Walkerton: Lessons learned in comparison with waterborne outbreaks in the developed world

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Abstract: An estimated 2300 people became seriously ill and 7 died from exposure to microbially contaminated drinking water in the town of Walkerton, Ontario, in May of 2000. The severity of this drinking water disaster resulted in the Government of Ontario calling a public inquiry by Mr. Justice Dennis O'Connor to address the cause of the outbreak, the role, if any, of government policies in contributing to this outbreak, and ultimately, the implications of this experience on the safety of drinking water across the province of Ontario. This paper summarizes relevant evidence presented at the inquiry by the expert panel together with Justice O'Connor's findings addressing the circumstances of the outbreak. These findings are reviewed in relation to the published causes of previous waterborne disease outbreaks that have been reported elsewhere in developed countries. The circumstances surrounding the Walkerton tragedy are an important source of knowledge for those concerned with providing safe drinking water to the public. Although some circumstances are obviously specific to this epidemic, others echo common themes in waterborne outbreaks that have occurred before. These common themes suggest the need for attention to broad issues of drinking water safety in addition to the individual specific details that often command attention.

Key words: waterborne disease, *Escherichia coli* O157:H7, *Campylobacter jejuni, Cryptosporidium, Giardia,* multiple barriers, health risk.

Résumé : Environ 2300 personnes sont devenues gravement malades et sept personnes sont décédées à la suite d'une exposition à de l'eau potable contaminée par voie microbienne dans la ville de Walkerton, en Ontario, en mai 2000. La gravité de ce désastre d'eau potable a fait que le gouvernement de l'Ontario a lancé une enquête publique, menée par M. le juge Dennis O'Connor, visant à déterminer la cause de cette éclosion, la contribution, s'il y a en une, des politiques gouvernementales à cette éclosion et, en bout de ligne, les répercussions de cette expérience sur la salubrité de l'eau potable partout en Ontario. Cet article résume les preuves pertinentes présentées à l'enquête par le panel d'experts et les conclusions du juge O'Connor sur les circonstances de cette éclosion. Ces conclusions sont revues à la lumière des causes publiées touchant les éclosions antérieures de maladies hydriques qui ont été rapportées ailleurs dans les pays développés. Les circonstances entourant la tragédie de Walkerton sont une source importante de connaissances pour les compagnies fournissant de l'eau potable salubre au public. Bien que certaines circonstances sont évidemment spécifiques à cette épidémie, d'autres font penser à des thèmes communs aux éclosions hydriques survenues auparavant. Ces thèmes communs suggèrent le besoin de porter attention aux grandes questions de la sécurité de l'eau potable en plus des détails uniques spécifiques qui doivent souvent être examinés.

Mots clés : maladie hydrique, *Escherichia coli* O157:H7, *Campylobacter jejuni, Cryptosporidium, Giardia,* barrières multiples, risque pour la santé.

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Introduction

The public health implications of serious drinking water contamination that occurred in May 2000 in Walkerton, Canada, a community of 4800 residents located about 175 km northwest of Toronto, Ontario, hold important lessons for the water industry. More than 2300 individuals experienced gastroenteritis, 65 were hospitalized, 27 developed haemolytic uremic syn-

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drome (HUS), a serious and potentially fatal kidney ailment, and 7 died. The pathogens identified as being primarily responsible were *Escherichia coli* O157:H7 and *Campylobacter jejuni*, although other pathogens were likely present. The Government of Ontario established a public inquiry to determine the causes and responsibility for this tragedy (Part 1) and to examine broader questions relating to the safety of drinking water in Ontario (Part 2).

We were retained by the Walkerton Inquiry to assist in establishing the physical cause of the contamination for Part 1 (Huck, Payment, and Gillham were expert witness panel members) and to advise the Commissioner on technical matters for Parts 1 and 2 (S.E. Hrudey was a member of the Research Advisory Panel). The determination of cause, based on all of the evidence before the Inquiry, was the purview of the Commissioner, Justice Dennis O'Connor. Part 1 of the Inquiry was held in Walkerton over a period of 9 months during which evidence was heard from 114 witnesses, including residents, local officials, senior civil servants, two former ministers of environment, and the Premier of Ontario.

The Part 1 report (O'Connor 2002) was made public on 18 January 2002. This landmark document provides a detailed and sobering account of the many factors that contributed to this tragedy and its serious consequences. Suffering was not limited to those who were ill, but included all those who struggled to cope with the severe illness of their loved ones. This report should become required reading for all parties involved in the delivery of drinking water to reinforce the magnitude of personal responsibilities and range of challenges that are inherent in undertaking to provide safe drinking water to the public.

Waterborne disease outbreaks continue to occur in North America and Western Europe despite wealthy economies and access to proven drinking water treatment technologies. The obvious question is — *why do serious failures continue to occur*?

Our analysis considers selected waterborne disease outbreaks reported in the accessible literature in relation to the failures documented by the Walkerton Inquiry. In seeking to prevent this type of tragedy from recurring, a minimum requirement ought to be to ensure that the main factors contributing to the Walkerton disaster and those that can be readily recognized from elsewhere are fully understood and considered as a basis for recommending improvements.

Methods

We attempted an analysis of the major factors contributing to drinking water disease outbreaks by searching the published English language literature over the past 30 years. We screened papers for those that discussed specific disease outbreaks and that described some of the failure modes contributing to the outbreak. Details on both were required for inclusion in our review. We did not attempt to review all outbreaks and this manuscript is intentionally limited to a selective description of the relevant literature. There was substantial variation in the quality and detail of description for failure mechanisms among the papers that we retrieved. The multiple barrier approach, as outlined below, was adopted as our reference framework for analyzing the outbreak literature.

Results and discussion

Selected outbreaks evaluated

Table 1 summarizes a selection of 15 outbreaks from 4 countries (Canada, U.S., England, and Denmark) each affecting between 47 and a potential of more than 400 000 people, including a total of at least 11 deaths attributed to waterborne disease. The factors reported to have contributed to these selected outbreaks are considered in relation to the documented failures contributing to the Walkerton outbreak.

Multiple barrier failures

The Commissioner of the Walkerton Inquiry (O'Connor 2002) adopted the expert evidence that a multiple barrier approach is necessary for providing safe drinking water, consisting of effective and robust measures (Huck et al. 2001) dealing with the following main elements:

(1) source: the best possible raw water quality should be maintained and protected

(2) treatment: effective treatment should be designed, operated, and maintained

(3) distribution: secure storage and distribution of treated water should be provided

(4) monitoring: appropriate and effective monitoring should be performed

(5) response: appropriate and effective responses to adverse monitoring or adverse circumstances are needed.

A water system must be robust or resilient to challenge. This means the ability of the system to withstand upsets. A robust system will continue to perform adequately despite failure of one or more of the mechanical or institutional components. The resilience of some elements of the system will influence the required resilience of others with the result that an overall robust system can be achieved in various ways. For example, a less secure water source that faces greater contamination challenges will require more robust treatment because of the correspondingly higher risk that is posed (Fig. 1).

The Walkerton tragedy involved evident or potential failures in barriers for all of these elements. The review of other outbreaks reveals that they commonly involve failures in more than one barrier, a finding that reinforces the need for the multiplicity of barriers and the need to assure the effectiveness of each barrier.

Table 1. Summary of selected waterborne disease outbreaks.

Locations and dates	Characteristics	Reference
Richmond Heights, Fla., U.S.A. Jan.–Mar. 1974	1200 cases of gastroenteritis, likely shigellosis in a chlorinated shallow (6–15 m) groundwater supply	Weissman et al. (1976)
Bradford, Pa., U.S.A. Sept.–Dec. 1979	3500 cases of giardiadiasis in a chlorinated but unfiltered supply	Akin and Jakubowski (1986)
Bramham, England, July 1980	3000 cases of gastroenteritis of unidentified etiology in a chlorinated groundwater supply	Short (1988)
Eagle-Vail, Colo., U.S.A. March 1981	80 cases of gastroenteritis, likely rotavirus, in a direct filtered and chlorinated supply	Hopkins et al. (1986)
Orangeville, Ont., Canada April 1985	241 cases caused by Campylobacter jejuni in a municipal water system of 6 “deep” wells with no chlorination required.	Millson et al. (1991)
Pittsfield, Mass., U.S.A. Nov. 1985 – Jan. 1986	3800 cases of giardiasis in a chlorinated but unfiltered surface supply	Kent et al. (1988)
Disraeli, P.Q., Canada August 1986	3 reported cases of campylobacteriosis plus at least 50 cases of gastroenteritis identified upon further investigation in an unchlorinated, unfiltered surface supply	Tessier et al. (1987)
Penticton, B.C. Canada June 1986	3000 cases of giardiasis in a chlorinated, but unfiltered, surface–groundwater supply	Moorehead et al. (1990)
Oakcreek Canyon, Ariz., U.S.A. April 1989	110 of 240 guests surveyed had gastroenteritis, likely caused by a Norwalk-like virus, in an unchlorinated private well	Lawson et al. (1991)
Cabool, Mo., U.S.A. Dec. 1989 – Jan. 1990	243 cases of gastroenteritis including 86 cases of bloody diarrhoea, 2 cases of HUS and 4 deaths caused by E coli O157:H7 in an unchlorinated community water supply	Swerdlow et al. (1992)
Uggelose, Denmark Dec. 1991 – Jan. 1992	1400 cases of gastroenteritis of suspected viral etiology occurred in a filtered but unchlorinated municipal supply	Laursen et al. (1994)
Warrington, England Nov. 1992 – Feb. 1993	47 confirmed cases of cryptosporidiosis in a water supply zone serving 38 000 consumers by groundwater with chlorination only	Bridgman et al. (1995)
Milwaukee, Wis., U.S.A. Mar.–April 1993	Possible 400 000 cases of cryptosporidiosis in a filtered, chlorinated surface supply	MacKenzie et al. (1994)
Gideon, Mo., U.S.A. Dec. 1993	600 cases of salmonellosis, 15 hospitalizations and 7 deaths in an undisinfected groundwater supply	Clark et al. (1996)
North Battleford, Sask., Canada April 2001	More than 5800–7100 cases of cryptosporidiosis in a chlorinated, filtered surface supply	Laing (2002)

Source

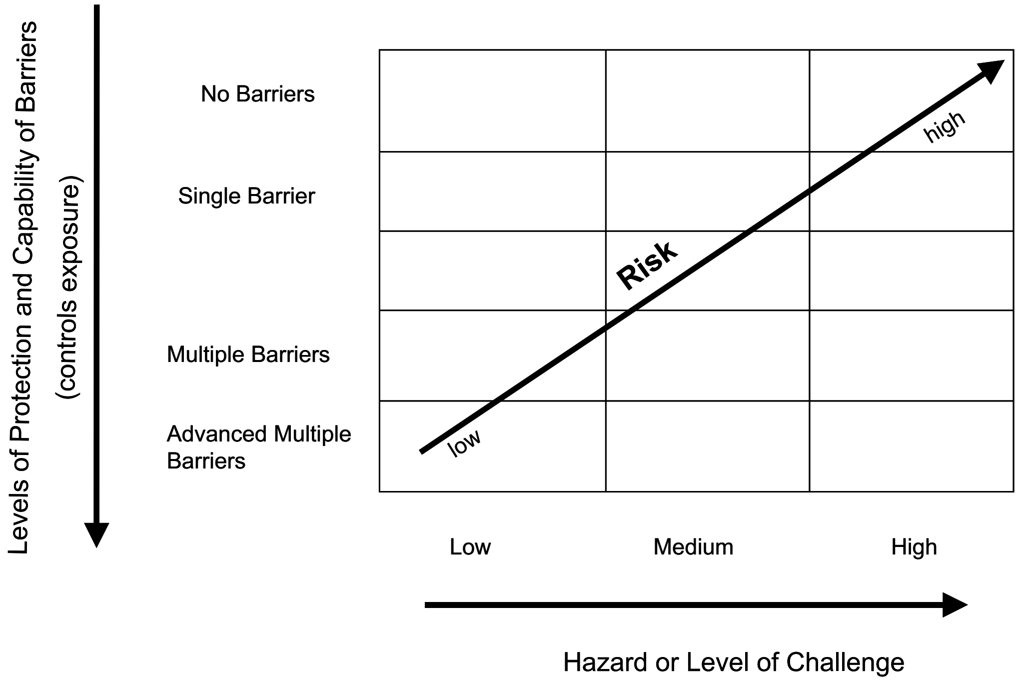
Contamination commonly affects the raw water source. The pathogens (*E. coli* O157:H7 and *C. jejuni*) causing the Walkerton outbreak were attributed to contamination arising from cattle manure from a local farm. These pathogens contaminated a shallow production zone (only 5–8 m depth) of Walkerton Well 5. The contamination was believed to have occurred following a period of exceptionally heavy spring rainfall, approximately 134 mm over 5 d, estimated to be a 1 in 60 year occurrence (O’Connor 2002).

A 1985 outbreak of at least 241 cases of gastroenteritis in Orangeville, Ontario, was described in 1991 (Millson et al. 1991). They reported that the outbreak was caused by *C. jejuni* contamination of unchlorinated groundwater drawn from six “deep” wells, one of which was found to be clearly under the influence of surface drainage (fecal coliforms at $> 600\ L^{-1}$) from mixed farming operations. Heavy snow accumulation was followed by heavy runoff and spring rainfall. Marginal contamination of the system was detected following two routine examinations a week apart. One week later, heavy contamination was detected and 4 d after that one well was shut down, chlorination of the water supply was started, and a “boil water” order was issued.

Considering the proximity of Orangeville to Walkerton (<100 km apart), it is sadly ironic to read from the paper in the *Canadian Journal of Public Health* describing the causes of the Orangeville outbreak 9 years before the Walkerton episode that

> This outbreak highlights the vulnerability of untreated municipal water supplies to contamination under conditions of spring thaw and (or) heavy rainfall. Inspection of wells in this case showed no structural deficiencies and it was concluded that bacterial contamination occurred by filtration through the watershed. Throughout Ontario, municipalities routinely carry out water sampling on a weekly basis all year round. This outbreak identified a need for daily sampling during critical time periods. Although the risk of contamination can be reduced with chlorination, increased sampling still is required because of the potential to overwhelm the chlorination system if it is not adjusted in response to environmental conditions. Since this outbreak, the town has continued to chlorinate its

Fig. 1. Relationship of drinking water risk to water contamination challenge and treatment system resilience (adapted from Hrudey 2001).



> water with no further episodes of contamination reported.

The importance of heavy precipitation as a contributing factor was also evident in the outbreak at Uggelose, Denmark, that occurred in 1992, causing more than 1400 cases of gastroenteritis of suspected viral etiology (Laursen et al. 1994). This water supply was filtered but not chlorinated. Contamination of a well was caused by a sanitary sewer backup during heavy rainfall. The authors concluded

> No other waterborne disease in Denmark has been as thoroughly studied as the present one. Of particular importance is the correlation between precipitation and the onset of reported gastrointestinal symptoms. ... To our knowledge, such a close correlation between precipitation and disease onset has not been reported in other studies.

The community of Penticton, British Columbia, was served by a chlorinated, but unfiltered, mixed surface and ground water supply. A giardiasis outbreak affecting more than 3000 with 362 laboratory-confirmed cases occurred in June 1986 and was likely caused by animal fecal contamination of one surface water intake accessible to giardia-infected beavers and domestic animals (Moorehead et al. 1990). The start of the outbreak appeared to coincide with the peak of spring runoff in the source water creek. The creek water is no longer being used during spring runoff.

Recently, a review of 548 outbreaks in the U.S. over almost 50 years found that 51% were preceded by precipitation events at the 90th percentile of intensity and 68% were preceded by precipitation events at the 80th percentile of intensity (Curriero et al. 2001). Our findings are consistent with Curriero et al. (2001) because, in addition to Orangeville, Uggelose, and Penticton, three other of the outbreaks in Table 1 (Warrington, Bradford, and Disraeli, totaling 40% of the outbreaks reviewed) directly implicated either heavy rainfall or runoff from heavy snowmelt as a contributory cause of the outbreak.

Constant vigilance is required to minimize contamination of source waters. An ability to recognize patterns that are associated with contamination potential is essential. Clearly, periods of heavy precipitation or runoff should demand heightened awareness and active inquiry by water personnel into the potential for contamination.

Walkerton Well 5 was located close to two farms posing a water contamination risk. One of these was judged to be the source of the May 2000 outbreak, notwithstanding having followed model environmental management farming practices. The original hydrogeology report for Well 5, in 1978, recognized the risk of contamination from nearby farms, most notably the other farm, which had been actively farming in 1978 but not in 2000. The hydrogeology report found that fecal coliforms appeared after 24 h during pump testing and stated in two of its five conclusions (O'Connor 2002)

> The results of the bacteriological examination indicate pollution from human or animal sources; however this was not confirmed by chemical analyses. The supply should definitely be chlorinated and the bacteria content of the raw and treated supply should or would [sic] be monitored ...
>
> The Town of Walkerton should consider establish-

> ing a water-protection area by acquiring additional property to the west and south in the vicinity of Well [5]. Shallow aquifers are prone to pollution, and farming and human activities should be kept away from the site of the new well as far as possible ...

On first inspections during operations in 1978 and 1979, the water levels were influenced by surface conditions leading the inspector to conclude (O'Connor 2002)

> This increase in pumping level coincided generally with the spring thaw and period of rain. This appears to confirm the relatively direct communication between this aquifer and the surface.

In 1979 and 1980 several raw water samples were positive for fecal coliforms with the highest concentration at 230 fecal coliforms per 100 mL, while the treated (chlorinated) water samples were all free of fecal coliforms. The inspection report concluded

> The bacteriological quality of Well 5 reveals a variable bacteria density in the raw water throughout the year. The variation in the bacteria density reflects surface activities with the influence of the aquifer. It is recommended that Well No. 5 continue to be monitored on a regular basis in the future to confirm the suitability of the water quality at all times.

No explicit source protection measures were ever adopted for Well 5 in Walkerton despite a series of clear warnings that this shallow groundwater supply was being contaminated by surface activities.

The most recent major waterborne outbreak in Canada occurred in North Battleford, Saskatchewan, in April 2001. The Commission of Inquiry under Mr. Justice Robert Laing found that this outbreak, which affected between 5800 and 7100 individuals in the immediate area and several hundred other visitors, was caused by *Cryptosporidium parvum* in the drinking water supply (Laing 2002). Furthermore, Justice Laing found that (*i*) the source water for the North Battleford water supply, the North Saskatchewan River, exhibited numbers of *Cryptosporidium parvum* as high as any water supply in North America, (*ii*) that there was no watershed protection program operative in Saskatchewan, (*iii*) that this source water is difficult to treat for drinking water, (*iv*) and that effluent from the upstream community sewage treatment plant passed over the drinking water intake from time to time. In the latter case, warnings of the risks of having a sewage treatment discharge immediately upstream of the drinking water treatment plant intake dated back to 1963. Over the years, various warnings and some remedial responses occurred, including chlorination of the sewage effluent. Despite these measures, fecal coliforms as high as 150 000 per 100 mL were measured at the drinking water intake in March of 1993.

Poor location was a factor at Disraeli, Québec, where approximately 50 cases of gastroenteritis were associated with three cases identified as campylobacterosis and subsequent detection of *C. jejuni* in the water supply reservoir. Water was pumped untreated from an intake submerged in a sand and gravel peninsula on the St-Francois River into a nearby reservoir. The intake was 300 m from a fish hatchery frequented by wild ducks, was near three open abandoned wells, and was 180 m from the river downstream from some pig farms. As well, the intake was adjacent to a public recreation area with inadequate sanitation facilities that hosted a festival attended by up to 3000 people a month before the outbreak. Heavy rains fell soon after the festival.

A more subtle, but nonetheless efficient source of raw water contamination was implicated in the outbreak at Uggelose, Denmark (Laursen et al. 1994). Sanitary sewerage backup during heavy rainfalls was able to access the drinking water well head source indirectly by means of a 14 m drainage pipe connecting the wellhead to an adjacent waterworks building that was no longer in use. An 8 m drainage pipe connected the waterworks building to the sanitary sewer that backed up. When the backup occurred, the flooding short-circuited the sump pump in the waterworks building, allowing the water level to rise high enough to flood the drainage pipe from the drinking water wellhead thereby filling the installation pit surrounding the wellhead with sewage contaminated water. Finally, a gasket seal at the wellhead was defective, allowing the contamination to seep into the well water supply. In 1990, prior to the outbreak, the local authorities had posed a question to the water authority about the risk of contamination from the sewer but their inquiry went unanswered by the waterworks management.

Poor geological conditions also existed at Walkerton Well 5, which had been shown to be subject to surface contamination from the time of first commissioning in 1978 (O'Connor 2002). The shallow production zone consisted of highly weathered bedrock with closely spaced horizontal and vertical fractures. Point

source breaching of soil overburden followed by rapid horizontal transport in the fractured bedrock was the most plausible contamination route.

In Richmond Heights, Florida, between January and March 1974, an outbreak of approximately 1200 cases of gastroenteritis occurred (Weissman et al. 1976). A total of 10 cases of shigellosis were culture proven. Similarity of symptoms suggested that most of the gastroenteritis may have been caused by *Shigella sonnei*. The residential suburb was served by a communal water system supplying chlorinated groundwater from shallow wells (6–15 m). A breakdown in chlorination caused inadequately chlorinated water to be distributed 48 h before the epidemic began. Dye testing during the investigation found that seepage from a septic tank located 38 m from one well appeared in the water after only 9 h.

At a resort hotel in Oakcreek Canyon, Arizona, in April and May of 1989, 110 of 240 guests surveyed had gastroenteritis that was likely caused by a Norwalk-like virus (Lawson et al. 1991). Investigation revealed that the unchlorinated private well supply of the resort had likely become contaminated by seepage from the sewage effluent infiltration fields of the resort. Dye-testing revealed travel times of only 3–11 d from the effluent infiltration fields to the drinking water well, much more rapid than the approximately 50 d that would have been expected if infiltration had been occurring strictly through intact bedrock.

At Bramham, England, an outbreak in 1980 of about 3000 cases of gastroenteritis without identified etiology occurred in a community of 12 000 supplied by chlorinated groundwater (Short 1988). The contamination was most likely the result of a blocked sewer overflow contaminating the well sources. Subsequent tracer testing showed leaking sewer seepage was able to travel the 100 m to the affected well in only 8 h.

These outbreaks have demonstrated several common themes (*i*) contamination arising following heavy rainfall or runoff after snowmelt, (*ii*) raw water sources that were located where they were vulnerable to obvious sources of contamination, and (*iii*) geology of groundwater sources that were highly vulnerable to rapid contamination from surface sources.

Treatment

There was sufficient recognition of the vulnerability of Walkerton Well 5 to bacterial contamination that an agreement was reached in 1978 that operators would provide a chlorine residual (majority to be free chlorine) of 0.5 mg L^{-1} after 15 min (O'Connor 2002). This requirement was never formally incorporated into the Certificate of Approval for Well 5, although it was clearly understood to be a requirement by all parties. Monitoring for chlorine residual was expected only once a day, in accordance with 1978 policy for groundwater that showed bacterial contamination. Evidence at the Inquiry revealed that chlorine dosage practice at Well 5 was insufficient to achieve a 0.5 mg L^{-1} residual, even in the absence of any chlorine demand. Although the evidence did not allow for an estimate of the chlorine demand at the time Well 5 was contaminated in May 2000, it is reasonable to assume that the contamination causing this outbreak was accompanied by a chlorine demand sufficient to consume entirely or almost entirely the low chlorine dose, thereby allowing inadequately disinfected water into the distribution system. For reference, maintaining a 0.5 mg L^{-1} free chlorine residual after 15 min would have satisfied the concentration time (CT) requirement for 99% kill of *E. coli* O157 at 5°C and pH 7.0, by 20 fold (Rice et al. 1999). This chlorine dosage would have satisfied the CT for 99.99% kill under these conditions by 7.5 fold.

Inadequate chlorine disinfection was evident in the Bradford, Pittsfield, Eagle-Vail, Richmond Heights, and Bramham outbreaks, and no disinfection was required for contamination-susceptible systems at Orangeville, Disraeli, Oakcreek Canyon, Gideon, and Uggelose (Table 1).

In the Richmond Heights outbreak in 1974, 48 h before the epidemic began, the chlorinator booster pump failed, with the result that no chlorine residual was measurable in the treated water (Weissman et al. 1976). Approximately 3.8 ML of unchlorinated or, at best, inadequately chlorinated water was distributed to the community. This system lacked any other effective barriers to prevent contaminated water from being distributed to consumers. Other potential problems noted with this system were

> ... pumping raw water when chlorine cylinders were being changed, inadequate chlorine contact times, substantial pressure drops in certain areas of the distribution system, and evidence of substantial water loss through leaks or illegal connections ...

An outbreak in the Eagle-Vail, Colorado, district was documented as a waterborne nonbacterial gastroenteritis outbreak affecting 50% of the community surveyed resulting in at least 80 cases, likely caused by a rotaviral pathogen (Hopkins et al. 1986). A sewage treatment plant located on a tributary stream that joined the source river upstream of the drinking water treatment plant was overloaded and was discharging excess biological solids (fecal coliforms at 14 000 per 100 mL) to the tributary. The water treatment plant operated with direct filtration (no chemical coagulation), which was compromised by severe channeling, absence of the fine sand component of the filter media, bottom laterals that were plugged, and chlorination failure for 24 h. Turbidity values averaged 2.5 to 3.5 nephelometric turbidity units (NTU) during the month when the outbreak occurred. Hopkins et al. (1986) observed that

> On Mar. 5, 1981, the chlorinator was the only effective barrier between the toilets of Vail and the water taps of Eagle-Vail and Avon. The other two barriers designed to ensure safe drinking water were compromised: protection of raw water quality and adequate pretreatment and filtration. The simultaneous existence of these defects made an outbreak nearly inevitable.

The protozoan pathogen *Cryptosporidium* is resistant to chlorine disinfection and *Giardia* demands more than minimal chlorine disinfection. Management of outbreak risks from these pathogens requires an effective filtration treatment barrier, either chemically assisted granular media filtration or membrane filtration. Accordingly, several outbreaks have occurred because of inadequate filtration performance, including Milwaukee and North Battleford.

The cryptosporidiosis outbreak of 1993 in Milwaukee was estimated to have caused more than 400 000 cases of diarrhoea in the water supply region (MacKenzie et al. 1994). Milwaukee was served by two water treatment plants (north and south) drawing raw water from Lake Michigan (Fox and Lytle 1996). Both plants provided conventional treatment involving coagulation, sedimentation, filtration, and disinfection (free chlorine before coagulant addition followed by subsequent chlorine and ammonia addition after filtration before distribution). The south plant experienced spikes in treated water turbidity rising to 2.7 NTU in late March and early April following severe storms that caused turbidity of the Lake Michigan water to rise sharply. These rapidly changing raw water turbidities combined with the relatively recent adoption of a new coagulant (polyaluminum chloride) and a short residence time through the treatment process caused the operators difficulty in matching coagulant dosage to raw water conditions appropriate to achieve satisfactory effluent turbidity. The operators changed the coagulant to alum on 2 April, but still experienced a turbidity spike on 5 April, after which this plant was shut down on 8 April. Although the treated water quality was suspect during this period, bacterial monitoring did not indicate any adverse results suggesting that disinfection of bacterial pathogens was adequately maintained. Investigation after the outbreak noted that the practice of recycling filter backwash water increased the risk of *Cryptosporidium* oocyst breakthrough, particularly at the times when turbidity removal was poor.

The outbreak in North Battleford occurred in a water treatment plant using coagulation in a solids contact unit (SCU) clarifier followed by dual media granular filtration with overall chlorine disinfection (Laing 2002). The primary coagulant used was alum, along with polyalumimum chloride, anionic polymer, and lime. The solids contact clarifier was taken out of service on 20 March 2001 for cleaning. After bringing the unit back into service, inadequate floc formation and essentially no floc settling occurred in the SCU for a month during which time the treated water turbidities rose above 0.5 NTU. Contamination of the treated water with *Cryptosporidium* is judged to have occurred during this period of inadequate coagulation performance. Justice Laing concluded from the evidence about the design and operation of this plant for North Battleford that

> Prior to April 2001, the surface water treatment plant was not a 'capable plant' by industry standards.
>
> The fact that the surface water treatment plant was not a 'capable plant' has direct bearing on the Cryptosporidium parvum contamination of March – April 2001.

Despite the relative simplicity of chlorine disinfection as a means for controlling health risks from bacterial pathogens, there have been a number of failures involving inadequate chlorination. Some of these failures reflect an inadequate appreciation of the critical role of the disinfection barrier and the severity of health consequences that may be caused by bacterial pathogens if inadequate disinfection is allowed to occur. In the case of protozoan pathogens like *Giardia* and *Cryptosporidium*, effective filtration is an essential additional barrier. The failures with these pathogens have indicated an inadequate appreciation that very low levels of treated water turbidity must be achieved to provide reasonable assurance that dangerous levels of protozoan pathogens are prevented from being distributed in the treated water.

Distribution

Possible scenarios whereby the distribution system at Walkerton could have been contaminated were investigated and carefully evaluated by the Inquiry. These included the installation of new water mains at three locations, a fire event with potential for associated depressurization, main breaks and repairs at four locations in March 2000, potential for contamination of two treated water storage standpipes, cross connections found at eight private wells and many private cisterns, potential for cross contamination of water mains by sanitary sewers, and surface flooding in the town during the heavy rainfall of 12 May 2000. Although one or more of these elements offered the potential for causing contamination of the Walkerton distribution system, none provided an adequate explanation for the contamination that caused the outbreak. Rather, Justice O'Connor concluded that the primary, if not the only, source of contamination of the Walkerton water system was cattle manure from a farm near Well 5. Residents of Walkerton were probably first exposed to this contamination shortly after the 12 May heavy rainfall (O'Connor 2002).

Previously, the most serious outbreak from *E. coli* O157 contamination of drinking water occurred in Cabool, causing 86 cases of bloody diarrhoea, 32 hospitalizations, and 2 cases of haemolytic uremic syndrome (HUS) (Swerdlow et al. 1992). There were four deaths, including one HUS case; the other HUS case (a 3-year-old child) recovered. Direct contamination of the unchlorinated groundwater source was judged to be unlikely. A more likely cause was the lack of a proper disinfection protocol following the replacement of 43 water meters and the subsequent repair of two broken water mains. The sanitary sewer system was found to be prone to infiltration of storm runoff with subsequent flooding of water distribution lines and sites of water meter boxes.

The Gideon, Missouri, outbreak involving an undisinfected groundwater supply caused an estimated 600 cases of diarrhoea including 31 laboratory confirmed cases of salmonellosis (*Salmonella typhimurium*), 15 hospitalizations, and 7 deaths in nursing homes from diarrhoea with 4 culture-confirmed for salmonellosis (Clark et al. 1996). Investigation into possible causes found that taste and odor complaints led to a sequential flushing program of all the hydrants in the system. This outbreak was believed to have been triggered when stagnant or contaminated water levels in a storage tank mixed following a thermal inversion caused by a sharp temperature drop. When distributed, this mixed water resulted in taste and odor complaints. Subsequent turbulence caused by the distribution system flushing program in response to these complaints is then believed to have stirred up sediments contaminated with pathogens. Storage tanks were poorly maintained and the water inside was black and turbid. Contamination of the municipal water storage tank by bird feces was judged to be probable because feathers and feces were found on and around the poorly maintained storage tanks.

Pittsfield, Massachusetts, experienced an outbreak of giardiasis that may have infected as many as 3800 residents with 703 laboratory confirmed cases among 50 000 served by a surface water supply that was chlorinated but not filtered (Kent et al. 1988). Ironically, this outbreak may have been caused by alterations to the water treatment system to allow for the addition of a filtration system. An auxiliary reservoir was used for the first time in over 3 years. When this reservoir was brought on line, increased turbidity occurred, possibly caused by reversals in water flow that suspended sediments in water mains. Furthermore, chlorine levels in water from this reservoir were low during the entire month of November because of a malfunction in the chlorinator. This reservoir was found to be vulnerable to contamination by beavers and muskrat although the original source of contamination may have been human.

Contamination of water in distribution systems poses a serious problem for water authorities because it is not realistic to expect that monitoring programs will be able to detect such localized contamination universally. Maintenance of a chlorine residual in the distribution system provides a limited degree of protection against bacterial recontamination, but the chlorine residual may be most helpful as an easily measured indicator that there has been a contamination challenge (i.e., the inability to maintain a residual at least provides an indication of chlorine demand that may be caused by contamination). However, it is essential for all parties involved in drinking water safety to appreciate that it is the chlorine residual and contact time (CT) that provides disinfection, not the chlorine dose. If the chlorine demand from contamination sources is sufficiently high to reduce the chlorine residual below the required levels, inadequate to no disinfection will follow.

Monitoring

The quality monitoring requirements for the Walkerton water system were daily measurement of chlorine residual and monthly sampling of raw water and the distribution system for microbiological testing. Samples were routinely mislabeled as to where they were actually taken. Notably, samples from the distribution system were usually not taken. Rather, samples were generally taken near the treated well water location so it was not possible to judge the microbiological quality of distribution system samples. Despite this deception, the microbiological monitoring program disclosed adverse results including the presence of *E. coli* in treated water on several occasions. This recurring presence of *E. coli* in treated water provided direct evidence of dysfunctional chlorination because of the documented susceptibility of *E. coli* to chlorine disinfection. Even more troubling was the disclosure that chlorine residuals were not measured daily as required and that daily chlorine residual monitoring logs were routinely falsified with repeated fictitious entries of exactly 0.5 or 0.75 mg L^{-1}. Chlorine residuals measured by Ministry of Environment inspectors were always lower than 0.5 mg L^{-1}, yet the discrepancies with the falsified records were neither formally challenged nor rectified.

The Inquiry noted that Ontario Drinking Water Objectives were updated in 1994 to recognize that unfiltered water supplied from groundwater that was under the direct influence of surface water required continuous chlorine residual monitoring and regular turbidity monitoring. Unfortunately, there was no program implemented to review Certificates of Approval to water systems that had been granted before the new policy. As a result, Well 5, which had shown evidence of being under the direct influence of surface water at commissioning in 1978, was not required to implement the new policy. Significantly, after considering all of the evidence presented, Justice O'Connor found that if the Walkerton system had been required to satisfy the 1994 policy, the fatal outbreak would have been prevented (O'Connor 2002).

Both the Bramham and the Bradford outbreaks documented failures in monitoring chlorine residual that contributed to these outbreaks. The Bramham outbreak revealed that when adverse bacterial results were reported, staff were told to increase chlorination, but they had no equipment to measure chlorine residual (Short 1988). As a result, operators relied upon monitoring the volume of hypochlorite solution consumed, but they failed to recognize that whatever the setting of the pump, they were achieving no chlorine residual in the treated water. During the outbreak investigation, it was discovered that a seal on the dosing pump had failed and that the hypochlorite solution was actually passing to the drain. Similar failures were reported to have occurred elsewhere in the U.K. At Bradford, Pennsylvania, the monitoring procedures were also inadequate to ensure a proper dosage to achieve a chlorine residual into the distribution system (Akin and Jakubowski 1986).

Unfortunately, the operators and management at North Battleford were still unaware in 2001 that (Laing 2002)

- *Cryptosporidium* oocysts posed a health risk in surface water supplies
- the North Saskatchewan River was a major source of these oocysts
- chlorine was ineffective in disinfecting *Cryptosporidium* oocysts
- allowing treated water turbidity levels to exceed 0.3 NTU could allow *Cryptosporidium* into treated water

Response

The operators at Walkerton were qualified by experience to operate the mechanical aspects of the water system, but the evidence indicated that they clearly lacked any substantive understanding of the need for disinfection to inactivate pathogens in drinking water and the serious health consequences that could arise from failing to maintain adequate disinfection of the Walkerton water supply. The General Manager of the system, Stan Koebel, and his brother Frank were both granted class 2 operator status as part of a voluntary "grandparenting" program in 1988 with neither having ever taken any training courses nor being required to pass any examinations. They were both upgraded to class 3 operators in 1996, again without any assessment of their knowledge or skills. Neither operator understood even the most basic elements of assuring effective chlorine disinfection. Stan Koebel testified that one of the reasons that they added less than the required amount of chlorine was because they had received complaints from town residents about the taste of too much chlorine in the water.

The contamination most likely entered Well 5 on 12 May when 70 mm of rainfall fell overnight. On the 13, 14, or 15 May, no chlorine residuals were measured and the opportunity to detect the contamination of Well 5 by the absence of a chlorine residual was foregone. On 15 May, Well 5 was shut down and Well 7 was brought on line without a chlorinator. Although the latter failing clearly played a role in the evasive behaviour of Stan Koebel over subsequent days, substantial contamination from Well 7 was judged to be unlikely. Microbial monitoring samples were taken on 15 May at sites that were undoubtedly mislabeled, but included samples that were most likely taken near Well 5. Results of these Walkerton distribution samples were reported to Stan Koebel on 17 May. They included membrane filter analyses that showed gross contamination with total coliforms and *E. coli*. Gastrointestinal illness began to appear in the health care system on 18 May and public health authorities were alerted on 19 May. The local health unit contacted Stan Koebel to ask whether there was any problem with the water supply. He replied that he thought the water was “okay”. Thereafter he began flushing the distribution system and superchlorinating so that when contacted again by the health unit on 20 May, Stan Koebel reassured the health unit that there was a chlorine residual in the distribution system. By midday on 21 May, the Owen Sound hospital laboratory had confirmed an identification of *E. coli* O157:H7 from one patient and announced a presumptive result for another. The local health unit then issued a boil water advisory despite the assurances from Stan Koebel over the previous 2 d.

Concerning the North Battleford outbreak, Justice Laing found that (Laing 2002)

> the city lacked an appreciation that safe drinking water is a public health priority that distinguishes the water utility from other public works administered by the city. The result of this lack of appreciation is that North Battleford’s surface water plant and the operations carried on therein were substandard by industry standards in April 2001.

Furthermore, Justice Laing noted

> that the goal of producing safe drinking water cannot be accomplished solely through better infrastructure. A commitment to excellence in operations is also required from civic administrators and politicians.

The human nature of these response failures is often such that a serious level of commitment and vigilance will be needed to prevent them from recurring elsewhere. This will involve responding more vigorously than in the past to adverse microbial results until corrected or demonstrated that they are due to sampling or analytical error. In the Bradford, Pennsylvania, outbreak, positive coliform results were detected in the water before and during the outbreak but these results only resulted in resampling without any other corrective actions being taken (Akin and Jakubowski 1986). In the Bramham outbreak, the initial adverse microbiological monitoring results that could have notified operators of the contamination problem were attributed to false positives on the suspicion that the sample bottles had been inadequately sterilized (Short 1988). Follow-up testing of the sites showing adverse results was delayed a full week by the intervention of a weekend and staff shortages due to holidays. The problem of residents complaining of chlorine taste being mentioned by operators as a reason for keeping chlorine residuals unacceptably low was also cited as a factor in the Bramham outbreak. Similarly, a review (Lahti and Hiisvirta 1995) of waterborne outbreaks in Finland referred to one unspecified community outbreak in which concerns about health risks from the formation of chlorinated organic compounds were cited as the reason for lowering chlorination to ineffective levels leading to an outbreak affecting a few hundred people.

Risk management responses once a problem is detected can also be ineffective. In the Gideon outbreak that caused seven deaths from salmonellosis, it was later found that many residents continued to drink un-boiled water after the boil water order was issued because they did not understand the severity of the situation (Angulo et al. 1997). Consumers only responded when information sheets that clearly explained the need and rationale for the boil water order were delivered to their homes.

Finally, at the extreme of response failure, from the Eagle-Vail outbreak, chlorination failed for 24 h when a chlorine cylinder emptied, triggering an off-site alarm, which was turned off without investigation (Hopkins et al. 1986). Subsequently, a continuous chlorine residual monitor with an alarmed, automatic water system shutoff requiring a manual restart was installed.

Discussion

Complacency appears throughout the cases reviewed and appears to be an endemic problem underlying waterborne disease outbreaks in developed countries. Perhaps the most striking evidence of this in Canada is that, despite the overwhelming publicity that surrounded the fatal outbreak in Walkerton, Ontario, from May of 2000, Justice Laing concluded the following about the City administration regarding the North Battleford outbreak that occurred 1 year later (Laing 2002)

> There was a systematic failure on the part of the City of North Battleford to recognize its responsibility to produce safe drinking water. This failure was brought about by the City’s collective lack of knowledge on what it takes to produce safe drinking water, and policies that discouraged the possibility that it might acquire such knowledge.

In fact, when the City of North Battleford received a letter from the Regional Manager for Saskatchewan Environment and Resource Management (SERM) following the Walkerton tragedy to emphasize the importance of maintaining and monitoring their drinking water supply, North Battleford city council took exception to the warning letter, which the mayor described as a "cover your butt" letter and replied on June 13, 2000

> We certainly understand and take our responsibility to provide safe drinking water to our citizens. The City of North Battleford has regularly tested our water and our staff have been very professional and diligent in their examination procedures.
>
> Your letter certainly alerts communities as to the need for ensuring safe drinking water for their citizens. We were dismayed in concluding that SERM is not aware of the procedures we use in our community to ensure safe drinking water.

The Mayor testified at the Inquiry that this letter was written "more on faith than as a result of any particular inquiries he had made at the time about the state of the city's water system ..."

Justice Laing also found that the Saskatchewan government and the department responsible for regulating drinking water, SERM, were failing to assure drinking water safety, noting

> That the current risk-based model employed by SERM since 1996 is arrived at on the basis of economics (what it or the government thinks it can afford among other priorities), and has nothing to do with how best to safeguard the health of the population, all of whom consume water.
>
> As presently structured, SERM is an inadequate and ineffective regulator of drinking water.
>
> SERM is well aware of what it takes to produce safe drinking water, including watershed management and protection of ground water sources, but the government of Saskatchewan has not provided it with a mandate to pursue an implementation strategy.

These findings suggest that the knowledge of the severe consequences of the Walkerton tragedy in May 2000 was, by itself, insufficient to cause either the City of North Battleford or the Saskatchewan government to substantially improve their approach to assuring safe drinking water by the spring of 2001.

Such observations are certainly discouraging and they suggest that we need to ensure a wider understanding of what is necessary to begin to assure safe drinking water. A short list that should be understood by anyone responsible for drinking water safety would include (Hrudey 2002):

(1) Pathogenic microorganisms still pose the greatest recurring risk to the health of drinking water consumers. Treatment and disinfection of pathogens that may be present in raw water must be maintained effective, by a substantial margin, to prevent waterborne disease outbreaks.

(2) Any sudden or extreme change in water quality, flow or environmental conditions (extreme precipitation, snow-melt, runoff or flooding) should arouse suspicion of adverse conditions that might cause drinking water contamination.

(3) The drinking water system must have and continuously maintain robust and resilient, multiple barriers appropriate to the level of contamination challenge to the raw water supply.

(4) System operators must have an effective, continuing capacity to learn from past problems, failures and near failures so as to respond quickly and effectively to adverse monitoring signals.

(5) System operators must be personally dedicated to continuously providing consumers with safe water. Concerns or complaints about water quality from consumers or other responsible parties must always be investigated.

Such principles are needed to promote a responsible attitude among individuals working in all drinking water agencies. Those in positions of responsibility need to embrace these principles and ensure that newly trained operators receive the proper support to deliver these responsibilities. Likewise, they need to ensure that those who will subscribe to these responsibilities will not be undermined by poor attitude or complacency that may be endemic among existing staff, civic officials or politicians and regulators.

Conclusions

A multiplicity of failures occurred in Walkerton despite the readily accessible experience from elsewhere warning of many similar failure modes. The challenge for improving drinking water system safety is to reform the pervasive culture of complacency that has been evident among so many key players in drinking water systems. Such complacency must be replaced with a culture of personal responsibility and vigilance. This poses a challenge, in part, because the drinking water industry has been successful in making waterborne disease outbreaks very rare in developed countries.

Because a single barrier failure may not cause a total system failure leading to an outbreak, there may be inadequate remedial attention given to individual failures. Each failure in isolation may appear to have limited or no consequences. For the multiple barrier framework to succeed in preventing outbreaks, when continuing feedback indicates that an individual failure will likely not cause catastrophe by itself, all individual elements must be maintained effective.

Finally, a sense of personal accountability, based on an understanding of a manageable set of principles, must be communicated to all those holding responsibility for protecting public health through safe drinking water. To this end, Chapter 2 of the Walkerton Inquiry report describing the impact of this tragedy on the community should become required reading for all parties involved in the delivery of drinking water to reinforce the magnitude of personal responsibilities and range of challenges that are inherent in undertaking to provide safe drinking water to the public.

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