

Incorporation of the Multiple Barrier Approach in drinking water risk assessment tools

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ABSTRACT

A number of existing risk assessment tools make reference to, or incorporate, a Multiple Barrier Approach to drinking water safety. Three waterborne disease outbreaks that occurred in developed nations were used as case studies to test a selected set of risk assessment tools. The outbreaks were used to determine how well the risk assessment tools identify hazards and vulnerabilities associated with different barriers to drinking water contamination.

Key words | drinking water, Multiple Barrier Approach, risk assessment, Walkerton

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INTRODUCTION

In May 2000, exposure to contaminated drinking water in the community of Walkerton, Ontario, resulted in 167 confirmed cases of *Escherichia coli* (*E. coli*) O157:H7, 116 confirmed cases of *Campylobacter* (Bruce-Grey-Owen Sound Health Unit 2000), and tragically, 7 deaths (O'Connor 2002a). Based on testimony given and evidence submitted to the Walkerton Inquiry, it became clear that the outbreak was caused by the concurrent failure of a number of the “barriers” that are relied upon to prevent contamination of drinking water and protect public health (Hrudey & Hrudey 2002). As a result, Justice Dennis O'Connor concluded that reliance upon a Multiple Barrier Approach (MBA) represents “the best way to achieve a healthy public water supply” (O'Connor 2002b). The five types of barriers were summarized as follows by Hrudey & Hrudey (2002):

- Source protection measures to maintain raw water quality and reduce the risk of contamination entering the water system;
- treatment processes to remove or inactivate contaminants;
- distribution system security to prevent the contamination of treated water and maintenance of a disinfection residual to ensure delivery of safe water to consumers;

- monitoring activities to control treatment processes and detect contamination; and
- response activities to address adverse water quality or system failure.

The Walkerton outbreak was not unique, in the sense that historical waterborne disease outbreaks have generally been caused by the failure of more than one water system barrier (O'Connor 2002b; Hrudey & Hrudey 2007). Due to the increasing awareness of the failure potential which may exist in the water supply systems in developed countries, a substantial number of jurisdictions and non-governmental organizations have developed risk assessment and management guidance documents or tools that incorporate the MBA to some extent. This list includes the Australian Drinking Water Guidelines (ADWG), British Columbia Comprehensive Drinking Water Source-to-Tap Assessment Guideline, Drinking Water Quality Management Standards for New Zealand, Private Water Supplies Technical Manual of the United Kingdom, and the World Health Organization Guidelines for Drinking-Water Quality. Different documents may use different definitions or descriptions of the MBA, which may result in variability in the understanding of how different

drinking water management practises and standards may identify the risk of failure to provide safe drinking water.

A number of these tools have incorporated qualitative or semi-quantitative risk assessment procedures in order to identify potential hazards to drinking water safety. The qualitative risk assessment process is often based on the user assigning likelihood and consequence scores to each of the hazards that he or she has identified. Risk assessment is an inherently subjective process, so the output for a given risk assessment process will vary between users for a given water system (Ministry of the Environment 2007). One of the weaknesses in some of the aforementioned risk assessment tools is that they rely on the user to identify all of the potential hazards associated with a drinking water system, which further adds to the subjectivity of the process. As a result, the output from the qualitative risk assessment process may vary significantly depending on the expertise of the user and his/her level of familiarity and objectivity with the drinking water system, and the degree to which they consider the MBA concept.

Historic outbreaks provide information regarding potential sources of microbial contamination, and demonstrate the importance of the events or conditions that contributed to the failure of the water system barriers (Deere *et al.* 2001). This paper uses a number of documented waterborne disease outbreaks that occurred in developed countries as case studies. These three outbreaks were selected because each case involves the contamination entering the water system at a different point either prior to, during, or after water treatment. As a result, these case studies will be used to test the ability of a set of risk assessment tools to identify hazards and vulnerabilities associated with individual barriers to contamination, and the degree to which the tools represent and incorporate the interdependence of the barriers. The conditions of the respective water systems at the time of the waterborne disease outbreaks have been documented in journal articles that were published in the wake of the outbreaks. The input to the risk assessment tools will be based on the condition of the water system immediately prior to the contamination event that led to the outbreak (i.e. as if an individual was completing the application of a particular tool just before contamination entered the water system).

For the purpose of this paper, the British Columbia Drinking Water Source-to-Tap Screening Tool (B. C. Screen-

ing Tool), the Montana Water Center Microbial Risk Assessment Ranking Tool (MRA Tool), and the Borehole Risk Assessment form from the Scottish Private Water Supplies Technical Manual (PWS Tool) will be applied to drinking water systems that have been implicated in waterborne disease outbreaks. These risk assessment tools were selected because each tool includes survey questions that address the physical infrastructure and historic water quality data of the water system. The specific survey questions are included to decrease the level of subjectivity associated with the input to the risk assessment tool.

METHODS

Risk assessment tools

B. C. Screening Tool

The B. C. Screening Tool was developed to be the first tier of the Comprehensive drinking water source to tap assessment (Comprehensive Assessment) (Ministry of Health Services and Ministry of Water, Land and Air Protection 2005). Separate surveys are included for the different barriers of the water system, in addition to surveys regarding the management of the water system and historical drinking water quality. Each survey includes a number of questions regarding the specific barrier, most of which are answered with a “yes” or “no”. The B. C. Screening Tool is meant to be completed by the owner of water system, with assistance from the local health authority as needed (Ministry of Health Services and Ministry of Water, Land and Air Protection 2004).

The completed B. C. Screening Tool is then evaluated by the Drinking Water Officer (DWO). If the DWO identifies what he or she believes are significant risks based on the input to the B. C. Screening Tool, the DWO can order the water system owner to complete a Comprehensive Assessment, and set out the scope for such an assessment (Ministry of Health Services and Ministry of Water, Land and Air Protection 2005). The Comprehensive Assessment is divided into modules that address the barriers of the water system. The DWO may order the owner to complete the relevant modules for only those barriers where a risk was identified.

The Comprehensive Assessment is meant to be completed by an inter-disciplinary team of qualified professionals (Ministry of Health Services and Ministry of Water, Land and Air Protection 2005). By completing the modules included in the Order, the team would identify and characterize hazards and vulnerabilities relevant to the barrier being evaluated, and then complete a qualitative assessment to develop a prioritized list of risk management alternatives to address the hazards and vulnerabilities for the evaluated barriers (Ministry of Health Services and Ministry of Water, Land and Air Protection 2005). It stands to reason that if the DWO orders the water system owner to complete a specific module based on the input to the B. C. Screening Tool, the assessment team would identify the hazards and vulnerabilities for that barrier when completing the module. If, for some reason, the DWO could not identify a potential hazard or vulnerability based on the input to the B. C. Screening Tool, then it is less likely that the DWO would order the supplier to complete the module that is relevant to that hazard or vulnerability. As a result, the risk assessment team would be less likely to identify that hazard or vulnerability when completing the required modules, which would severely limit the effectiveness of the Comprehensive Assessment process. Thus, the ability of the B. C. Screening Tool to identify hazards and vulnerabilities was used to determine whether the factors that led to the respective waterborne disease outbreaks would be identified in the Comprehensive Assessment process.

MRA Tool

The MRA Tool was developed as a self-assessment tool for use by small water system personnel (Butterfield & Camper 2004). There is no regulatory involvement in completing the assessment or interpreting the output of the MRA Tool.

The MRA Tool is available as a Microsoft[®] Excel spreadsheet. The MRA Tool is organized as a series of surveys, with each survey addressing a barrier of the water system. Each survey has a separate worksheet where the user inputs answers to the individual survey questions. Based on user input, each survey question receives a numerical score in the range of 0 to 1, where a score of 1 represents the greatest potential for microbial contamination (Butterfield & Camper 2004). Each survey question was assigned a weighting based

on the relative importance of that question compared to the other questions in the survey, such that the sum of weights for a given survey is equal to one. The weightings are based on expert opinion, and cannot be viewed or modified by the user. Ranked pairwise comparison was employed to convert expert opinion regarding the relative importance of the questions in a given survey to numerical weights (Butterfield & Camper 2004).

The score of 0 to 1 assigned to each survey question is multiplied by the weighting for that question to calculate the weighted score for each survey question. The weighted scores for the individual questions are then summed to calculate the total score for the survey. If there are multiple facilities (i.e. multiple wells or storage tanks) for a given barrier, the survey is completed separately for each facility, and the MRA Tool assigns a weighting to the input for each facility based on the fraction of the water system capacity that each facility represent (Butterfield & Camper 2004). The total score for each survey is then multiplied by its respective weight, and the weighted survey scores are summed to calculate a total water system score in the range of 0 to 1.

The MRA Tool output includes comments regarding individual survey questions that receive elevated scores. In addition, the scores assigned to the individual survey questions and the contribution of each survey to the total score for the water system can be viewed in both graphical and tabular form (Butterfield & Camper 2004), which helps illustrate the water system barriers that are calculated to be at the greatest risk of microbial contamination.

PWS Tool

The Private Water Supplies (Scotland) Regulation 2006 states that, the local health authority must complete a risk assessment of a private water supply prior to the supply being used if it is new or has been out of service for a period of greater than one year, or if the local authority believes that the water supply is no longer wholesome. This applies to all "Type A" supplies, which serve greater than 50 persons, provide greater than ten cubic metres of water per day, or supply water for a commercial or public activity (The Scottish Ministers 2006).

The risk assessment protocol for private water supplies in the United Kingdom was developed using guidance from the WHO regarding the development of Water Safety

Plans (Scottish Executive 2006). Both the WHO Guidelines for drinking-water quality and the Private water supplies technical manual make reference to the MBA. The WHO states that a Water Safety Plan (WSP) represents “the most effective means of consistently ensuring the safety of a drinking water supply ... through the use of a comprehensive risk assessment and risk management approach that encompasses all steps in water supply from catchment to consumer” (WHO 2006). The risk assessment forms included in the PWS Tool are considered to be the first stage in the development of WSPs for private water supplies in Scotland (Scottish Executive 2006).

There are four risk assessment forms; each addresses a different type of water supply: boreholes (drilled wells), springs, surface water supplies, and wells (dug wells). Since all of the case studies used in this paper received their water supply from drilled wells, only the one form was used for this paper. However, it should be noted that the four surveys have a similar structure, scoring system, and many common survey questions, so the output from the borehole risk assessment form is representative of the output from the other three forms. The “front end” of each form collects contact information for the water system, recent monitoring results, historical regulatory involvement, and water system documentation. The risk assessment section of each form is divided into surveys, including the general site survey and supply survey. The spring and well risk assessment forms also have a soil leaching risk survey. In the general site survey and supply survey, each question is assigned a risk characterization score of high, medium, or low, which is pre-selected on the form based on the presence or absence of a hazard or vulnerability. If a “high” risk characterization score is assigned based on the user input, the user must also calculate a hazard assessment score for the survey question. The semi-quantitative hazard assessment score is calculated by multiplying the pre-selected consequence score for the survey question by a likelihood score selected by the user. Both the consequence and likelihood scores use the same non-ordinal scale of one to sixteen. It should be noted that the hazard assessment score does not have any implied mathematical relationship to risk, but is used to prioritize the aspects of the water system that require corrective action (Scottish Executive 2006). Upon completion of the surveys, the highest risk characterization score assigned to a survey question is taken

as the risk characterization score for that survey. The risk characterization score for the source survey is recorded as the overall risk assessment score for the water system (Scottish Executive 2006).

CASE STUDIES

Walkerton, Ontario

At the time of the outbreak, the Walkerton municipal drinking water system was supplied with water by three drilled wells, Wells No. 5, No. 6, and No. 7. Each well was completed in an unconfined fractured bedrock aquifer (O'Connor 2002a). Well No. 5 was completed at a shallow depth of 15 metres (m) compared to Well No. 6 (72.2 m) and Well No. 7 (76.2 m) (Hrudey & Hrudey 2004). Each well was outfitted with a separate chlorination system to achieve primary disinfection prior to the treated water reaching the first user.

According to the Walkerton Inquiry, approximately 134 millimetres (mm) of rain fell in Walkerton over the period of May 8 to 12, 2000 (O'Connor 2002a). This was equivalent to a 60-year storm event for this region for the month of May. Flooding occurred in the town and in the area of Well No. 5. On May 9, 2000, the water supply was switched from Well No. 7, which was in operation despite not having a functioning chlorination system at that time, to Wells No. 5 and No. 6. Well No. 5 operated continuously and was the primary water source from May 10 until the afternoon of May 15. Walkerton Public Utilities Commission (PUC) staff recorded free chlorine residual concentrations for treated water from Well No. 5 on May 13 and 14, but it is unlikely that the recorded numbers were accurate, as PUC staff often falsified records with respect to free chlorine levels (O'Connor 2002a). On May 15, PUC staff collected several water samples, a number of which may have been labelled with the incorrect sampling location, and shipped them to a private laboratory for analysis of microbiological parameters. On May 17, the PUC was notified that the majority of these samples were positive for both *E. coli* and total coliform bacteria. PUC staff withheld these results from Ministry of the Environment (MOE) and Bruce-Grey-Owen Sound Health Unit (PHU) staff until May 22, 2000 (O'Connor 2002a).

During the Walkerton Inquiry, manure storage and application activities at a farm located near Well No. 5 were identified as the primary source of microbial contamination (O'Connor 2002a). On April 22 and 23, 2000, approximately 70 tons of manure were applied and incorporated into the soil at the farm. The edge of the application area was approximately 80 m from Well No. 5. Expert evidence from the Inquiry indicated that it was likely that contamination entered the water supply aquifer through fractures in the bedrock, and not via surface run-off (O'Connor 2002a).

Due to exposure to *Campylobacter* and *E. coli* O157:H7 present in the Walkerton water system in May 2000, approximately 2,321 people became ill, 27 people developed Hemolytic Uremic Syndrome (HUS), and 7 people died (O'Connor 2002a).

Greenville, Florida

At the time of the outbreak, a single groundwater well completed at a depth of approximately 60 m provided the Greenville municipal water system with its water supply. Raw water was pre-chlorinated prior to entering an open-top tank that is referred to as an "Aerator and Settling Tank" in the available literature (Sacks *et al.* 1986). There is no information available regarding the aeration equipment or addition of water treatment chemicals that would promote flocculation and settling prior to the water entering the tank. As a result, it is assumed that the open-top tank was designed to provide passive aeration and the necessary settling time for iron, sulphide, or other dissolved compounds present in the raw water to precipitate and settle. The settling tank effluent then passed through two open-top sand filters piped in series. The filtered water was then chlorinated prior to entering a clear well, which pumped to the municipal distribution system (Sacks *et al.* 1986).

Literature published regarding the outbreak indicates that the pre-chlorination system failed on April 13 and the post-chlorination system failed on April 27, 1983. These issues were not discovered by the untrained operator responsible for the water system until May 11 (Sacks *et al.* 1986), which raises questions about how the dates of equipment failure were identified.

The local public health office was notified of an apparent outbreak of acute gastroenteritis on May 9, 1983, and collected water samples from the distribution system to

investigate. The analytical results received on May 11 showed that all four samples were positive for total coliform bacteria. A Boil Water Notice was issued that day as a result (Hrudey & Hrudey 2004).

Follow-up sampling activities indicated that contamination likely entered the water system infrastructure prior to the sand filters but after the supply well (Sacks *et al.* 1986). Birds had been observed roosting on the open-top aeration tank over the course of the outbreak, and bird droppings were found on the grating covering the tank. Birds were trapped in the vicinity of the aeration tank in late June 1983. *Campylobacter jejuni* was isolated from fourteen birds (37% of the birds trapped), and *Plesiomonas shigelloides* was isolated from one bird. These observations suggest that bird droppings were likely the source of contamination that caused the waterborne disease outbreak (Sacks *et al.* 1986), and that contaminated water was allowed to enter the municipal distribution system due to the unnoticed failure of both the pre and post-chlorination systems.

Due to exposure to *Campylobacter jejuni* and *Plesiomonas shigelloides*, there were an estimated 865 cases of gastroenteritis and one case of Guillain Barre Syndrome associated with the outbreak (Sacks *et al.* 1986).

Gideon, Missouri

At the time of the outbreak, the Gideon water system was supplied with water by two adjacent wells, Wells No. 5 and No. 6, which alternated as the water supply well on a monthly basis. The wells were artesian, and were completed at a depth of approximately 390 m (Angulo *et al.* 1997). The supply aquifer was considered to be secure due to geologic isolation (Hrudey & Hrudey 2004). As a result, the water supply was distributed without treatment.

The municipal water system was constructed in the 1930s (Clark *et al.* 1996a). Two large municipal water towers, which will be referred to as T200 and T300, were connected to the distribution system. T200 and T300 had capacities of 190 and 380 cubic metres (m³) respectively. Precipitation and vermin could potentially enter T300 due to a poorly constructed vent and an uncovered access hatch (Angulo *et al.* 1997). A large private water storage tank also received water municipal water, although it was isolated from the distribution system by a backflow prevention device (BFP) (Clark *et al.* 1996a).

In response to taste and odour complaints, the municipality performed distribution system flushing activities on November 10, 1993 that included sequential flushing of all 50 fire hydrants connected to the distribution system for a period of 15 minutes each (Clark *et al.* 1996a). On November 29, 1993 the Missouri Department of Health (DOH) was notified that two high school students in Gideon had been hospitalized with confirmed cases of salmonellosis (Clark *et al.* 1996a). Three water samples collected from the distribution system by the Missouri Department of Natural Resources (DNR) on December 17, 1993 were positive for both fecal and total coliform bacteria. As a result, a Boil Water Order (BWO) was issued on December 18. After additional samples collected on December 20 were positive for fecal and total coliform bacteria, the DNR installed an in-line chlorination system at the active water supply well on December 23, 1993. A sample collected from a fire hydrant on December 23 after chlorination had started was positive for dulcitol-negative *Salmonella serovar typhimurium* (*S. typhimurium*), as well as fecal and total coliform bacteria (Clark *et al.* 1996a).

Due to the vulnerabilities in the construction of the water towers, the outbreak investigation focused on the storage facilities. Birds were observed roosting on the roof of T300, and bird feathers were observed floating on the surface of the stored water during the field investigation performed after the outbreak (Angulo *et al.* 1997). The circumstantial explanation for the contamination entering the Gideon distribution system is that the cold temperatures on November 9 caused a thermal inversion in T300, which allowed contamination near the water surface to mix with the bulk storage volume and enter the distribution system. The contamination resulted in the taste and odour complaints (Hrudey & Hrudey 2004). Distribution system modelling of the flushing program showed that the high school, the fire hydrant where the sample that was positive for *S. typhimurium* was collected, and a number of the residences where people with confirmed cases of salmonellosis lived were located in area that was supplied with water from T300 during the first 6 hours of the flushing program (Clark *et al.* 1996a). As a result, T300 was identified as the point of entry for the contamination that led to the waterborne disease outbreak.

For the period of November 11 to December 27, 1993, approximately 600 residents and visitors to Gideon experi-

enced cases of gastroenteritis, including seven nursing home residents who died (Clark *et al.* 1996b).

RESULTS AND DISCUSSION

Failure of the source protection barrier

Since the Walkerton outbreak is the only case study considered in this paper that involved contamination of the water source, it is the only case that will be used to determine how well the selected risk assessment tools incorporate the source water protection barrier.

Due to the fact that it pumped water from a shallow unconfined bedrock aquifer, Well No. 5 would be considered to be a vulnerable water supply. Surface water could enter the aquifer after undergoing minimal natural filtration, resulting in minimal removal and die-off of bacteria present in surface run-off (O'Connor 2002a). The vulnerability of the aquifer was increased by both natural features and human activities in the area of Well No. 5. There were two springs located within 30 m of Well No. 5 that were hydraulically connected to the water supply aquifer. Potential manmade conduits to the water supply aquifer located near Well No. 5 included fence post holes (O'Connor 2002a) and improperly abandoned water supply wells (Howard 2006).

Based on the input to the B. C. Screening Tool, Well No. 5 would be correctly identified as being vulnerable. The B. C. Screening Tool also identifies livestock, manure storage and application activities, and other wells as potential sources of contamination located within 300 m of Well No. 5.

In the MRA Tool source survey, a high risk score was assigned to the question regarding the water supply aquifer, since Well No. 5 does draw from an unconfined fractured bedrock aquifer that was in need of a Groundwater Under the Direct Influence of Surface Water (GUDI) assessment at the time of the outbreak (O'Connor 2002a). The source survey also identifies potential microbial contaminants in the area of influence (confined animal pens or yards, in this case) and within 60 m of the wellhead (surface water bodies), but the risk score assigned to this question is relatively small compared to risk scores assigned to most other questions in the survey. As a result, the MRA Tool identifies Well No. 5 as being vulnerable as well as identifying some of the activities

responsible for the contamination of Well No. 5, although it is unlikely that the user would consider these hazards to be priorities based on the relatively low risk score assigned to this survey question.

The PWS Tool includes a question regarding stagnant or standing water, such as the springs located near Well No. 5 and the ponds located near Wells No. 6 and No. 7 (O'Connor 2002a). Based on this question alone, all three wells would receive a high risk score. There are additional survey questions regarding livestock rearing, manure storage and land application, and out-of-use wells that would also receive high risk scores for Well No. 5 specifically. However, there are no questions in the PWS Tool that address the vulnerability of the water supply aquifer directly, which may lead the inspector to underestimate the vulnerability of a shallow well that draws from an unconfined bedrock aquifer.

Failure of the treatment barrier

Walkerton case study

As mentioned previously, each of the wells supplying the Walkerton water system was outfitted with a separate chlorination system to achieve primary disinfection prior to the treated water reaching the first user.

With respect to the Walkerton case study, neither the B. C. Screening Tool nor the MRA Tool would have identified any issues with water treatment equipment installed at Wells No. 5, No. 6 and No. 7 at the time of the outbreak. Chlorination alone is generally considered to provide sufficient treatment for a secure groundwater source. However, based on the input to the respective tools regarding the vulnerability of the aquifer that Well No. 5 draws from, the raw water supply does not appear to be secure.

For the B. C. Screening Tool, it would be the responsibility of the DWO to understand that the downstream treatment process must be capable of removing pathogens associated with surface water due to the vulnerability of Well No. 5 to surface contamination. For the MRA Tool, the survey questions and their respective weights for a particular barrier of the water system are not impacted by the input to surveys that address other barriers. As a result, vulnerabilities identified in the source survey (such as Well No. 5 drawing water from an unconfined bedrock aquifer that

may be GUDI) do not have an impact on the risk scores assigned to questions regarding the presence of relevant downstream barriers (such as treatment processes that are capable of removing *Cryptosporidium* oocysts and *Giardia* cysts, pathogens associated with surface water).

The questions included in the PWS Tool for water treatment are geared towards Point of Entry (POE) or Point of Use (POU) treatment systems. POE treatment systems are typically installed near the point where water enters a building, and are associated with the plumbing for that building alone (MOE 2010). POU treatment systems are installed to provide treatment at a point where water is consumed (Scottish Executive 2006). Since these treatment units are typically installed in private residences or commercial buildings by the owner of the premises, operation and maintenance of POE and POU systems are not the responsibility of the owner or operator of the water system in most cases. As a result, the questions regarding water treatment equipment in the PWS Tool do not apply to the water treatment equipment installed at the Walkerton water supply wells.

Greenville case study

Based on the input to the B. C. Screening Tool regarding the treatment equipment serving the Greenville water system, the treatment system appears to be suitable for a groundwater source. In addition to the survey questions regarding the specific treatment processes that are in use, the B. C. Screening Tool includes a question regarding the security of water system infrastructure with respect to tampering and unauthorized access. There is a similar question regarding the vulnerability of intermediate tanks to vermin and surface water access in the PWS Tool. The open-top settling tank and sand filters are clearly vulnerable to tampering and contamination due to animal or human access. As a result, both the B. C. Screening Tool and the PWS Tool identified the vulnerability in the Greenville water system infrastructure that allowed for contamination to enter the system.

For the purpose of the MRA Tool treatment survey, the aeration-settling tank was assumed to be best described as a shallow aeration basin. Air would enter the tank by passing through the screen on top of the tank, but would not undergo any filtration or disinfection prior to coming into contact with the water. The MRA Tool correctly identifies the vulnerability

associated with allowing untreated atmospheric air to come into contact with water. As a result, the MRA Tool also successfully identifies and assigns a relatively high risk score to a survey question addressing the vulnerability in the treatment system that led to the contamination of the treated water.

Failure of distribution and storage barrier

Gideon case study

Both the B. C. Screening Tool and PWS Tool include survey questions that identify the physical vulnerabilities in the construction of T300 that allowed contamination to enter the tank. Both T200 and T300 were inspected on January 12, 1994; municipal officials had no records of any previous inspections being performed on the storage towers (Angulo *et al.* 1997). Both the B. C. Screening Tool and PWS Tool also have survey questions that identify the lack of recent cleaning and maintenance activities prior to the outbreak, activities that could have reduced the amount of contamination that accumulated in the storage tank.

Since there were two municipal storage tanks, the storage survey for the MRA Tool is completed for each tank separately. The total weighted score for the survey question is then calculated based on the scores assigned to each storage tank for that question, and the contribution that each storage tank makes to the total storage capacity for the water system.

The MRA Tool storage survey includes questions that identify the vulnerabilities in the condition of T300, such as the improper vent construction and uncovered access hatch, as well as the lack of a regular inspection and cleaning program. The storage survey question regarding tank cleaning and inspection receives the highest risk score for both water towers. The survey questions regarding the presence of open holes in the tank roof (i.e. the uncovered hatch) and air vent construction receive the second and third highest risk scores, respectively, for T300. However, since there are no records of holes in the roof or poor vent construction for T200, these questions received risk scores of zero for T200. As a result, the contribution that the physical vulnerabilities of T300 make to the total weighted risk score for the storage survey is reduced due to the relatively good condition of T200.

Based on the condition of the system immediately prior to the contamination event that led to the outbreak, a total

score of 0.608 was assigned to the Gideon water system. The total weighted score for the storage survey is 0.104, which represents 17 percent of the total system score. Even if T300 had been the only municipal storage tank in use at the time, the total weighted score for the storage survey would increase only slightly to 0.116, which would be 19% of the total system score of 0.620. The contamination that caused the outbreak entered the Gideon water system through the storage tank T300, but the total weighted score for the storage survey does not properly represent the degree to which the vulnerability of this infrastructure influenced the microbial risk to the water system. This is largely due to the relatively low weighting assigned to the storage survey by the experts who completed the pairwise comparison. Despite the fact that the MRA Tool storage survey includes questions that identify the vulnerabilities in the storage infrastructure and operation of that infrastructure that allowed contamination to accumulate in T300, these vulnerabilities may not be considered a high priority for the implementation of preventative measures or corrective actions due to the relatively small contribution they make to the total water system score.

In hierarchical assessment tools such as the MRA Tool, the phenomenon where the high risk scores assigned to a number of survey questions are not reflected in the aggregated score for the assessment tool is referred to as eclipsing (Sadiq *et al.* 2004). The aggregated score may be sensitive to the aggregation operator used to combine the scores assigned to individual survey question, or the weights assigned to those survey questions. During the development of hierarchical assessment tools, sensitivity analyses can be used to determine the impact that changes in the aggregation operator or weighting have on the output of the assessment tool (Sadiq *et al.* 2004).

Ideally, a risk assessment tool should be designed such that it maintains the high risk scores assigned to components of the water system that only receive a fraction of the system flow, or are used on an intermittent or rare basis. A vulnerability that is present in one component of a system can lead to the failure of the entire system (McBean & Rovers 1998).

Failure of the monitoring barrier

The Walkerton and Greenville case studies, where contamination entered the water system prior to or during the treatment process, emphasize the importance of raw water

and treated water monitoring in addition to monitoring water quality in the distribution system. As a result, these case studies will be used to determine whether the different tools detect deficiencies in monitoring activities at the source, during treatment, and in the distribution system.

Walkerton case study

At the time of the outbreak, no continuous chlorine or turbidity monitoring equipment was in use. Grab samples for analysis of free chlorine and microbial parameters were collected by Walkerton PUC personnel (O'Connor 2002a). Sampling frequencies and parameters were listed in the Ontario Drinking Water Objectives based on the service population of the water system. At the time of the outbreak, Walkerton PUC personnel should have been collecting raw and treated water samples from all operating wells on at least a weekly basis, in addition to twelve distribution samples per week (MOE 1999). Based on sampling records for the period of October 1996 to April 2000 (O'Connor 2002a), PUC personnel may have been submitting a sufficient number of raw and treated samples, but were collecting a fraction of the distribution samples that were required.

Over the period of October 1996 and April 2000, raw water samples from all three wells had had positive total coliform results (O'Connor 2002a). Immediately prior to the outbreak, three of four raw water samples collected from Well No. 5 in April 2000 tested positive for total coliform bacteria, as well as two treated water samples collected downstream from Well No. 5 on April 3 and April 17, and two distribution samples collected on April 3. The presence of coliform bacteria in multiple distribution samples that were submitted on the same date would be considered an indication of unsafe water quality (MOE 1999).

The B. C. Screening Tool includes separate sections addressing source water and tap water quality that would have identified the on-going issues with raw and distribution water samples exceeding the relevant standards for health-related parameters. The B. C. Screening Tool also identifies the lack of alarmed continuous chlorine or turbidity monitoring equipment. The installation of continuous free chlorine monitoring systems was identified by Justice O'Connor as a measure that would have prevented the outbreak (O'Connor 2002a).

The MRA Tool includes questions regarding historical monitoring results in the source and distribution surveys, and questions regarding continuous monitoring equipment and alarms in the treatment surveys. The MRA Tool also has a separate monitoring survey that collects information regarding the frequency and parameters included in the raw, treated, and distribution monitoring programs, although this survey typically makes a minimal contribution to the overall score for the water system due to its relatively low weighting. For each of the wells, the highest risk score in the source survey was assigned to the question regarding historical microbial contamination, due to the positive total coliform results between October 1996 and April 2000. The second highest risk score in the treatment survey was assigned to the question regarding disinfection system monitoring alarms, based on the lack of alarmed continuous monitoring equipment for chlorine. The third highest risk score in the distribution survey was assigned to the question regarding residual disinfection, based on expert testimony at the Walkerton Inquiry that suggested the free chlorine residual in the distribution system was very low (O'Connor 2002a). In summary, the treatment survey question regarding monitoring equipment helps identify one of the vulnerabilities that lead to the outbreak. The questions in the source and distribution surveys regarding historical monitoring results identify historical adverse water quality results, but do not identify the hazards or vulnerabilities that led to those results.

A question in the "front end" of the PWS Tool regarding sample results for the previous 12 months would bring the monitoring results for April 2000 to the attention of the inspector. In addition, the supply survey includes questions regarding fluctuations in the well water level and in the raw water colour or turbidity after storm events. Fluctuations in water and turbidity levels were recorded for Well No. 5 in inspection reports completed by MOE environmental officers over the period of 1978 to 1980 (O'Connor 2002a). As a result, these questions would receive high risk characterization scores, and would ensure that the inspector was aware of the vulnerability of Well No. 5.

Greenville case study

Based on raw water monitoring results for the period of 1980 to 1984, the water supply well serving the Greenville water

supply appears to be a secure water source with no historical contamination. Published literature indicates that there were no adverse water quality results in the months leading to the outbreak (Sacks *et al.* 1986).

Both the B. C. Screening Tool and the MRA Tool identify the vulnerability with respect to the absence of alarmed continuous free chlorine monitoring equipment. If monitoring alarms were present, they would not have prevented the contamination from entering the aeration/settling tank, but would have notified the operator when the pre and post-chlorination systems failed, which would have limited the scope of the outbreak. There are no questions regarding continuous monitoring equipment in the PWS Tool.

Failure of the response barrier

There is far better documentation regarding the response on the part of the Walkerton PUC and the relevant governmental agencies during the Walkerton outbreak than there is for the other outbreaks discussed herein. As a result, the Walkerton outbreak will be used to determine how well the selected risk assessment tools incorporate the response barrier.

As stated earlier, the laboratory notified the Walkerton PUC that the majority of the samples collected on May 15, 2000 were positive for both *E. coli* and total coliform bacteria on May 17. Although Walkerton PUC personnel did increase the chlorine feed rate and flush the distribution system over the period of May 19 to May 22 in an attempt to address the problem, Walkerton PUC staff did not share the adverse water quality results until May 22, 2000, despite receiving phone calls from the MOE Spills Action Centre (SAC) and the PHU regarding the safety of the water supply in the meantime (O'Connor 2002a). Sharing the relevant information regarding the adverse water quality results and the recent operational history of the drinking water system and coordinating corrective actions with governmental agencies would have likely reduced the scope of the outbreak significantly. Regardless of the lack of communication, a Boil Water Advisory (BWA) was issued on the afternoon of May 21, 2000 after the first case of *E. coli* had been confirmed based on a patient's stool sample and a second presumptive positive case was reported (O'Connor 2002a).

Both the B. C. Screening Tool and the MRA Tool include questions regarding corrective actions taken by operators

in the event of a potential health risk, or a positive total coliform result specifically. With respect to the Walkerton water system, the corrective actions performed after receiving an adverse water quality result were generally minimal. The flushing of the distribution system from May 19 to May 22 was the first time the distribution system had been flushed in response to an adverse result (O'Connor 2002a). As a result, both of these tools would have identified the lack of appropriate corrective actions taken by Walkerton PUC personnel.

A similar question is included in the "front end" of the PWS Tool, although the wording in the Technical Guide suggests that this question provides the inspector and the relevant person(s) associated with the water system the opportunity to identify and agree on actions that can be taken to prevent future adverse water quality results, not actions that should be taken to respond to an adverse water quality result that has occurred. The MOE had most recently inspected the Walkerton water system in February 1998. The inspection report outlined action items that were necessary to bring the Walkerton water system into compliance with provincial treatment and sampling objectives (O'Connor 2002a). There is no indication that the report addressed corrective actions in the event of future adverse water quality incidents.

Water safety and emergency response plans should provide water system personnel with detailed instructions regarding "well-conceived, thorough and effective" (Hrudey & Hrudey 2002) actions to be taken in response to an event such as a waterborne disease outbreak, loss of the water supply, or any other significant event that would impact the ability of the water system to supply consumers with a safe drinking water supply. A survey question included in the B. C. Screening Tool asks whether the water system in question has an approved Emergency Response Plan; the PWS Tool has a similar question regarding a Water Safety Plan. Of the three risk assessment tools, the PWS Tool is the only one that requires the user to assess the water safety or emergency response plan and identify any deficiencies (Scottish Executive 2006). An Emergency Plan had been developed in accordance with the Emergency Plans Act for the Municipality of Brockton (O'Connor 2002a), where Walkerton is located. However, the Brockton Emergency Plan would not have been developed to respond to a waterborne disease outbreak.

Response activities are generally not addressed as well as the infrastructure barriers in the existing risk assessment tools. This is likely due to the relatively large amount of effort and involvement that would be required to review existing emergency response procedures and determine whether the procedures are suitable for the water system and can be implemented effectively by personnel. Such a review could not be easily completed as part of an on-site assessment by an inspector from a regulatory authority or third party.

The Drinking water quality management standard (DWQMS) developed by the Ontario MOE requires municipal water systems to develop a list of potential emergencies that could have an impact on the operation of the individual components or the water system as a whole, and develop and implement emergency response procedures (MOE 2007). The DWQMS recommends that these procedures be reviewed and updated on an annual basis, and that the review process be documented (MOE 2007). These review documents can then be made available to internal and external auditors, in addition to the emergency response procedures themselves. Regular, documented internal reviews and testing of emergency response procedures could allow an auditor or inspector to assess the suitability of procedures and documentation that represent the response barrier for a water system in a relatively short period of time compared to the inspector completing an individual review of each document.

CONCLUSIONS

The three case studies evaluated in this research, which represent drinking water outbreaks that occurred due to contamination of the water supply at different points from the source to the tap, illustrate the issues associated with incorporating the Multiple Barrier Approach.

While each of the risk assessment tools incorporated the MBA to some extent, the barriers are typically addressed independently, such that vulnerabilities in upstream barriers do not have an impact on downstream barriers. Waterborne disease outbreaks usually occur due to the failure of more than one barrier (O'Connor 2002b; Hrudey & Hrudey 2007). The Walkerton case study in particular emphasizes the impact that vulnerabilities in upstream barriers can have on downstream barriers. Each of the selected tools was capable of identifying

some of the hazards and vulnerabilities associated with the contamination of Well No. 5, but none of the tools identified the need for a more robust treatment system as a result. To address this shortcoming, future risk assessment tools could modify the survey questions regarding the treatment barrier and the respective weights of those questions based on the vulnerabilities that are identified in the source barrier. If properly implemented, these changes to the programming of the risk assessment tool would ensure that the treatment survey for a GUDI source includes questions regarding the ability of the existing treatment infrastructure to remove pathogens associated with surface water contamination.

Calculating qualitative or semi-quantitative risk scores for a water system provides easily interpreted output that shows the user the components of the water system that are most in need of corrective action. However, if these risk scores are aggregated in a hierarchical assessment tool in order to calculate a total risk score for an individual barrier or for the water system as a whole, the total risk score must be calculated in such a way that a high risk score assigned to a specific question or barrier is not diluted or eclipsed by relatively low risk scores assigned to other survey questions or barriers. The questions included in the MRA Tool storage survey identified the vulnerabilities in the construction and current condition of the T300 municipal water storage tank that led to the outbreak in Gideon, Mo. However, the contribution that these vulnerabilities made to the total score for the storage barrier was reduced due to the relatively good condition of the T200 water storage tank, and the contribution of the storage survey to the total risk score for the water system was limited by the relatively low weighting assigned to the storage survey. The PWS risk assessment tool avoids the problem of eclipsing by not assigning weights to individual survey questions. Instead, the highest risk characterization score assigned to a survey question is selected as the score for that survey. While this strategy prevents the risk associated with a water system from being understated due to eclipsing, it may lead to the risk being overstated in some cases. Future risk assessment tools will need to use aggregation operators and methods of assigning weights to individual survey questions that balance the issues of eclipsing and overstating.

In general, the selected risk assessment tools identified hazards and vulnerabilities associated with the water system

infrastructure that provide barriers to contamination, but did not focus on the response barrier. Water system owners and operators should not wait until water quality issues occur to test their corrective action and emergency response procedures. Thoroughly documented desktop and field exercises can help ensure that the existing procedures are suitable and can be implemented by water system personnel. In addition, the records from these exercises could be evaluated by the regulatory authority or a third party as part of the risk assessment for the water system, in order to allow for the response barrier to be assessed without an outbreak occurring.

During the development of new risk assessment tools, historic waterborne disease outbreaks can be used as desktop case studies to ensure that the tools incorporate the MBA and address the shortcomings of the existing tools. In addition, field verification testing will be necessary to ensure that the risk assessment tool remains user friendly, and can typically be completed based on observations and documentation that are typically available during the inspection of a small drinking water system.

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