. These changes create both opportunities and risks across a variety of categories, including (Pollard et al., 2004):

(i) *Financial risk.* These are risks arising principally from the financial operations and management of drinking water as a business enterprise, whether or not the operating agency is a private entity.

(ii) *Commercial risk.* In many jurisdictions, drinking water utilities are no longer protected as a public monopoly so they are no longer insulated from competition or financial instability.

(iii) *Environmental risk.* Equipment failure or human error can lead to adverse environmental impacts including waste discharges to the atmosphere, ground or water environment.

(iv) *Public health risk.* The most vital duty of care that a drinking water utility holds is to assure the safety of the water provided to avoid adverse impacts on public health.

(v) *Reputation risk.* Even in the absence of dangers to public health, a water utility can experience harm if water quality characteristics of importance to consumers (taste, odour, appearance) are impaired or customer trust is damaged.

(vi) *Compliance/legal risk.* Legislation, regulations and common law liability set out minimum standards for water quality, the handling and storage of treatment chemicals, the discharge of wastes, and the health and safety of the operational staff and the people living nearby.

The foregoing analysis of failures and the discussions to follow on assuring safe drinking water are focussed primarily on public health risk combined with some obvious elements of reputation and compliance risk.

3.2. A comprehensive risk management approach for drinking water safety (NHMRC)

A comprehensive framework has been developed in Australia to outline a Total Quality Management (TQM) approach for drinking water quality and safety (Rizak et al., 2003; Hrudey, 2004; Sinclair & Rizak, 2004). It is a broad approach to the entire scope of providing drinking water and can readily incorporate the excellent details that have been developed by other initiatives and it has now been adopted as the introductory framework for the Australian Drinking Water Guidelines (NHMRC, 2004). Figure 3 captures the 12 elements that make up the framework, starting with a policy commitment at the highest levels of responsibility in the organization to achieving drinking water quality. Commitment means more than just meeting regulatory requirements by minimal margins, but a fundamental commitment to continuous improvement, serving as a cornerstone for employee responsibility and motivation. From this commitment flows the series of elements related to system analysis and management with which we are perhaps more familiar as risk management tools.

Fig. 3 Framework for Management of Drinking Water Quality (reprinted by permission of the National Health and Medical Research Council, Canberra, Australia)

Assessment of a drinking water system includes: water-supply systems analysis, the review of water quality data, hazard identification, and risk assessment. Preventive measures include: the emplacement of multiple barriers and the analysis and maintenance of critical control points. Operational procedures and process control include: operating protocols, equipment capability, materials and chemicals, operational monitoring and, ultimately, preventive and corrective actions. Verification of drinking water quality includes: conventional water quality monitoring, consumer satisfaction, short-term evaluation of results and corrective actions as required. Incident and emergency response include communication planning and response protocols.

The supporting requirements for this Framework are elements often overlooked in the short term, but which are vitally important to long-term performance. Employee issues include awareness, involvement and training, with particular consideration given to the role of contractors. Community issues include consultation and communication to ensure that the drinking water provider is meeting the needs of the consumer. Research and development has also been neglected in some perspectives when addressing assurance of safety. A commitment to research is vital to assure that emerging risks are managed as thoroughly as possible, based on some predictive capability. Applied research studies can include investigations and research monitoring, validation of process performance and design of equipment. Documentation and reporting are necessary to prove that systems have been working as planned.

Finally, to assure everyone concerned that the systems are functioning as they should be, there must be review processes. These include periodic evaluation of long-term performance and an external audit of drinking water quality management performance. All must be subject to review by senior management for evaluation in view of the goal of continual improvement. This framework has been used to restructure the Australian Drinking Water Guidelines into a TQM risk management approach that will provide consumers with the means for judging whether their water provider is functioning as safely and effectively as circumstances reasonably allow. The elements of this approach are flexible enough to allow implementation by each state in Australia, according to its own regulatory regime. The TQM approach is intended to facilitate and support an effective regulatory process by helping to define the details of best practice in every jurisdiction and by providing consistent approaches for demonstrating best practice to the regulatory authority. The TQM approach is not intended to replace an effective regulatory process that must be accountable to the public, only to improve the manner in which constructive improvements are achieved.

Now that the framework is being adopted in Australia, more detailed supporting documents are being developed to guide its implementation for individual water utilities. The core capacity of this approach to deliver risk management for the purposes of assuring drinking water safety is found in the second and third elements of the Framework: 2. Assessment of the Drinking Water System; and 3. Preventive Measures for Drinking Water Quality Management. These are based on the key concepts of hazard, hazardous event and risk, terms which are too often subject to confusion in applications of risk management. Accordingly, they are defined in the Framework and more recently were adopted within the concept of Water Safety Plans of the Third Edition of World Health Organization Guidelines for Drinking Water Quality (WHO, 2004a):

- A *hazard* is a biological, chemical, physical or radiological agent that has the potential to cause harm.
- A *hazardous event* is an incident or situation that can lead to the presence of a hazard (what can happen and how).
- *Risk* is the likelihood of identified hazards causing harm in exposed populations in a specified time frame, including the magnitude of that harm and the consequences.

These concepts can be illustrated with a pathogen. *Cryptosporidium is* a hazard for any surface water system because it is always potentially present given its occurrence in human sewage and/or livestock wastes. A challenge to a water system by a waste source containing *Cryptosporidium* such as a sewage spill is a hazardous event. The risk associated with *Cryptosporidium* is the likelihood that this pathogen will pass through the treatment system to reach consumers in an infectious state and in numbers sufficient to cause illness.

An important contribution for implementing this element of a risk management approach is a report by Nadebaum et al. (2004) that provides comprehensive guidance on performing the hazard identification and risk assessment of the drinking water supply. The assessment methodology is organized into six steps: (1) understand your system; (2) identify hazards, hazardous events and sources; (3) estimate risk for each identified hazard/event; (4) plan preventive measures for each identified hazard/event; (5) implement and monitor preventive measures; and (6) document a risk management plan. The hazard identification and risk assessment methodology provided by Nadebaum et al. (2004) is supported by individual hazard fact sheets, case studies and summaries of hazards for microbial and chemical contaminants. These are extremely valuable to any water utility committed to implementing a risk management plan because the details of implementation must be based on local experience and the overall approach should be comprehensive, taking full advantage of valuable experience from others. The extent of experience captured in this reference is illustrated by the range of 36 hazard fact sheets and seven case studies that are provided (Table 2).

3.3. Risk management for small treatment system

The New Zealand Ministry of Health (NZMOH) recognized that the vast majority of the country's drinking water systems were small, yet faced important challenges in providing safe drinking water (NZMOH, 2001). The NZMOH also recognized that the traditional approach of relying primarily on water quality monitoring in relation to drinking water quality standards is inherently a reactive approach. Monitoring results are typically available only long after drinking water has left a treatment plant and been consumed. Thus, the NZMOH has developed a pragmatic, down-to-earth program for encouraging Public Health Risk Management Plans (PHRMP). This approach focuses on "*events*," defined as incidents or situations that may lead to hazards being introduced into or not being removed from water (Nokes & Taylor, 2003). In developing this approach, four barriers were identified that, if maintained effectively, will adequately control hazards:

- prevention of contaminants entering the raw water of the supply;
- removal of particles from the water;
- inactivation of microorganisms in the water; and
- maintenance of the quality of the water during distribution.

This approach is meant to ensure that these barriers are present and functional to minimize the chance of failure that would give rise to "*events*." It was adopted on the premise that small water operators could relate better to the tangible concept of an event rather than a hazard, which some operators find to be more hypothetical. Currently, the NZMOH has produced 40 specific, practical guides for various elements of typical water supply and treatment systems, all available at the NZMOH web site (www.moh.govt.nz/water). Their sensible, pragmatic approach for developing a PHRMP is implemented in 11 steps:

1. Produce an overview of the supply and decide which of the PHRMP guides are needed.
2. Identify the barriers to contamination.
3. Use the guides to identify events that may introduce hazards into the water.
4. Use the guides to identify causes, preventive measures, checks and corrective actions.
5. Decide where improvements should be made in the supply to better protect public health.
6. Decide on the order in which improvements need to be made.
7. Draw up a timetable for making the improvements.
8. Identify links to other quality systems.
9. Prepare contingency plans.
10. Prepare instructions for performance assessment of the plans.
11. Decide on communication policy and needs.

The New Zealand system of Public Health Risk Management Plans are an excellent contribution towards greater drinking water safety and deserve wider application.

4. Discussion

A clear message that emerges from the case studies is that the painful experience at locations that have had drinking water outbreaks has not been readily recognized by other vulnerable utilities (Hrudey & Hrudey, 2004). In a few cases, outbreaks recurred in the same community indicating a failure to determine and correct the flaws in the system. In other cases, cogent warnings have been missed, such as the Washington County Fair outbreaks which had a highly relevant warning for Walkerton, but which failed to change the course of events in Walkerton. The New York State Department of Health investigation was made public in March of 2000, less than two months before the Walkerton outbreak happened 600 km to the west.

In another case, Orangeville, a community only one hour away from Walkerton, experienced a spring outbreak caused by agricultural runoff contaminating the town's shallow wells in April 1985. The analysis of this outbreak published in the *Canadian Journal of Public Health* in 1991 noted that chlorination required close monitoring because manure contaminated runoff could overwhelm a fixed dose of chlorine, which is exactly what happened in Walkerton in May 2000.

There are several key aspects of waterborne pathogens that characterize the challenge they pose to drinking water safety. Some of these are readily evident from the outbreak case studies:

- Fecal (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 fecal 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 fecal 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.

Many of these challenges are intuitive for experienced drinking water professionals, but they are not necessarily established in the corporate memory of a water utility, particularly where substantial staff turnover is a reality. The intuitive experience within a successful organization needs to become accessible to struggling organizations. This implies the need for some form of networking to share experience and good practice.

Responses to these challenges are compounded by a number of basic limitations in relation to the public health significance of available monitoring capabilities:

- Monitoring methods for pathogens and useful indicators are generally neither sufficiently sensitive nor sufficiently specific to capture the full range of pathogen threats facing a water system.
- Monitoring for pathogens and useful indicators cannot be achieved in real time.
- Monitoring methods cannot be directly interpreted for public health significance because the viability and infectivity for most pathogens is usually not determined by routine methods.
- Interpretation of monitoring results will be challenged by a preponderance of false positives because of the low frequency of pathogen hazards (Hrudey & Leiss, 2003).
- Population health surveillance is insensitive and is likely blind to low-level endemic disease and all but the largest outbreaks.

- Adaptation and tolerance (immunity) in resident populations may hide local, chronic problems while leaving visitors vulnerable to infection that may be difficult to trace back to the source, particularly in resort communities.

Despite the challenges and limitations, the best drinking water providers have shown an ability to respond to a wide range of challenges with effective prevention programs. The processes in these organizations may bend under stress, but they do not break, so failures are not allowed to accumulate to the point where they can impact the health of a consumer. An optimal preventive approach will be creative and forward-looking:

- Informed vigilance is actively promoted and rewarded.
- Understanding of the entire system, its challenges and limitations is promoted and actively maintained.
- Effective, real-time treatment process control, based on understanding critical capabilities and limitations of the technology, is the basic operating approach.
- Fail-safe multi-barriers are actively identified and maintained at a level appropriate to the challenges facing the system.
- Close calls are documented and used to train staff about how the system responded under stress and to identify what measures are needed to make such close calls less likely in future.
- Operators, supervisors, lab personnel and management all understand that they are entrusted with protecting the public’s health and are committed to honouring that responsibility above all else.
- Operational personnel are afforded the status, training and remuneration commensurate with their responsibilities as guardians of the public’s health.
- Response capability and communication are improved, particularly as post 9-11 bioterrorism concerns are being addressed.
- An overall continuous improvement, total quality management (TQM) mentality will pervade the organization.

5. Conclusions

Risk management approaches offer a means to benefit from the experience of past failures. A rigorous and comprehensive approach such as reflected in the 2004 Australian Drinking Water Guidelines makes it possible for water utilities to improve their operations to the level of the best water utilities, making it extremely unlikely that consumers ever need face a drinking water outbreak. Safe drinking water is a remarkable bargain for consumers and should be valued much more highly than commonly occurs in our affluent societies.

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Table 1

Summary of fatal drinking water outbreaks in affluent countries over the past 20 years (Hrudey & Hrudey, 2004)

Date	Location	Source Water	Treatment	Major Failure Factors	Pathogens	Health Consequences	Risk Management Comments
1983 Feb	Drumheller Alberta Canada	Red Deer River	granular filtration chlorination	sewage spill upstream of water intake not reported, likely leading to pathogen contamination of drinking water supply that was vulnerable because of treatment by filtration without coagulation	not identified but likely viral	1326 confirmed cases of gastroenteritis, 3000 estimated cases **2 deaths**	• vulnerable situation of sewage pump station upstream not recognized • failure of internal reporting of sewage spill to water operations • operating winter treatment without coagulation made system vulnerable
1989-90 Dec-Jan	Cabool Missouri USA	deep ground water	none	likely contamination of distribution system by unseasonably cold weather causing water main breaks leading to sewage cross contamination	Escherichia coli O157:H7	243 confirmed cases of E. coli O157:H7 32 hospital admissions **4 deaths**	• risks associated with water main break repair during extreme weather not recognized • poor sewerage systems maintenance exposing water distribution to risk • no treatment barrier in place
1993 Mar-Apr	Milwaukee Wisconsin USA	Lake Michigan	chlorination, $KMnO_4$, coagulation, granular filtration, chloramination	sanitary sewage contaminated drinking water intake either directly or via combined storm sewer outfalls during winter storms filtration was not being operated at optimum performance and measures recognized in the UK for reducing Cryptosporidium risk were not in use.	Cryptosporidium parvum (genotype I, human strain).	285 confirmed cases, 400,000 estimated cases ~4,400 hospital admissions **50-70 deaths** among immune-compromised over the following 2 years	• risks associated with sewage contamination of water intake not recognized • apparently not aware of Cryptosporidium risk • failure to maintain optimum filtration performance • failure to recognize signal from consumer complaints
1993 Nov-Dec	Gideon Missouri USA	deep ground water	none	bird faeces likely contaminated water storage tanks and flushing of system drew contaminated tank water into service	Salmonella typhimirium	31 cases confirmed 650 cases estimated 15 hospital admissions **7 deaths**	• poor maintenance of water storage allowed fecal contamination • water quality management not based on good knowledge of system • no treatment barrier in place
1999 Sept	Washington County Fair New York USA	shallow ground water	none	some food and drink vendors used unchlorinated well water for beverages and ice; shallow well was located ~11 m from a septic tank seepage pit with a rapid hydraulic connection to this well	E. coli O157:H7 Campylobacter jejuni	161 confirmed cases 2800 – 5000 estimated 71 hospital admissions 14 cases of haemolytic uremic syndrome (HUS) **2 deaths**	• not aware of risk to well from septic seepage field • allowed use of unchlorinated water from a shallow well • failure to consider that extreme drought of previous summer might affect water supply safety
2000 May	Walkerton Ontario Canada	shallow ground water	chlorination only	inadequate chlorination or other barriers to cope with influx of manure contaminated water following heavy rains	*E. coli* O157:H7 Campylobacter jejuni	163 cases of *E. coli* confirmed 105 cases of *Campylobacter* 12 cases with both 2300 cases total estimated 65 hospital admissions 27 cases of HUS **7 deaths**	• ignored warnings about vulnerability of shallow well when first installed in 1978 • failed to adopt source protection recommendations at installation • regulator failed to implement policy requiring continuous chlorine residual monitors on vulnerable shallow wells • operators inadequately trained with no knowledge that contaminated water could kill consumers • failure to recognize that extreme weather and flooding could cause water contamination • failure to maintain chlorine residuals • failure to monitor chlorine residuals as required

Table 2 (Nadebaum et al., 2004)

Hazard Fact Sheets and Case Studies	
Catchment and Groundwater Systems	**Pipelines and Distribution Systems**
Agriculture within catchments	Pipeline repairs and maintenance
Environmental hazards within catchments	Cleaning of mains
Human access to catchments	Pipe materials, private mains & plumbing
Industrial development within catchments	High flow in pipelines
Forestry within catchments	Backflow and cross connections
Waste / wastewater management facilities	Reverse flow in pipelines
Land use within catchments	Stagnant water in pipelines
Roads within catchments	Aqueducts
Urban development within catchments	**Case Studies (from the literature)**
Reservoirs and Basins	Backflow in pipelines
Algal blooms within reservoirs	Inadequate disinfection of source water
Key hydraulic factors for reservoirs	Contamination and disinfection failure
Contaminated inflows into reservoirs	Distribution system contamination
Excessive draw or fill of reservoirs	Contamination & treatment failure
Water Treatment Plants (WTPs)	Groundwater arsenic contamination
WTP reliability	Shallow groundwater contamination
WTP design capability - toxins	Reservoir & catchment contamination
WTP design capability - alkalinity	Reservoir contamination & disinfection failure
WTP design capability - colour	Groundwater contamination not located
WTP design capability - iron & manganese	Suspected breaching of mains
WTP design capability - industrial chemicals	Distribution system contamination
WTP design capability - pathogens	Unidentified contamination
WTP design capability - taste & odour	Overdose of fluoride
WTP design capability - turbidity	Lead leaching from domestic plumbing
Disinfection Systems	Sabotage of mains
Disinfection system - reliability	Cyanobacterial bloom in source water
Disinfection system - capability	
Service Reservoirs and Tanks	
Floating Cover system contamination	
Timber system contamination	
Internal contamination	
External contamination	

Fig. 1. Drinking water risk management and the multiple barrier approach (Hrudey, 2001)

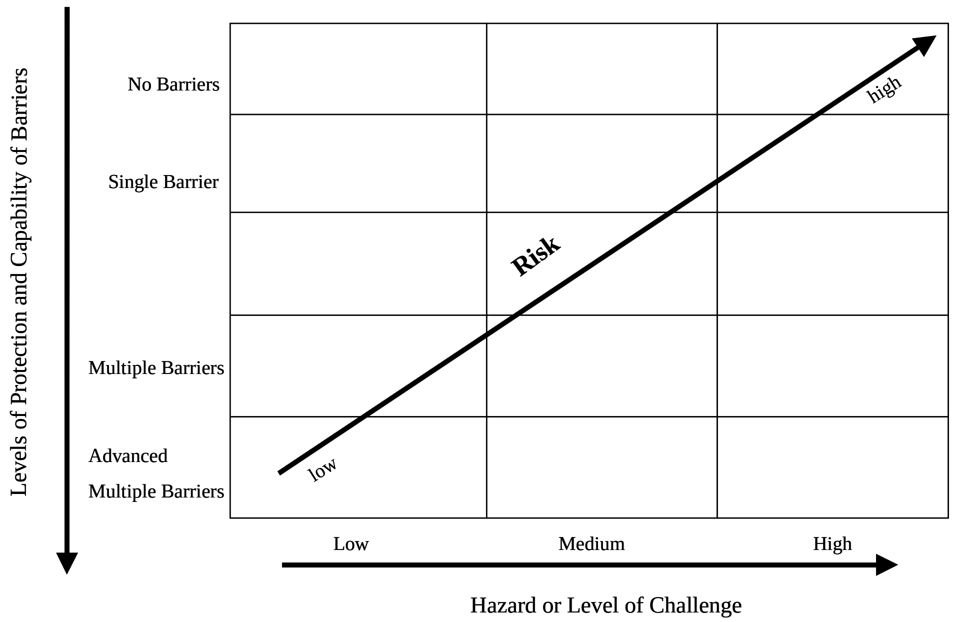

Fig. 2. Reasons for system failures (after Hurst, 1998).

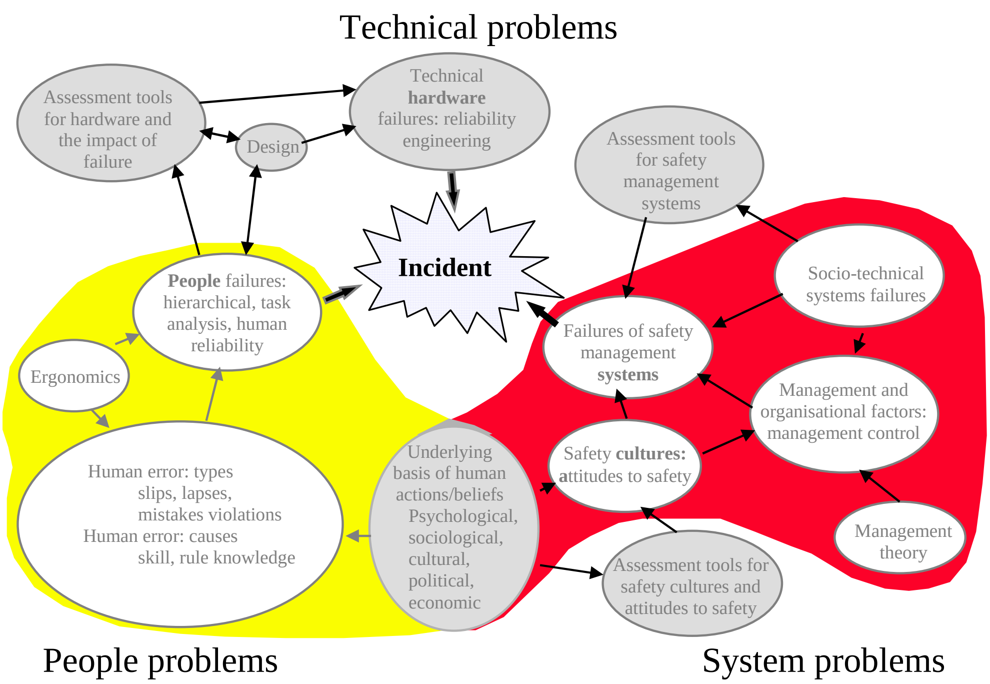

Fig. 3 Framework for Management of Drinking Water Quality (reprinted by permission of the National Health and Medical Research Council, Canberra, Australia)