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Evaluation of Risk Assessment Tools to Predict Canadian Waterborne Disease Outbreaks

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A number of risk assessment tools and guidance documents have been developed by regulatory and nongovernmental bodies to enable risk assessment of drinking water systems. To evaluate the strengths and weaknesses of available risk assessment tools, three of the existing risk assessment tools were applied to waterborne disease outbreaks in North Battleford, Saskatchewan, and Walkerton, Ontario, to determine whether the risk assessment tools would have indicated that the water systems were at risk of failure. Both of these outbreaks are sufficiently well documented to allow testing of the risk assessment tools. Both of the outbreaks occurred partly due to vulnerabilities that prevented the respective water systems from having effective multiple barriers to drinking water contamination. The risk assessment tools generally identified the hazards that resulted in contamination of the source water. However, the different tools had different levels of success in identifying vulnerabilities in the downstream barriers such as treatment processes and water quality monitoring activities. None of the risk assessment tools successfully incorporated the interdependent nature of the multiple barriers of drinking water safety.

***Key words*: drinking water, risk assessment, Walkerton, North Battleford, multiple barrier approach**

Introduction

A number of drinking water risk assessment tools have been developed by various regulatory agencies. Some of the tools include specific survey questions regarding water quality data, operation and maintenance practises, and the presence and robustness of barriers to prevent contamination of the drinking water supply. Basing the risk assessment and ranking process on clearly worded surveys that address water system infrastructure, operation, and performance helps to promote a thorough risk assessment process that reduces variability between users in the risk assessment output, based on their level of expertise or familiarity with the drinking water system.

For the purpose of this paper, the British Columbia Drinking Water Source-to-Tap Screening Tool (B.C. Tool) (Ministry of Health Services and Ministry of Water, Land and Air Protection 2005), the Montana Water Center Microbial Risk Assessment Ranking Tool (MRA Tool) (Montana Water Center 2010), and the risk assessment forms in the Scottish *Private Water Supplies: Technical Manual* (PWS) (Scottish Executive 2006) were applied to drinking water systems that have been implicated in waterborne disease outbreaks to determine whether these tools can identify the hazards and vulnerabilities that resulted in the respective outbreaks. These tools were selected because they include specific risk assessment surveys that address different aspects of the water system. Although the tools have some common survey questions, they use different scoring systems to identify and rank risks and have varying levels of involvement from regulatory authorities.

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To test the utility of the three risk assessment tools, they were applied to the waterborne disease outbreaks that occurred in North Battleford, Saskatchewan, and Walkerton, Ontario, in order to determine whether they could identify the issues that led to the failure of these water systems. Both outbreaks were followed by inquiries that investigated the circumstances that led to the respective outbreaks. The conditions of the water systems at the time of the respective waterborne disease outbreaks have been documented in the reports compiled from these inquiries. Hence, this research used the available information regarding the condition of the water systems prior to the contamination events that led to the respective outbreaks as input to the risk assessment tools. The intent was to determine whether these tools would have identified the hazards that ultimately led to the outbreak, and to determine the degree to which the tools identify the strengths and vulnerabilities associated with the barriers to drinking water contamination present at each system prior to the respective outbreaks. Given the nature of the two outbreaks, this paper will focus on the source protection, treatment, and monitoring aspects of the multiple barrier approach to drinking water safety.

Selected Risk Assessment Tools

B.C. Tool

Under Part 3 of British Columbia's *Drinking Water Protection Act*, the drinking water officer (DWO) may order a water supplier to complete a drinking water assessment if the DWO "has reason to believe that an assessment is necessary to properly identify and assess threats" to drinking water quality (Ministry of Healthy Living and Sport 2009). The B.C. Tool represents the first tier of the assessment process (Ministry of Health Services and Ministry of Water, Land and Air Protection 2005).

The B.C. Tool is used to compile information regarding the operation and management of the water system, the quality of tap water supplied by the system, the water system infrastructure, and chemical and microbial hazards that could enter the water supply. The B.C. Tool is completed by the water supplier and submitted to the DWO for review (Ministry of Health Services and Ministry of Water, Land and Air Protection 2005). In the event that the DWO feels that potentially significant risks have been identified based on the input to the B.C. Tool, the DWO may issue an order for the supplier to complete selected modules of the B.C. comprehensive drinking water source-to-tap assessment process (source-to-tap assessment process) in order to further investigate and assess the identified risks. The modules are completed by a multidisciplinary team of qualified professionals with experience relevant to drinking water systems (Ministry of Health Services and Ministry of Water, Land and Air Protection 2005). The hazards identified when completing any of modules 1 through 6 are then ranked using a qualitative risk assessment procedure as part of module 7. A flowchart of the source-to-tap assessment process is included as Fig. 1.

For the purpose of this study, it was assumed that a qualified DWO would have an undergraduate degree in science or engineering, several years of professional experience in the drinking water field, and would have completed any necessary job-specific training programs with respect to the source-to-tap assessment process. It stands to reason that if the DWO orders the water supplier to complete a risk assessment module addressing a particular aspect of the drinking water system based on the input to the B.C. Tool, the assessment team would identify the hazards and vulnerabilities associated with that aspect of the system when completing the module. If for some reason the DWO did not have sufficient experience with small drinking water systems or the necessary training with respect to the source-to-tap assessment process to identify a potential hazard or vulnerability based on the input to the B.C. Tool, then the DWO would be less likely to order the supplier to complete the risk assessment module relevant to that hazard or vulnerability. As a result, the risk assessment team would be more likely to overlook that hazard or vulnerability when completing the modules included

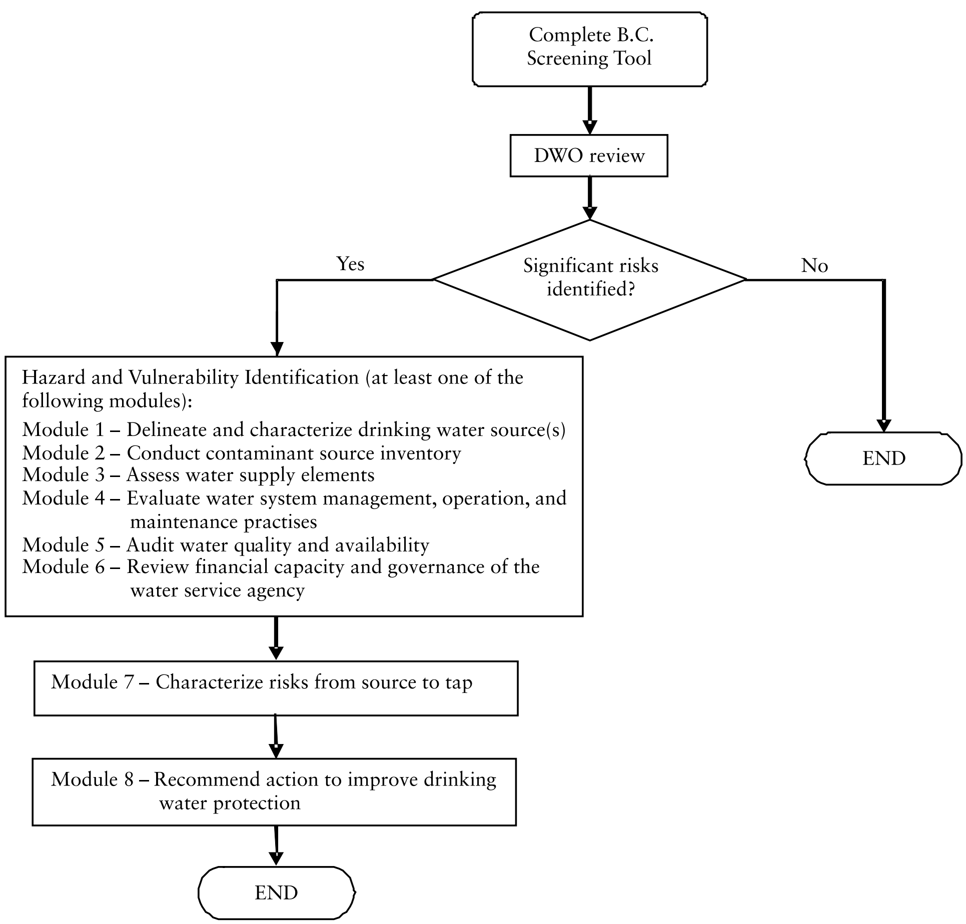

Fig. 1. British Columbia comprehensive source-to-tap risk assessment flowchart.

in the order, which would limit the effectiveness of the source-to-tap assessment process.

In this manner, the ability of a qualified DWO to identify hazards and vulnerabilities based on the input to the B.C. Tool was used to determine whether the source-to-tap assessment process would identify the factors that led to the waterborne disease outbreaks in North Battleford and Walkerton.

MRA Tool

The MRA Tool is available from the Montana Water Center at Montana State University and the National Environmental Science Center at West Virginia University (Montana Water Center 2010). The MRA Tool is meant to assist small water system operators and managers in identifying potential microbial risks and corrective actions that can be taken to manage those risks. Using the MRA Tool does not eliminate the need for a sanitary survey or vulnerability assessment of the water system (Butterfield and Camper 2004).

The MRA Tool is available as a Microsoft Excel spreadsheet. The MRA Tool includes a number of different survey forms specifically tailored to alternative water supplies (i.e., streams and rivers, lakes and impoundments, wells, or springs) and treatment systems (i.e., treatment of groundwater or surface water), as well as survey forms addressing other water system infrastructure and water quality monitoring activities (Butterfield and Camper 2004). A flowchart for the MRA Tool is included as Fig. 2.

Based on the input from the operator, each survey question receives a numerical risk score ranging from 0 to 1 (Butterfield and Camper 2004). The MRA Tool provides comments and recommendations regarding measures that can be taken to reduce the risk associated with survey questions that receive high relative risk scores. The relative risk scores associated with each question for a particular survey are weighted and summed to calculate a total microbial risk score for the survey, which is also in the range of 0 to 1. The risk scores for all surveys are then weighted and summed again to determine the overall risk score for the water system (Butterfield and Camper 2004).

The weights assigned to the survey questions were calculated using the ranked pairwise comparison method (Saaty 1980). The version of the MRA Tool that is available to the public does not list the weights, nor does it allow the user to access the matrices used to calculate the weights. If the user does not agree with relative risk scores assigned to the individual survey questions, the user can request access to the Excel spreadsheet that was used to calculate the weights from the developers of the MRA Tool. The weights can then be adjusted by having an expert complete the pairwise comparison matrices (Butterfield and Camper 2004). Since the MRA Tool is

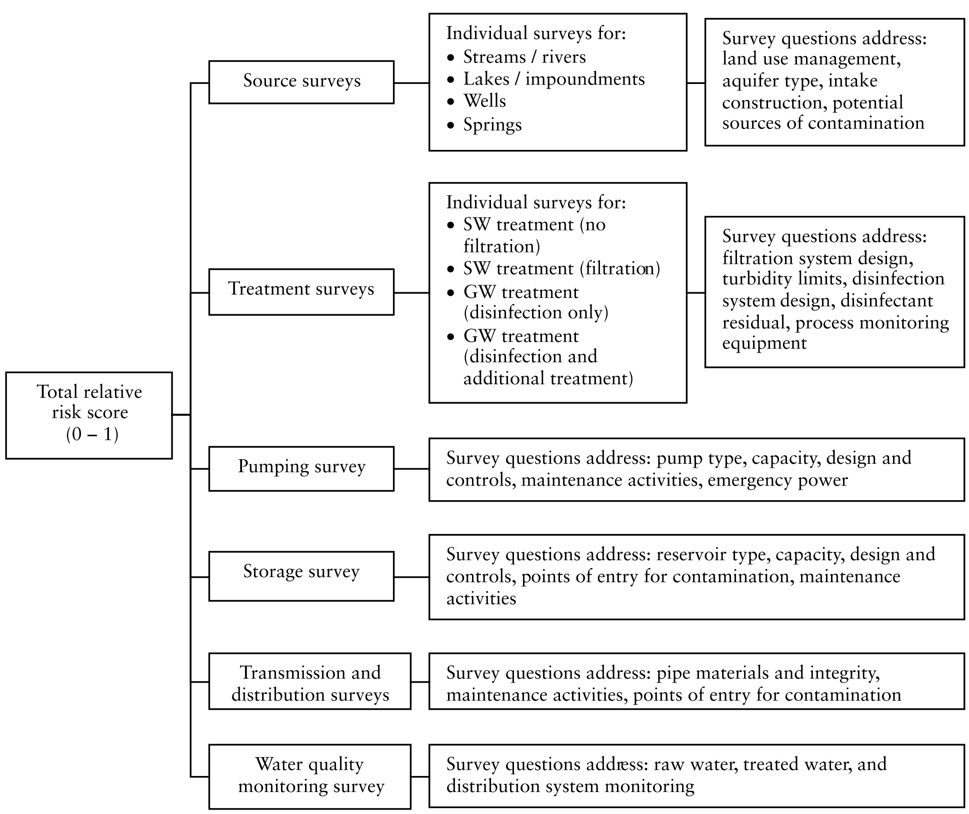

Fig 2. MRA tool schematic.

meant to be used by the owner or operator of a small water system, and small water system personnel are unlikely to have the necessary risk assessment expertise to make accurate revisions to the weights (Butterfield and Camper 2004), the default weights were not adjusted for the purpose of this study.

The inquiry reports and other literature published regarding the waterborne disease outbreaks generally focused on the hazards or vulnerabilities of the water systems that led to the waterborne disease outbreaks. As a result, the authors made assumptions that they felt were reasonable in order to complete the survey forms for water system components that were not implicated in the outbreaks. The risk scores associated with the different components of the water system were then compared to determine if the MRA Tool correctly identified the aspects of the water system that contributed to the waterborne disease outbreak.

PWS Risk Assessment Forms

This risk assessment process is completed by the local authority with input and assistance from the "Relevant Persons" responsible for the water supply (Scottish Executive 2006). An assessment is completed when a new water supply is brought into service, an existing supply is returned to service after being out of use for a period of greater than one year, or if the local authority has reason to believe the water supply is no longer "wholesome" (The Scottish Ministers 2006).

The PWS includes separate risk assessment forms for different water supplies (surface water supplies, springs, wells, and boreholes). Each risk assessment form has common sections that collect information regarding relevant contact information, historic water quality data, and the results of past risk assessments. The inspector must also complete a process flow diagram for the water system in this section. The information required to complete the General Site Survey, Supply Survey, and Soil Leaching Risk Survey (for springs and wells only), varies depending on the type of water supply (Scottish Executive 2006). Since neither of the water systems reviewed in this paper were supplied by springs or wells (i.e., dug or sand point wells), the Soil Leaching Risk Survey could not be assessed.

Each survey has two scores associated with it: the risk characterization and the hazard assessment scores (Scottish Executive 2006). Qualitative risk characterization scores are assigned to survey questions regarding the presence or absence of hazards and vulnerabilities that could have an impact on water quality. For each survey question, the user must answer "yes," "no," or "don't know." One of three risk characterization scores (high, medium, or low) is preselected for each of the potential answers. The highest risk characterization score for a survey question is recorded as the risk characterization score for that survey (Scottish Executive 2006).

The hazard assessment score uses a semiquantitative risk assessment procedure (Scottish Executive 2006). The user selects a likelihood score based on a five-point nonordinal scale, where a score of 1 represents a hazard that is rarely present and a score of 16 represents a daily or permanent hazard. The severity is scored based on the same five-point nonordinal scale, and is preselected on the survey form for each question. The likelihood and severity scores are multiplied to determine the hazard assessment score, which is considered to be "an index with no implied mathematical relationship to risk" (Scottish Executive 2006). The maximum hazard assessment score is 256; the PWS recommends that a threshold score of 16 be used to prioritize hazards for corrective action (Scottish Executive 2006). A flowchart for the completion of one of the survey questions listed in a PWS risk assessment form is included as Fig. 3.

Completing the General Site Survey and the Supply Survey for this tool requires a detailed survey of potential chemical and microbial hazards in the vicinity of the source, as well as vulnerabilities present based on the current condition of the source and other water system infrastructure. Since all of the survey questions could not be accurately answered based on published information for the selected case studies, the authors made assumptions that they felt were reasonable in order to complete the survey forms. In the event that the MRA Tool and PWS risk assessment forms included similar questions that could not be answered based on published information, the same assumption was made when completing both risk assessment tools.

Case Studies

North Battleford, Saskatchewan

Background. The City of North Battleford is located on the north banks of the North Saskatchewan River, approximately 140 km northwest of the City of Saskatoon. At the time of the outbreak, the City had a population of approximately 15,000 (Hrudey and Hrudey 2004).

The North Battleford distribution system is served by two water treatment plants, a groundwater treatment plant (GWTP) and a surface water treatment plant (SWTP). Since the GWTP was not implicated in the outbreak, it will not be discussed further.

The SWTP receives raw water from a surface water intake located in the North Saskatchewan River. According to the North Battleford Water Inquiry, the SWTP did not operate continuously, but provided supplemental flow to the GWTP (Laing 2002). At the time of the outbreak, water treatment chemicals added prior to the solids contact unit (SCU) included coagulants, oxidizing agents to oxidize organic compounds that can cause taste and odour issues, and chlorine to achieve primary disinfection. No rapid mixing was provided prior to water entering the SCU to promote coagulation or mixing of the disinfectant and the raw water. In the SCU, a polymer was added to assist with flocculation, and lime was added to adjust the pH. The effluent from the SCU was directed to one of two sets of two multimedia

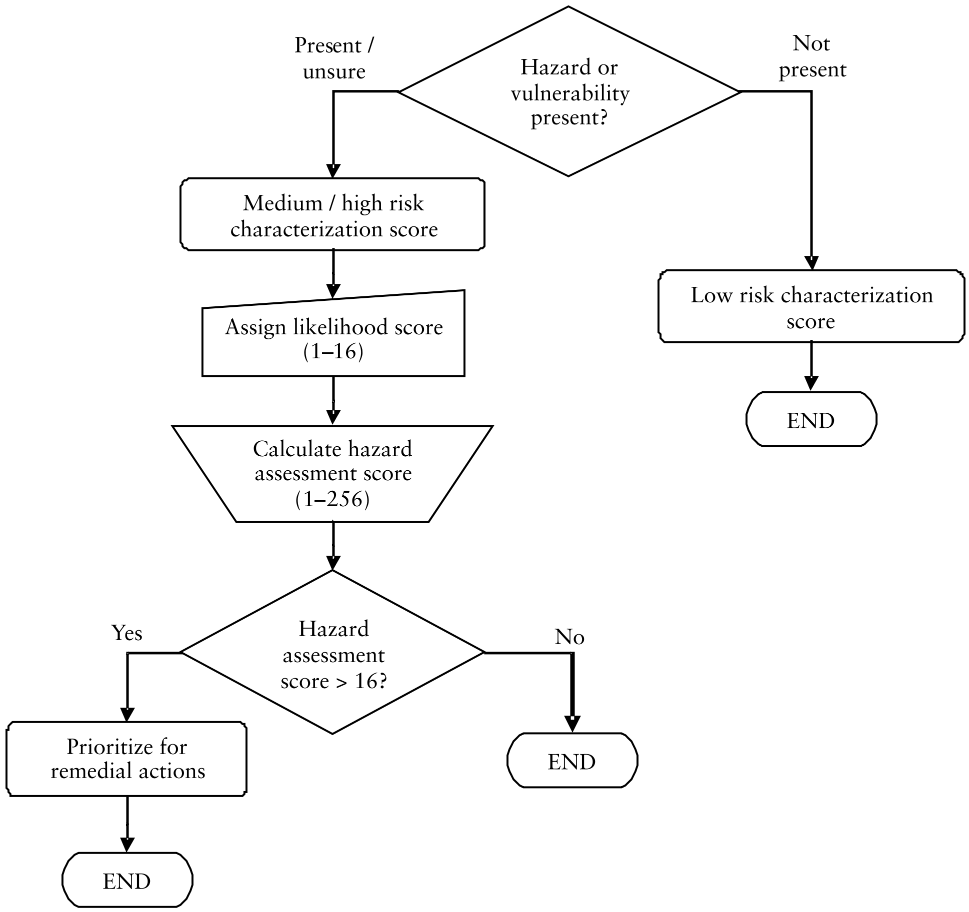

Fig. 3. PWS risk assessment form flowchart.

filters piped in parallel. The effluent from the filters then entered the clear wells (Laing 2002).

According to the North Battleford Water Inquiry, the SWTP was shut down in order to repair a crack in the floor of the SCU on March 20, 2001. The SCU was completely drained such that there was no remaining sludge blanket. When repairs were completed, the SWTP was returned to service after a relatively short commissioning period, despite the fact that negligible settling was being achieved in the SCU (Laing 2002). The poor performance of the SCU resulted in the multimedia filters being backwashed on a more frequent basis. Since filters No. 3 and No. 4 were not designed with "filter-to-waste" capabilities, and the SWTP operators were not in the practise of directing effluent from filters No. 1 and No. 2 to waste after a backwash cycle was completed (Hrudey and Hrudey 2004), water that had undergone minimal solids removal entered the clear wells and was eventually pumped to the distribution system. The SCU continued to achieve negligible settling until April 24, 2001. Due to evidence of gastroenteritis in the community and the poor settling in the SCU, a Precautionary Drinking Water Advisory (PDWA) was issued on April 25, 2001, and was upgraded to a boil water order the following day. The boil water order remained in effect until July 25, 2001 (Laing 2002).

The first confirmed case of cryptosporidiosis was identified on April 4, 2001 (Laing 2002); a total of 275 cases were confirmed for residents and visitors to the City by May 2001 (Stirling et al. 2001). An estimated 5,800 to 7,100 area residents suffered from gastroenteritis between March 20 and April 26, 2001 (Laing 2002).

Results for B.C. Tool. Based on the input to the B.C. Tool, a number of hazards were identified that could impact the water quality in the North Saskatchewan River. Although little information was available regarding potential sources of contamination within 50 m of the surface water intake, a number of sources were identified within the watershed. Livestock operations and municipal wastewater treatment plant (WWTP) operations are two activities present in the watershed that represent potential sources of *Cryptosporidium* oocysts (Laing 2002).

To complete the treatment survey of the B.C. Tool, the water supplier would have indicated that treatment at the SWTP consisted of the addition of chlorine to achieve primary disinfection, the SCU (which generally provided coagulation, flocculation, and sedimentation), and then filtration. Based on this limited information, the DWO would have likely concluded that the SWTP was capable of treating a surface water source, despite the lack of alarms for chlorine dosing and monitoring equipment.

However, information collected in other sections of the B.C. Tool regarding historical water quality issues, including a previous PDWA due to total coliform counts and low free chlorine levels in the distribution system in September 2000 (Laing 2002), would have suggested that the SWTP was probably not achieving optimal performance. As a result, it is likely that the DWO would order the water supplier to perform an assessment of water system infrastructure (Module No. 3), which would have identified vulnerabilities in the design of the SCU, filters, and chlorination equipment. In addition, the order would likely also require the owner to complete the following modules:

- Module 1, which would have demonstrated the highly variable levels of turbidity and *Cryptosporidium* oocysts in the raw water supply (Laing 2002), assuming that the assessment team requested relevant monitoring data collected by larger upstream municipalities;
- Module 2, which would have identified sources of microbial contamination in the watershed;
- Module 5, which would have identified historical trends in raw, treated, and distribution water quality, and the effect that variations in raw water quality and treatment performance have had on distribution water quality in the past.

Modules 7 and 8 would be completed based on the identified hazards and vulnerabilities. By completing these modules, the risk assessment team would have identified the hazards and vulnerabilities associated with the surface water source and SWTP that led to the waterborne disease outbreak in North Battleford. However, the time and resources required to complete the process, from the submission of the screening tool by the water supplier through to the completion of the qualitative risk assessment and risk assessment identification modules, would not result in the hazards and vulnerabilities being addressed promptly.

Results for MRA Tool. Since the GWTP was not implicated in the outbreak, the MRA Tool surveys that address the groundwater wells and GWTP infrastructure were not completed. Based on the information input to the MRA tool spreadsheet, the North Battleford water system received a relatively high overall risk score of 0.537. The components of the water system that made the greatest contribution to the overall risk score were the surface water (SW) source (0.214, 39% of the overall score), the SWTP (0.143, 26% of the overall score), and the distribution system (0.074, 14% of the overall score).

The SW survey question that received by far the highest risk score addressed upstream wastewater discharges. The risk score assigned to this question was approximately twice that of the second-highest risk score, which was assigned to the question regarding upstream stormwater discharges. The survey question regarding stormwater discharges addresses potential discharges from livestock activities as well as from urban areas. The SW survey identified and assigned significant risk scores to the two hazards in the watershed that are most likely to have resulted in *Cryptosporidium* oocysts entering the North Saskatchewan River.

The two SWTP survey questions that received the highest risk scores address the percent of time that the SWTP met treatment requirements with respect to CT limits—where CT is calculated by multiplying the effluent residual disinfectant concentration in milligrams per litre by contact time in minutes—and turbidity limits, respectively. It was assumed that each of these limits was met 90% of the time, which may in fact be an underestimate that would result in artificially high risk scores for these questions. It is also worth noting that these questions do not address hazards or vulnerabilities associated with the operation of the SWTP directly, but are based on available monitoring data. Typically, one would expect this information to be used as a line of evidence in the risk assessment process instead of it receiving a risk score directly. The SWTP survey question that received the third highest risk score addresses the lack of alarms associated with the disinfection system. Connecting the gas chlorination system and the clear well chlorine monitoring equipment to an alarm system would alert operators when the disinfection equipment failed or water entered the clear wells with a low chlorine residual. While this would not have prevented the waterborne disease outbreak in North Battleford, it would help promote adequate inactivation of other pathogens, such as *Giardia* cysts and viruses, in the clear wells.

The MRA Tool requires far more information regarding the design of the treatment system than the other two risk assessment tools that were evaluated as part of this study. As a result, the MRA treatment survey identified design flaws in the SWTP, including the absence of rapid mixing prior to water entering the SCU and the inability to filter-to-waste prior to returning the multimedia filters to service after a backwash cycle. However, the risk scores assigned to these survey questions were relatively low, so it is highly unlikely that they would be identified as areas where remedial action was necessary based on the results from the MRA Tool.

While the SWTP survey identified issues with the performance and the design of the SWTP, it did not identify the operating decisions that led to the cryptosporidiosis outbreak. It would require a significant increase in the number of survey questions regarding plant operations in order to determine that sludge was completely drained from the SCU in order to complete repairs, and that there was poor settling in the SCU when it was returned to service. Further increasing the number of survey questions would increase the effort required to complete the tool, making it less user-friendly. A more effective solution might be to modify the tool to focus on the design of the SWTP and the lack of multiple barriers with respect to *Cryptosporidium* removal or the lack of redundancy with respect to the SCU. The presence of multiple barriers that are capable of removing or inactivating pathogens is particularly important for raw water sources that contain *Cryptosporidium* (Jameson et al. 2008). This would allow the MRA Tool to better represent the integrated nature of the multiple barrier approach to drinking water safety.

The highest risk score for the distribution survey was assigned to the question regarding dead ends and low flow areas in the distribution system. The risk score was not based on the presence of these low flow areas so much as the results of recent sampling activities performed in these areas, such as the positive total coliform and low residual chlorine results that led to the September 2000 PDWA (Laing 2002). The other survey question to receive a relatively high risk score addresses residual disinfection and whether the free chlorine concentration drops below 0.2 mg/L in the distribution system. As a result, the low residual disinfectant concentrations in the distribution system is identified twice in the distribution survey, making the risk score for the distribution system highly dependent on water quality monitoring results. While the presence of coliform bacteria or low chlorine residuals does indicate a water quality problem, it does not help to identify the source of that problem.

Results for PWS surface water risk assessment form. Although the risk characterization and hazard assessment scores for the water system are based on the information input in the General Site Survey and Supply Survey, information that is relevant to the risk assessment process is also collected in the "front end" of the risk assessment forms. The question regarding water quality results for the previous 12 months would bring the September 2000 PDWA to the attention of the inspector.

For the purpose of evaluating the risk assessment form, it was assumed that any activity that is known or assumed to occur in the North Saskatchewan River watershed could impact water quality at the intake. As a result, survey questions regarding the following hazards were assigned high risk characterization scores:

- Livestock production, which would be a permanent feature due to the presence of cattle operations in the watershed;
- Surface runoff from agricultural activities, which was assumed to occur during storm events and snowmelt;
- Land application of manure, which was likely to occur based on the cattle operations present in the watershed;
- Sewer lines and the WWTP discharge, which was located approximately 3.5 km upstream of the SWTP intake (Laing 2002).

Both the livestock production and WWTP discharge questions received the maximum hazard assessment score of 256. The activities in the watershed that represent the likely source of *Cryptosporidium* oocysts in the North Saskatchewan River were identified and received high hazard assessment scores.

The questions in the Supply Survey were applied to all infrastructure associated with the SWTP and distribution system. The survey question regarding the integrity of piping material received a high risk characterization score because the majority of the distribution system piping was constructed of asbestos cement (MR2-McDonald and Associates 2006). The PWS specifically identifies asbestos concrete as a piping material that is likely to fracture or deteriorate (Scottish Executive 2006). The two other survey questions that received high risk characterization scores addressed fluctuations in the flow and quality of the source water. Based on these results, the PWS surface water risk assessment form does not address water treatment or operational practises in sufficient depth to identify the vulnerabilities in the SWTP.

Walkerton, Ontario

Background. Walkerton is a rural community located in Bruce County, Ontario. At the time of the outbreak, the town had a population of approximately 4,800 (Hrudey and Hrudey 2004).

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. Based on the *Report of the Walkerton Inquiry*, each well was completed in an unconfined fractured bedrock aquifer (O'Connor 2002). Well No. 5 was completed at a shallow depth of 15 m; Well No. 6 and Well No. 7 were significantly deeper (72.2 and 76.2 m, respectively). Each well was outfitted with a separate chlorination system to achieve primary disinfection prior to the treated water reaching the nearest consumer (O'Connor 2002).

According to the *Report of the Walkerton Inquiry*, the accumulated rainfall for the Walkerton area over the period of May 8 to 12, 2000 was 134 mm, which was equivalent to a 60-year storm event for this area in the month of May (O'Connor 2002). 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, with the exception of a period of approximately 16 hours between the evening of May 12 and the afternoon of May 13 when it was shut down (O'Connor 2002). Since Wells No. 6 and No. 7 were not implicated in the outbreak, they will not be discussed further.

According to the Report of the Walkerton Inquiry, Walkerton Public Utilities Commission (PUC) staff recorded free chlorine residual concentrations of 0.75 mg/L for treated water from Well No. 5 on May 13, 14, and 15. It is unlikely that the recorded numbers were accurate, as PUC staff often falsified records with respect to free chlorine levels (O'Connor 2002). On May 15, PUC staff collected several water samples, a number of which may have been labelled with the incorrect sampling location (O' Connor 2002), and shipped them to a private laboratory for microbiological analysis. On May 17, the PUC was notified that the majority of these samples were positive for both *Escherichia coli* and total coliform bacteria. PUC staff increased chlorine feed rates and began flushing the distribution system on May 19, 2000. PUC staff withheld the adverse water quality results from the Ontario Ministry of the Environment and Bruce-Grey-Owen Sound Health Unit (PHU) staff until May 22, 2000 (O'Connor 2002).

The first confirmed case of *E. coli* was identified on May 21, 2000. Based on this case and a stool sample from another patient that was presumptive positive for *E. coli*, the PHU issued a boil water advisory on the afternoon of May 21. The outbreak resulted in an estimated 2,321 cases of illness (O'Connor 2002), 167 confirmed cases of *E. coli* O157:H7, 116 confirmed cases of *Campylobacter* (Bruce-Grey-Owen Sound Health Unit 2000), 27 cases of Hemolytic Uremic Syndrome due to exposure to *E. coli* O157:H7, and 7 deaths (O'Connor 2002).

Results for B.C. Tool. Well No. 5 was correctly identified as being vulnerable as it is a shallow well that draws water from an unconfined fractured bedrock aquifer, and was located within 30 m of two springs (O'Connor 2002). The B.C. Tool also identified manure storage and application (activities thought to be responsible for the contamination of the water supply; O'Connor 2002) and improperly abandoned wells (Howard 2006) as potential sources of contamination located within 300 m of Well No. 5.

The only issue that was identified with respect to treatment was that the chlorination and disinfection monitoring equipment were not connected to alarms. Although chlorination was the only form of treatment at each well, it is generally thought to be sufficient for disinfection of a secure groundwater source. However, based on the input to the B.C. Tool regarding Well No. 5, the raw water supply would not be considered secure. In addition, information collected in other sections of the B.C. Tool regarding historical water quality issues, including raw and distribution samples that exceeded *Guidelines for Canadian Drinking Water Quality* limits for *E. coli* and total coliform bacteria (O'Connor 2002), would indicate that the chlorination equipment may not be achieving primary disinfection.

As a result, the DWO would likely have ordered the water supplier to complete the following modules:

- Module 1, which would have shown that the aquifer Well No. 5 draws from is vulnerable based on its geology and historic raw water quality data;
- Module 2, which would have identified sources of microbial contamination in the capture zone, and natural and man-made vulnerabilities that could act as conduits to the aquifer;
- Module 3, which would have likely shown that the treatment equipment installed at Well No. 5 was not sufficient to treat a vulnerable groundwater source;
- Module 5, which may not have effectively identified trends in raw or treated water quality due to the aforementioned PUC practise of mislabelling water samples.

By completing these modules, the risk assessment team would likely have identified all of the hazards and vulnerabilities associated with Well No. 5 and its treatment system that led to the waterborne disease outbreak in Walkerton. However, the time and resources required to complete the process, from the submission of the screening tool by the water supplier through to the completion of the qualitative risk assessment and risk assessment identification modules, would not allow for the hazards and vulnerabilities to be addressed promptly.

Results for MRA Tool. Since Wells No. 6 and No. 7 were not implicated in the outbreak, surveys were not completed for these wells or their treatment systems. Based on the information input to the MRA tool, the Walkerton water system received an overall risk score of 0.537. The surveys that made the largest contributions to the overall risk score are the treatment survey (0.137, 26% of the overall risk score), the source survey (0.128, 24% of the overall risk score), and the distribution survey (0.110, 20% of the overall risk score).

Due to the periodic positive coliform results in the four-year period preceding the outbreak (O'Connor 2002), the source survey question regarding historical microbial contamination received the highest relative risk score. The second highest risk score for the source survey was assigned to the question regarding aquifer type. Based on information regarding the geologic formation that the well was completed in, and the fluctuations in water level and water quality observed at Well No. 5 (O'Connor 2002), the well was in need of a groundwater under the direct influence of surface water (GUDI) assessment at the time of the contamination event. The need for a GUDI assessment results in a significant increase in the relative risk score assigned to the survey question regarding the aquifer type compared with a non-GUDI well. As a result, the source survey identifies one of the vulnerabilities that contributed to the waterborne disease outbreak.

The third and fourth highest risk scores for the source survey were assigned to questions regarding the completion of a source water assessment and source water protection plan. While preparing these documents would help identify the hazards or vulnerabilities that were present, the survey questions themselves do not address hazards or vulnerabilities directly. The same issue exists with the survey question regarding historical microbial contamination, which determines whether there is recent evidence of contamination, but does not identify the source of the contamination. As a result, the risk scores assigned to survey questions addressing actual hazards (such as livestock activities in the area of influence) and vulnerabilities (such as the shallow static water depth and relatively short well casing depth of Well No. 5) are eclipsed by the relatively high risk scores assigned to survey questions that address lines of evidence.

The survey question regarding corrosion control made the greatest contribution to the total risk score for the treatment survey. Since the survey question does not account for the physicochemical characteristics of the raw water supply or the pipe materials used in the transmission mains and the distribution system, the MRA Tool may not accurately reflect the microbial contamination risk associated with corrosion. The second highest risk score was assigned to the survey question regarding monitoring alarms for disinfection equipment. If continuous free chlorine monitoring equipment was installed and connected to an alarm system at Well No. 5, PUC operators would have been notified when insufficiently treated water entered the distribution system. This could have drastically reduced the scope of the outbreak (O'Connor 2002), provided that PUC operators took appropriate action to address the problem. Similarly, installing continuous turbidity monitoring equipment and connecting it to an alarm system may have notified the operator when contaminated water entered the distribution system. Despite that fact, the lack of turbidity monitoring alarms makes a relatively small contribution to the total risk score for the treatment survey. A relatively low weighting may have been assigned to this survey question because turbidity monitoring is generally not required for secure groundwater sources. However, the user input to the source survey indicated that a GUDI assessment was required for Well No. 5. The need for a GUDI assessment increased the risk score assigned to the question regarding the aquifer type in the source survey, but it did not have an impact on the risk score calculated for the GWTP despite the fact that GUDI sources generally have more stringent treatment and monitoring requirements.

The treatment survey question regarding the residual chlorine concentration after treatment, which was assumed to be in the range of 0.2 to 0.5 mg/L based on evidence presented at the Walkerton Inquiry (O'Connor 2002), also received a relatively high risk score. Unlike the SWTP survey, the GWTP survey does not include a question regarding the percent of time that the treatment facility meets CT requirements, only a question to determine whether the equipment has sufficient capacity to meet the CT requirements at all flow rates. A question should be included in the treatment survey to determine whether the necessary CT level is consistently being achieved, as CT values are directly correlated to the log inactivation achieved for a given disinfectant and pathogen (Hrudey and Hrudey 2004). If the treatment equipment has the capacity to meet CT requirements, but the CT requirements are not being met on a consistent basis, then the need for improved operating and monitoring practises would be identified. Poor operating and monitoring practises were identified as one of the factors contributing to the Walkerton outbreak (O'Connor 2002). In summary, a number of treatment survey questions identified factors that allowed contamination to enter the distribution system in Walkerton, but the MRA Tool did not assign the highest risk score to those survey questions.

In the distribution survey, the question regarding distribution system repairs and the required commissioning activities (flushing, disinfection, and bacteriological sampling) received the highest relative risk score. The high score was assigned because the work was performed by outside contractors. If water system operators performed the work, the risk score assigned to the question would be zero. Based on the poor operations and maintenance practises of Walkerton PUC staff, one would expect that properly trained private contractors would be more likely to follow the necessary safety and disinfection procedures when completing distribution system repairs. The risk scoring for this question, as well as for other survey questions regarding distribution system construction and maintenance activities, suggests that there is less risk associated with these activities when they are performed by water system personnel. This may not be a valid assumption for small water systems where operators are less likely to have the necessary equipment and training to perform this work in a safe manner.

Similar to the results for the North Battleford water system, distribution survey questions regarding dead end and low flow areas and residual disinfection also received relatively high risk scores. Due to the PUC practise of maintaining low chlorine doses (O'Connor 2002), the low chlorine residual in the distribution system may be due to the low chorine concentration in treated water as it entered the distribution system.

Results for PWS borehole risk assessment form. The front end of the risk assessment form would bring recent adverse water quality results to the attention of the inspector. Three of four raw water samples collected from Well No. 5 in April 2000 tested positive for total coliform bacteria, as did two treated water samples collected for the Well No. 5 treatment system on April 3 and April 17 and two distribution samples collected on April 3 (O'Connor 2002).

For the purpose of the survey question regarding stagnant or standing water, it was assumed that the springs located near Well No. 5 qualified as "standing water." Well No. 5 received a high risk characterization score for this question as well as for other General Site Survey questions regarding manure application activities and out-of-use wells. These questions identified the source of contamination responsible for the outbreak, and potential routes for that contamination to enter the supply aquifer.

The questions from the Supply Survey were applied to all infrastructure associated with the Walkerton water system. There is no indication that a suitable physical barrier was in place to prevent Well No. 5 from being flooded. As a result, a high risk characterization score and the maximum hazard assessment score were assigned to this survey question. Survey questions regarding fluctuations in the well water level and raw water turbidity at Well No. 5 also received high risk characterization scores. Fluctuations in water level and turbidity were recorded in inspection reports completed by Ontario Ministry of the Environment environmental officers over the period of 1978 to 1980 (O'Connor 2002). Other Supply Survey questions regarding the water system infrastructure, specifically the number of unprotected cross-connections in the distribution system (Ministry of the Environment 2000) and the lack of maintenance activities performed in the previous year (O'Connor 2002), also received high risk characterization scores. In summary, the PWS borehole risk assessment form identified the hazards and vulnerabilities that led to the contamination of Well No. 5, but did not address water treatment or monitoring activities in sufficient depth to identify vulnerabilities in the chlorination system.

Conclusions

Each of the selected risk assessment tools successfully identified the hazards that led to contamination of the water source in both case studies. However, the tools have different levels of success when identifying vulnerabilities associated with the water source and treatment, and water quality monitoring activities.

Although the B.C. Tool did not successfully identify vulnerabilities associated with water treatment directly, in both cases the DWO would have ordered the water supplier to complete the source-to-tap assessment modules necessary to identify the risks that led to the outbreaks based on the input to the B.C. Tool. The concern with the tiered approach of the source-to-tap assessment process is that it would be too onerous for a small water system operator to complete in a reasonable amount of time.

Alternatively, the MRA Tool is a single-tier risk assessment tool that requires more information regarding the design of the water treatment system than the B.C. Tool. However, the relatively high risk scores assigned to questions regarding historical treated water quality monitoring data can eclipse the risk scores associated with the vulnerabilities in the treatment system that led to the outbreak, which may decrease the likelihood that the water supplier will take direct action to address these vulnerabilities.

The PWS risk assessment forms do not include questions regarding water treatment or monitoring equipment, with the exception of two questions addressing a point-of-entry or point-of-use treatment system. These questions are designed for very small water systems, and are generally not applicable to larger water systems that serve residential or mixed-use developments.

The major shortcoming for all of the selected risk assessment tools is that they do not reflect the interdependent nature of the barriers to drinking water contamination. The survey questions addressing the source, treatment, and distribution of the water system are considered in isolation from one another. If the water system barriers were properly integrated in a risk assessment tool, the vulnerability of Well No. 5 to surface water contamination would result in an increase in the weightings or risk scores being assigned to survey questions regarding downstream treatment and monitoring barriers. The presence of alarmed continuous monitoring equipment would have likely prevented the Walkerton outbreak.

The three risk assessment tools also fail to address redundancy of key equipment or processes capable of removing pathogens. The installation of parallel "stand by" equipment can help to ensure that high quality water is supplied to the user in the event of equipment breakdown or scheduled maintenance. For example, the installation of a second SCU in parallel with the duty unit at the North Battleford SWTP would have provided the water system operators with sufficient time and operational flexibility to ensure that the duty SCU was achieving adequate settling prior to returning it to service, which would have likely prevented the North Battleford outbreak.

Recommendations

The development of future risk assessment tools must account for the interdependent nature of the barriers to drinking water contamination, as this important concept is not adequately addressed by the existing risk assessment tools assessed herein. Vulnerabilities in an upstream barrier would have an impact on the weights or risk scores assigned to survey questions regarding relevant downstream barriers. Elevated weights or risk scores would be assigned to survey questions regarding a hazard when there is only one process or barrier capable of removing or inactivating it. Future risk assessment tools must also incorporate the importance of redundancy within individual water system barriers, such that an elevated risk score is assigned if there is no "stand by" equipment that can be brought into service in the event that the process fails.

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Abbreviations/Acronyms

B.C. Tool: British Columbia Drinking Water Source-to-Tap Screening Tool

CT: Effluent residual disinfectant concentration in milligrams per litre multiplied by contact time in minutes

DWO: Drinking water officer
GUDI: Groundwater under the direct influence of surface water
GWTP: Groundwater treatment plant
MRA Tool: Microbial risk assessment ranking tool
PDWA: Precautionary drinking water advisory
PHU: Bruce-Grey-Owen Sound Health Unit
PUC: Public Utilities Commission
PWS: Scottish *Private Water Supplies: Technical Manual*
SCU: Solids contact unit
Source-to-tap assessment process: B.C. comprehensive drinking water source-to-tap assessment process
SW: Surface water
SWTP: Surface water treatment plant
WWTP: Wastewater treatment plant

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