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Drinking-water management in Canadian provinces and territories: a review and comparison of management approaches for ensuring safe drinking water

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Abstract

Drinking-water management systems (DWMSs) represent the primary means for preventative management of a drinking-water supply and are defined as a system of policies, procedures and administrative/behavioral controls designed to ensure safe drinking water from source to tap. With influence and inspiration ranging from safe food handling to industrial quality management, DWMSs can take, and have taken, many different forms throughout the world. This variability is especially true in Canada, a country with a decentralized governance structure, where provincial and territorial governments are mostly autonomous in regard to drinking-water governance and management. While this has resulted in comprehensive DWMSs in provinces such as Ontario, less-proactive provinces and territories have fallen behind and may be exposing consumers to under-protected and vulnerable drinking-water supplies. This paper includes a review and comparison of the existing Canadian national, provincial and territorial approaches to drinking-water management, the World Health Organization Water Safety Plan Recommendations, national DWMSs from Australia and New Zealand, and also includes widely applied, generic quality management systems. This information is then used to gauge the comprehensiveness of DWMSs in Canada and highlight potential management gaps and policy recommendations for the development of new, or improving existing, DWMSs.

Keywords: Drinking-water policy; Drinking-water management; Integrated water resources management; Preventative management; Water safety plans

Introduction

Throughout the world, waterborne disease outbreaks and drinking-water supply issues have drawn attention to the importance of properly governing and managing drinking water and public health (Dunn *et al.*, 2014). While these issues are rare and isolated in developed countries, their occurrence

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can be catastrophic, resulting in significant public health, social and economic repercussions (Hrudey *et al*., 2003; Jayaratne, 2008; Rizak & Hrudey, 2008). Ultimately, drinking-water suppliers are accountable for ensuring drinking-water quality and safety, but they cannot be expected to undertake this massive task alone (Rizak & Hrudey, 2008). The proper management and maintenance of a drinking-water supply system (DWSS) require a thorough understanding from catchment to consumer and must include preventative management planning strategies (i.e. the comprehension and integration of mitigation actions for potential hazards and failure events that can lead to drinking-water quality issues and increased human health risk) (Rizak & Hrudey, 2008; Baum *et al*., 2015). While regulatory standards or guidelines provide threshold values for measuring drinking-water quality, they do not provide a means to achieve compliance or any incentive for improvement (Bereskie *et al*., 2017b).

For the purpose of this paper, drinking-water management systems (DWMSs) are defined as systems of policies, procedures and administrative/behavioral controls designed to ensure safe drinking water from source to tap. They are designed not only to achieve regulatory compliance, but also to meet the need for preventative management of DWSSs and incentivize continuous performance improvement. A study by Baum *et al*. (2015) stated, 'Over 35 countries worldwide have multiple water systems that have well documented cases of either voluntarily or mandatorily implemented water safety plans (WSPs), or their equivalent under other names, that served as a preventative risk management approach in an effort to ensure the safety of drinking water quality.' While there may be some countries that have implemented less-documented approaches to drinking-water management, it still leaves dozens of countries and hundreds of millions of people depending on under-protected and vulnerable DWSSs.

DWMSs provide the foundation and framework for ensuring safe drinking water and have historically taken many different forms and with elements incorporated from safe food handling practices and industrial quality management applications (Sinclair & Rizak, 2004; Yokoi, 2006; Gunnarsdóttir & Gissurarson, 2008; Jayaratne, 2008). This varied approach is especially evident in Canada, a country with a decentralized governance structure, where provincial and territorial governments are mostly autonomous in the context of drinking-water management and governance (Bakker & Cook, 2011). Despite Canada being well known for its relative abundance of high-quality freshwater supplies, it is far from immune to drinking-water quality and quantity issues (Exall *et al*., 2006; PaiMazumder *et al*., 2013; Yusa *et al*., 2015).

Exall *et al*. (2006) reported that in 2001 approximately 25% of municipalities with public DWSSs reported water quantity shortages. Recent assessments on the impacts of climate change in Canada indicate further freshwater supply shortages in the future in some areas, especially within the Prairie Provinces (i.e. Alberta, Saskatchewan, and Manitoba) (Exall *et al*., 2006; PaiMazumder *et al*., 2013; Yusa *et al*., 2015). There are also significant drinking-water quality concerns. A study by Murphy *et al*. (2016) reported that municipal DWSSs (serving more than 1,000 people) in Canada may be responsible for over 300,000 cases of acute gastrointestinal illness per year, and Vinson (2012) estimated the annual economic burden of Canadian waterborne disease outbreaks at approximately 2.7 billion dollars (CAD). Along with water quality and quantity issues, there is a global trend towards privatization and public–private partnerships of DWSSs; Rahaman & Varis (2005) commented that this privatization may encourage fragmentation.

Given governmental dynamics, vastly differing policies, regulatory requirements and management practices both between and within provinces and territories, and the uncertainty of Canadian drinking-water into the future, steps must be taken to document the current state of practice and improve drinking-water management practices throughout the country (Saunders & Wenig, 2007; Simms &

de Loë, 2010; Dunn *et al.*, 2014, 2015; Bereskie *et al.*, 2017b). The objective of this paper is to review and compare the existing DWMSs within Canada to each other, World Health Organization (WHO) WSP Recommendations, international approaches, and industrial quality management systems (QMSs) (i.e. formal systems of procedures and policies designed to ensure quality objectives are met, documented and improved upon) (ISO, 2015). By comparing the Canadian state of practice and the included drinking-water management elements to best management practices, context can be provided to gauge the comprehensiveness or lack thereof in Canadian national, provincial and territorial DWMSs. While the effectiveness and impact of management practices and principles can be difficult to quantify, Hrudey (2011) noted, '…much of Canada remains out of step with the international leaders in adopting management systems for assuring safe drinking'. This comparison is then used to identify management gaps and areas potentially requiring improvements for both the development of new DWMSs and the improvement of existing DWMSs throughout Canada.

Materials and methods

In order to review and compare the selected DWMSs and QMSs, information from literature, non-governmental organization publications and governmental documents was used to compile a brief history and description of each approach. Tables and figures summarizing objectives, principles and elements were also included to highlight specifics within individual management systems. After each QMS/DWMS was reviewed individually, the systems were compared across 41 management elements categorized into six categories.

It is important to note that jurisdictional and/or organizational definitions and interpretations of what constitutes a DWMS vary widely, much as the approaches themselves. In order to properly review and fully understand the existing approaches to drinking-water management and quality management across provinces/territories, countries and differing applications, jurisdictional/organizational definitions and interpretations were used in the review and description portion of this paper. However, when comparing the selected DWMSs and QMSs in the 'Discussion' section and proposing policy recommendations in the 'Recommendations' section of this paper, common elements with more general terminology were selected for standardization and ease of comparison.

Quality management systems

The Hazard Analysis and Critical Control Points (HACCP) method and the International Organization for Standardization (ISO), 9001:2015 QMS Requirements were selected for comparison as they have diverse applications, are often associated with food and drink, and a review of applicable literature highlighted these approaches as foundations for many existing DWMSs (Sinclair & Rizak, 2004; Martinez-Costa *et al.*, 2009; Kafetzopoulos *et al.*, 2013).

These QMSs were included as part of this review to highlight the differences between more-traditional QMSs and the more-specific DWMSs.

Hazard analysis and critical control points. The HACCP QMS is a risk-based approach to quality management. It was originally developed for use in food production, manufacturing and distribution, and was designed to encourage safe practices through incorporating transparency (Kafetzopoulos

et al., 2013). The HACCP approach is generally defined as a systematic method for the identification, assessment and control of hazards, and was established as a proactive alternative to end-point testing (Ropkins & Beck, 2000). It is widely recognized as one of the best methods to ensure product safety and control safety hazards (Kafetzopoulos *et al.*, 2013). Historically, the basis for the first HACCP system was developed in the late 1960s by The Pillsbury Company to ensure food safety for space flights (Ropkins & Beck, 2000). In 1972, it was applied to their commercial division for the production of consumer food products. At the time, it consisted of three primary principles (Ropkins & Beck, 2000; Sperber, 2005): (1) conducting hazard analyses to identify and assess hazards associated with the final product; (2) determining critical control points – the steps or stages within production at which hazards may be controlled, reduced or eliminated; and (3) monitoring and reviewing of identified critical control points.

In 1997, the HACCP approach was redeveloped to meet the specific needs of modern food producers, manufacturers and distributors (Ropkins & Beck, 2000; Sperber, 2005). It was based on 12 principles and had an increased emphasis placed on documentation (Table 1).

A DWMS based on the principles of the HACCP has been used in Iceland since 1995, when legislation classified water as a food and required management strategies to prevent contamination (Hulsmann & Smeets, 2011; Gunnarsdóttir *et al.*, 2012). Since its inception, this DWMS has resulted in water quality performance increases throughout the country and has also led to the development of a modified process tailored to small drinking-water utilities (i.e. serving between 500 and 5,000 people) (Gunnarsdóttir & Gissurarson, 2008; Jayaratne, 2008; Gunnarsdóttir *et al.*, 2012). This QMS has also been implemented in Slovenia where, much as in Iceland, drinking water is covered under food legislation (Hulsmann & Smeets, 2011).

Table 1. Modern HACCP principles (Ropkins & Beck, 2000; Sperber, 2005; Jayaratne, 2008).

No.	Step	Description
1	Assemble team	Assemble a team to develop, implement and verify the system.
2	Describe product	Develop a detailed description of the product, including water quality standards and/or health-based targets.
3	Identify intended use	Identify use (i.e. human consumption).
4	Construct flow diagram	Identification (and development of a flow diagram) of all elements in a system from beginning to end.
5	Confirm flow diagram	Confirmation of flow diagram developed in Step 4.
6	Conduct a hazard analysis	Conduct a hazard analysis to identify and assess hazards associated with the final product.
7	Determine critical control points	Determine critical control points – the steps or stages within production at which hazards may be controlled, reduced or eliminated.
8	Establish critical limits	Establish critical limits for controlling each critical control point.
9	Establish a system to monitor control of the critical control points	Establish monitoring procedures to determine if limits have been exceeded.
10	Establish corrective actions	Establish corrective actions to be taken if control is lost and define procedures for maintaining control.
11	Validation and verification of the HACCP plan	Establish verification procedures for assessing effectiveness of the HACCP system.
12	Establish documentation and record keeping	Establish documentation and record keeping procedures to provide proof of compliance.

ISO, 9001:2015. The ISO, 9001:2015 standard is a process-based approach developed from the plan-do-check-act cycle (i.e. an industrial improvement concept designed to coordinate continuous improvement plans by categorizing improvement actions into a dynamic cycle of four steps – plan, do, check, act), designed for use by an organization that needs to demonstrate its ability to consistently provide products and/or services that meet customer and regulatory requirements (Langley *et al*., 1994; Moen & Norman, 2006; Moen, 2009; Lodgaard & Aasland, 2011; ISO, 2015). ISO, 9001: 2015 states that 'All of the requirements of this International Standard are generic and are intended to be applicable to any organization, regardless of its type or size, or the products and services it provides', and since 1987, the ISO 9001 standard has been used by many organizations across industries throughout the world (Cianfrani & West, 2014). The ISO, 9001:2015 standard is broken down into seven quality management principles consisting of customer focus, leadership, engagement of people, process approach, improvement, evidence-based decision making, and relationship management (ISO, 2015). Although ISO 9001 was originally intended for manufacturing companies, it has since been used as a foundation for DWMSs, such as the *Australian Framework for Management of Drinking Water Quality* (Sinclair & Rizak, 2004; Martinez-Costa *et al*., 2009). This can be attributed to the fact that the ISO 9001 standards offer a reasonable pathway to implementing quality management and require a high level of documentation and auditing, leading to increased transparency and verification of quality (Terziovski *et al*., 2003; Martinez-Costa *et al*., 2009).

Drinking-water management system approaches

In reviewing Canadian provincial/territorial DWMSs, investigating their comprehensiveness, and exploring areas for improvement, it is important to first understand the accepted fundamental core concepts of drinking-water management and identify best management practices throughout the world. In this section, the WHO WSP Recommendations and national DWMSs from Australia and New Zealand are reviewed and compared with the Canadian Council of Ministers of the Environment (CCME) Multi-barrier Approach. The WHO WSP Recommendations and DWMSs from Australia and New Zealand represent some of the more-studied and replicable drinking-water management approaches found throughout the world and provide a strong baseline for comparison (Hrudey *et al*., 2006).

The United States was not included in this review, as DWMSs in the United States are generally handled at the state level (e.g. the California Safe Drinking Water Plan) with the United States Environmental Protection Agency having federal oversight over issues related to the *Safe Drinking Water Act*, specifically including the *Lead and Copper Rule*, the *Surface Water Treatment Rule*, the *Total Coliform Rule*, and the *Disinfectants/Disinfection By-Products Rule* (National Research Council, 2006). While the United States Environmental Protection Agency does not have a recommended DWMS, they have promoted the WHO WSP Recommendations for international partner countries to improve drinking-water management since 1998 (USEPA, 2016).

World Health Organization. WSPs represent an alternative management framework to many current DWMSs. While conventional DWMSs often rely on mitigating risks already present in a water supply system, a WSP-based approach focuses on preventing risks from entering and, therefore, reducing likelihood of a negative impact on human health (WHO, 2009). Based on WHO *Guidelines for Drinking-water Quality*, Bartram *et al*. (2001) developed one of the first drinking-water management frameworks to incorporate public health concerns, risk assessment, the establishment of health-based

targets and risk management. This approach to managing drinking water has provided a foundation for many current DWMSs and, since 2004, a WSP has been recommended by the WHO for preventative management of water supplies regardless of size or level of sophistication (WHO, 2004; Yokoi, 2006).

In the fourth edition of the *Guidelines for Drinking-water Quality,* the WHO (2011) promotes a 10-step WSP which builds on a foundation of multiple barriers, the HACCP QMS system, and other systematic management approaches. The WHO (2009) also published the *Water Safety Plan Manual* (based on Chapter 4 of the 2004 third edition of the *Guidelines for Drinking-water Quality*), which provides a step-by-step guide for drinking-water suppliers to develop and implement a WSP. The WHO WSP recommendations consist of five key elements (Table 2) and three key components (Table 2, Nos. 2–4) (Davison *et al*., 2006).

Based on these elements, the WHO (2011) defined six primary objectives for WSPs to effectively ensure safe drinking water: (1) development of an understanding of specific systems and their capability to supply water that meets water quality targets; (2) identification of potential sources of contamination and how they can be controlled; (3) validation of control measures employed to control hazards; (4) implementation of a system for operational monitoring of the control measures within the water system; (5) timely corrective actions to ensure that safe water is consistently supplied; (6) verification of drinking-water quality to ensure that the WSP is being implemented correctly and is achieving the performance required to meet relevant national, regional, and local water quality standards or objectives.

Australia. The *Australian Framework for Management of Drinking Water Quality* was developed by the Australian National Health and Medical Research Council in collaboration with the Co-operative Research Centre for Water Quality and Treatment to incorporate preventative risk management in a drinking-water supply context to support consistent and comprehensive implementation by suppliers (Sinclair & Rizak, 2004; NHMRC, 2011). This framework incorporates elements of the HACCP QMS, ISO 9001 (Quality Management), ISO 14001 (Environment Management), and Australia/New

Table 2. WHO WSP component descriptions (Davison *et al*., 2006; WHO, 2011).

No.	Element	Description
1	Setting health-based targets	Health-based targets are based on an evaluation of health concerns and can be coordinated with other regulatory guidelines and standards.
2	System assessment	A system assessment is used to determine whether or not the drinking-water supply chain (source to tap) can deliver water quality that meets identified targets. This also includes assessment of design criteria of new systems.
3	Effective operational monitoring	Effective operational monitoring refers to the identification of control measures in a drinking-water system that will control identified risks and ensure that health-based targets are met.
4	Management and communication	Management and communication refer to actions to be conducted during normal operation or incident conditions and documenting the system assessment, including upgrade and improvement planning, monitoring and communication plans, and supporting programs.
5	Surveillance	Independent monitoring verifies that the above components are operating properly and effectively.

Zealand Standard (AS/NZS) 4360:2004 (Risk Management) for the management of drinking-water quality from source to tap (Sinclair & Rizak, 2004; NHMRC, 2011). The framework addresses four general areas (Table 3) and includes 12 elements considered good practice for system management of drinking water supplies (Table 4).

As part of the Australian Framework, the Australian National Health and Medical Research Council (2011) also developed a specific DWMS for small drinking-water suppliers serving less than 1,000 people. This modified framework places an emphasis on a preventative approach to managing water quality with less of a focus on water quality testing and monitoring programs. It consists of four main components: the assessment of the drinking-water supply, preventative measures for drinking-water quality management, implementation of operational procedures and process control, and verification of drinking-water quality (NHMRC, 2011).

New Zealand. The New Zealand Ministry of Health is responsible for the regulation of public health under the *Health Act 1956* and subsequent amendments (NZMOH, 2015). *The Health (Drinking Water) Amendment Act 2007* to the *1956 Health Act* mandated that all drinking-water suppliers have a duty to ensure safe drinking water (NZMOH, 2008). This amended act also required the development and implementation of a WSP (originally known as a Public Health Risk Management Plan) for all DWSSs serving over 500 people and is complemented by the *Drinking-water Standards for New Zealand* (NZMOH, 2008; Hrudey, 2011; Hubbert, 2013).

The New Zealand DWMS is based on the WHO (2004) *Guidelines for Drinking-water Quality* and generic QMSs (Table 5) (Taylor, 2002; Hubbert, 2013). This DWMS was designed to promote interaction and support throughout the entire DWSS from the drinking-water supplier and the public health officers to other stakeholders and the public (Taylor, 2002). In small communities serving between 25 and 5,000 people, the New Zealand Ministry of Health has developed the *Drinking Water Assistance Programme* and a risk-management kit to help small communities meet the technical and financial needs of smaller suppliers (NZMOH, 2014).

Canada. Drinking-water management in Canada has dramatically shifted since waterborne disease outbreaks in the early 2000s, headlined by Walkerton, Ontario and North Battleford, Saskatchewan

Table 3. *Australian Framework for Management of Drinking Water Quality* general areas (NHMRC, 2011).

No.	General area	Description
1	Commitment to drinking-water quality management	The development of a commitment (active participation) to drinking-water quality management within an organization.
2	System analysis and management	The understanding of an entire water supply system, the hazards and events that can comprise drinking-water quality, and the preventative measures and operational control necessary for assuring safe and reliable drinking water.
3	Supporting requirements	Requirements include basic elements of good practice such as employee training, community involvement, research and development, validation of process efficacy, and systems for documentation and reporting.
4	Review	Evaluation and audit processes and their review by senior executives to ensure that the management system is functioning satisfactorily. These components provide a basis for review and continual improvement.

Table 4. Process for *Australian Framework for Management of Drinking Water Quality* (NHMRC, 2011).

No.	Step	Description
1	Commitment to drinking-water quality management	Organizational support and long-term commitment, in the form of drinking-water quality policy, regulatory and formal requirements, and engaging stakeholders, serve as a foundation in implementing an effective DWMS.
2	Assessment of the DWSS	Assessment of the DWSS includes a full water supply system analysis, assessment of water quality data, hazard identification and risk assessment.
3	Preventative measures for drinking-water quality management	Preventative measures for drinking-water quality management include the use of multiple barriers and critical control points. These measures are used to prevent hazards from occurring or reducing them to acceptable levels.
4	Operational procedures and process control	Operational procedures and process control measures are designed to achieve a high-quality water supply and effectively control processes and activities that govern drinking-water quality.
5	Verification of drinking-water quality	Verification of drinking-water quality and consumer satisfaction provides an assessment of overall performance of the system. It also provides a useful indication of problems within the water supply system and the necessity for any immediate corrective actions or incident and emergency response.
6	Management of incidents and emergencies	Management of incidents and emergencies is essential for protecting public health and maintaining consumer confidence. Whenever possible, emergency scenarios should be identified, and incident and emergency protocols should be planned and documented.
7	Employee awareness and training	Employee awareness and training are essential to enable and motivate employees to make effective decisions.
8	Community involvement and awareness	Community involvement and awareness can beneficially impact public confidence in the water supply by providing transparency and education.
9	Research and development	Research and development include research monitoring, validation of processes, and design of equipment, and help to ensure continual improvement.
10	Documentation and reporting	Proper documentation and reporting provide the foundation for the establishment and maintenance of effective DWMSs.
11	Evaluation and audit	Long-term evaluation of drinking-water quality results and auditing of a DWMS are required to determine efficiency of preventative strategies.
12	Review and continual improvement	Review by senior executives can lead to continual improvement of the DWMS.

(O'Connor, 2002b; Hrudey *et al.*, 2003). Subsequent investigations resulted in the establishment of the *CCME Multi-barrier Approach* for drinking-water management in Canada (O'Connor, 2002b; CCME, 2004). In this approach, barriers in the form of physical or administrative/behavioral improvements are implemented to improve the overall quality and management of drinking water (CCME, 2004; Hrudey *et al.*, 2006; Alberta Environment, 2009). In the event that one barrier fails, back-up systems and processes are in place to protect the safety of drinking water (Government of the Northwest Territories, 2005).

Using the *CCME Multi-barrier Approach*, all potential control barriers are identified along with potential limitations (CCME, 2002). This DWMS is categorized into three main components: the source, drinking-water treatment, and drinking-water distribution (CCME, 2002, 2004).

Table 5. New Zealand Ministry of Health suggested steps for WSP development (NZMOH, 2015).

No.	Step	Description
1	Produce overview of supply	Identification (and development of a flow diagram) of all elements in a water supply system from the catchment to the consumer's property.
2	Identify barriers to contamination	Inventory of protective barriers in place to contribute to the safety of the entire water supply. These fundamental barriers must achieve the following: (1) prevention of contaminants entering the raw water of the supply; (2) removal of particles from the water; (3) inactivation of micro-organisms in the water; (4) maintenance of the quality of the water during distribution.
3	Identify events that may introduce hazards	Identification of potential events that may introduce hazards into the drinking-water supply using the New Zealand Ministry of Health Water Safety Plan Guides.
4	Identify possible causes of each event, preventative measures, and corrective actions	Identification of causes, preventative measures and corrective actions (using the New Zealand Ministry of Health Water Safety Plan Guides) associated with the identified hazards from Step 3.
5	Decide where improvements should be made	This is the first of three steps for preparing an improvement schedule designed to list any of the four fundamental barriers, preventative measures, checks and corrective actions missing from a supply.
6	Decide on order of improvements	Prioritization of improvements based on the improvements identified in Step 5. Factors such as public-health impact (using the New Zealand Ministry of Health Water Safety Plan Guides), availability of resources and ease with which improvements can be implemented must be considered.
7	Draw up timetable	Development of an improvement schedule to assign completion dates and responsibility for each improvement.
8	Identify links with other quality-assurance systems	Identification of other quality-assurance systems in place (such as ISO 9000/14000) and implementation into WSPs.
9	Develop contingency plan	Preparation of contingency plans (suggested contingency plans are provided in each of the New Zealand Ministry of Health Water Safety Plan Guides) to ensure that there is a protocol for situations that may pose a threat to drinking-water quality.
10	Performance assessment of plans	Development of a procedure for the review and updating of the WSP. Reasons to update a plan may include: a change in the circumstances of a water supply, the identification of possible new events and their causes, the discovery that one or more preventative measures or corrective actions are unsatisfactory, and/or a contingency plan has failed when implemented.
11	Development of communication policy	Creation of a communication policy should identify and record the people to whom reports concerning the management of risk to the supply should be made, what information these reports should contain, and how often they should be made.
12	Review and improvement	Review and improvement of the WSP process.

Water source (i.e. source water protection) – this entails the coordinated approach to develop plans (short-term and long-term) to protect and potentially enhance drinking-water source quality. This component can be broken down further into three categories: delineating source water protection areas, identifying contaminants of concern, and assessing and ranking risk vulnerability.

Treatment system (i.e. water treatment process selection) – this entails the selection of drinking-water treatment based on source water quality and quantity, finished water quality, reliability of equipment, regulatory requirements and human resources/financial demands.

Distribution system (i.e. distribution system development and operation) – this entails the designing and operating of a drinking-water distribution system to sustain minimum operating pressure at the

maximum hourly flows and meet or exceed pipe performance standards. These elements are then addressed using a system of procedures and tools (Table 6).

When discussing drinking-water management in Canada, it is important to highlight the roles and responsibilities of the federal, provincial/territorial and municipal governments. The provincial and territorial governments are directly responsible for drinking-water management and governance in Canada, with the federal government providing more of an oversight role (i.e. leadership, research and development, guidelines, recommendations, responsibility on federal lands), and the municipal government handling administration, performance monitoring, and management and maintenance (de Loë & Kreutzwiser, 2007). This decentralized structure has resulted in no legally enforceable federal drinking-water standards and a broad approach to drinking-water management (Bakker, 2007; Bakker & Cook, 2011; Bereskie *et al*., 2017a).

Canadian provincial DWMSs

While the CCME recommends the multi-barrier approach for the management of DWSSs in Canada, it allows significant autonomy and flexibility for individual provinces and territories (Bakker & Cook, 2011). This can be attributed to the decentralized governance structure and variability between provinces and territories (i.e. differing climates, populations, water use, water sources) (Bakker & Cook, 2011;

Table 6. *CCME Multi-barrier Approach* elements and descriptions (CCME, 2002).

No.	Element	Description
1	Legislative and policy frameworks	Legislative and policy frameworks highlight responsibilities for each aspect of the drinking-water system and should be reviewed and revised as necessary.
2	Public involvement and awareness	Public involvement and awareness include appropriate levels of partnership and communication among stakeholders to increase transparency and availability of public-health information.
3	Guidelines, standards, and objectives	Regulations provide utility managers and system owners with water quality targets to meet and can be used as part of the decision-making process.
4	Research, science, and technology	Research, disease surveillance and other scientific and technological advancement/development allow for more-integrated water-quality monitoring and potential for improving operations.
5	Management	Drinking-water supply management requires cooperation of stakeholders in different fields (e.g. health, environment, industry) and requires qualified personnel to ensure treatment facility and distribution system are operating at optimum levels.
6	Monitoring	Water-quality monitoring includes the sampling of water quality at the source, after treatment and within the distribution network. This allows operators to modify treatment if water quality fluctuates to ensure regulatory compliance and safe drinking water.
7	Source water protection and management	Protection of source water based on watershed management involving a coordinated approach among stakeholders to develop short- and long-term plans to prevent, minimize, or control potential sources of pollution or enhance water quality.
8	Drinking-water treatment	Drinking-water treatment is key to eliminating pathogens and chemical substances found in source waters. There should be a regular review and upgrade as necessary.
9	Drinking-water distribution systems	Distribution systems are the final physical barrier in the multi-barrier approach. After water is treated, its quality must be maintained throughout the distribution system.

Dunn *et al*., 2014). Although this approach has resulted in strong DWMSs in some provinces, others are less comprehensive (or non-existent) and may be leaving consumers unnecessarily exposed to vulnerable drinking-water supplies.

Alberta (AB). The province of Alberta became the first jurisdiction to regulate WSPs in North America with the introduction and implementation of the Drinking Water Safety Plan in 2011, moving away from a more-traditional source to tap multiple-barrier approach (Alberta Environment, 2009; Perrier *et al*., 2014; Reid *et al*., 2014). The Government of Alberta (2012) established four principle processes for the successful implementation of this DWMS (Table 7).

The Government of Alberta (2012) also lists three other important considerations for developing a drinking-water safety plan. (1) A drinking-water safety plan cannot work in isolation, so you must communicate and discuss findings with stakeholders and other relevant parties. (2) For the drinking-water safety plan to work, the identified necessary actions to mitigate risks must be implemented. (3) The drinking-water safety plan is a 'living document' that should be reviewed regularly and updated when necessary.

Based on these principles and considerations, the Alberta Environment and Sustainable Resource Development developed a Microsoft Excel-based template, which provides generic risk for four key risk areas (i.e. source, treatment, distribution network, consumer), designed to act as a single source for all relevant information about a water supply system (Perrier *et al*., 2014; Reid *et al*., 2014). While the long-term success of this program is still uncertain, literature has shown that it presents a practical option for effective water management and has the potential to be applied throughout Canada (Gagnon, 2014).

British Columbia (BC). The *British Columbia Comprehensive Source-to-Tap Assessment* is an assessment program designed to integrate the various components of a DWSS by determining strengths and weaknesses and identifying existing and potential threats to safe drinking water to assist in the

Table 7. Principle processes for the *Alberta Drinking Water Safety Plan* approach (Government of Alberta, 2012).

No.	Principle processes	Description
1	Collection of best available information about the water supply system	Collection of information about a water supply system will vary by complexity, but typical sources of information can include water-quality records, public-health incidents, plant records and watershed activities.
2	Identification of present risks and circumstances that will threaten public health	Identification of risks and circumstances that will threaten safe drinking water can be conducting using risk sheets (e.g. source, treatment, network, consumer) as part of the Government of Albert *Drinking Water Safety Plan Template*. Other site-specific risks and causes may need to be added.
3	Assessment of improvement actions to reduce risk to an acceptable level	Assessment of improvement actions can be addressed using the Government of Alberta *Action Summary Sheet* and *Key Risks Sheet*.
4	Inventory of available resources, prioritization (and auditing) of improvement actions, and timetable for implementation of improvements	Inventory of available resources, prioritization of improvement actions and creation of a timetable for implementation of improvements can be addressed using the Government of Alberta Action Summary Sheet to address the identified improvement actions from Principle 3.

decision-making process (BCMHLS, 2010). It consists of eight modules (Table 8) and was developed based on ten guiding principles:

1. Drinking-water protection is a public-health issue, hence drinking-water assessments should focus on threats to public health.
2. Drinking-water assessments should be a tool to assist in the protection of drinking water.
3. Drinking-water assessments should be conducted in an integrated manner, with consideration for both source and system components.
4. Drinking-water assessments should embody the multi-barrier approach.
5. Drinking-water assessments should be an opportunity for education and communication among stakeholders.
6. Drinking-water assessments should focus on preventing problems.
7. Drinking-water assessments should be science-based.
8. Drinking-water source assessments should be flexible and tailored to the size and type of the water system and the level of risk to its users.
9. Drinking-water assessments should result in the development and implementation of specific actions and/or recommendations.
10. Drinking-water assessments should foster and promote the highest water quality possible through stewardship and involvement of the broader community.

Table 8. *British Columbia Comprehensive Drinking Water Source-to-Tap Assessment* modules (BCMHLS, 2010).

No.	Module	Description
1	Delineate and characterize drinking-water source(s)	The delineation and characterization of the drinking-water source area allow the evaluation of the integrity and location of surface water intakes and groundwater wells.
2	Conduct contaminant source inventory	A contaminant source inventory is to be used to identify and describe land uses, human activities and other potential contaminant sources that could potentially affect source water quality.
3	Assess water supply elements	The assessment of water supply elements includes the identification of factors such as source water type, water quality and quantity, size of population served, and age of the system, and is designed to be used to identify problems or concerns.
4	Evaluate water system management, operation, and maintenance	Water system management, operation, and maintenance provide a systematic approach for investigating the human aspect of how the water system is operated to provide safe drinking water.
5	Audit water quality and availability	Auditing of water quality and quantity provides an evaluation of the success of the water system in meeting the goal of providing safe, palatable drinking water to all users and encompasses a review of water-quality monitoring and customer feedback.
6	Review financial capacity and governance of water systems	Reviewing of the financial capacity and governance of a water system includes a review of the financial management of the water system, available funding mechanisms, governance and accountability, and the response to development pressures.
7	Characterize risks from source to tap	The characterization of risks from source to tap is the focal point of this DWMS. It includes a structured approach for identifying the areas of greatest risk and is designed to foster an understanding of the strengths and weaknesses throughout a water supply system.
8	Recommend actions to improve drinking-water protection	The recommendation of actions to effectively manage the risks identified throughout the assessment process is important to enhance the safety and sustainability of the drinking-water supply.

The British Columbia DWMS was developed not as a prescriptive assessment methodology or a set of detailed instructions, but as a flexible methodology for use in identifying and evaluating drinking-water risks from source to tap (BCMHLS, 2010). While there is no specific approach for smaller systems, this DWMS was designed to be adaptable for DWSSs of all types and sizes.

Manitoba (MB). Drinking water in Manitoba is governed by the Manitoba Water Stewardship's Office of Drinking Water, which enforces *The Drinking Water Safety Act* and the *Manitoba Water Quality Standards, Objectives, and Guidelines* (2011) (Manitoba Water Stewardship, 2011a, 2011b). The province also helps to protect drinking water at the source through *The Water Protection Act* (Legislative Assembly of Manitoba, 2005; Manitoba Water Stewardship, 2011a). Combined, the regulatory structure provides a source to tap framework for the protection of the provincial drinking-water system (Manitoba Water Stewardship, 2011a).

In 2003, the Manitoba Water Stewardship released *The Manitoba Water Strategy*, which documented the importance of the development of an integrated water planning and management system (Manitoba Water Stewardship, 2003). Eight years later, the Legislative Assembly of Manitoba introduced the *Save Lake Winnipeg Act*, a bill requiring planning authorities in the Capital Region to prepare a drinking-water plan (DWP) as part of a development plan review or major amendment (Legislative Assembly of Manitoba, 2011). While this act is not province-wide and places an emphasis on water supply over water quality, it provides the closest thing to a DWMS currently in use within Manitoba (Manitoba Provincial Planning Regulation, n.d.). Manitoba does not have a specific DWMS for smaller utilities, however, it is important to note that the Manitoba Water Stewardship (2007) provides a *Best Practices Manual for Small Drinking Water Systems*, designed to assist small drinking-water systems in achieving regulatory compliance and meeting management and operational challenges.

New Brunswick (NB). The population of New Brunswick is generally rural, with approximately 40% of the population obtaining drinking water from domestic groundwater wells (Government of New Brunswick, 2009). The remaining 60% of the population relies on municipal DWSSs (Government of New Brunswick, 2009). The New Brunswick Department of Health and Department of the Environment and Local Government cooperatively lead the regulation of public drinking-water supplies with the Department of Health holding responsibility for assessing public-health risk and the Department of the Environment and Local Government being responsible for regulating and protecting drinking-water systems. Despite having a population of 756,800 people and strong drinking-water legislation in place, New Brunswick is one of the only provinces without an established approach to drinking-water management (Conservation Council of New Brunswick, 2016; Statistics Canada, 2016).

Newfoundland and Labrador (NL). Drinking-water treatment in Newfoundland and Labrador is generally simple, usually consisting only of the addition of chlorine to raw surface source water, often resulting in aesthetic, biological and chemical water-quality issues (Scheili *et al.*, 2014). In the province, the *Multi-barrier Strategic Action Plan* is used for the management of drinking water (Government of Newfoundland and Labrador, 2015). The Government of Newfoundland and Labrador (2015) states that 'The *Multi-barrier Strategic Action Plan* is considered to be the most effective method of managing drinking water system and has been implemented by other jurisdictions throughout Canada' and its implementation involves collaboration between four provincial government departments: Environment

and Conservation, Government Services, Health and Community Services, and Municipal Affairs (Government of Newfoundland and Labrador, 2010).

The Government of Newfoundland and Labrador (2015) has broken down their DWMS into three levels of components, with Level 1 focused on operations, Level 2 focused on management, and Level 3 focused on legislation and supporting programs (Table 9). Despite 90% of all public drinking-water systems serving 1,500 people or fewer, Newfoundland and Labrador does not have a modified DWMS specifically for smaller utilities.

Nova Scotia (NS). Drinking water in Nova Scotia has been at the forefront of environmental policy and management since the early 1990s, when the Government of Nova Scotia published the *Clean Water Task Force Report* in 1991 and the *Sustainable Development Strategy for Nova Scotia* in 1992, which resulted in the 1995 *Environment Act* (Government of Nova Scotia, 2002). This piece of legislation strengthened drinking-water management across the province and was supplemented by the 2000 *Water and Wastewater Facility Regulations* and adoption of the *Guidelines for Canadian Drinking Water Quality* (Government of Nova Scotia, 2002). The Government of Nova Scotia (2002) developed the *Nova Scotia Drinking Water Strategy* to protect and manage drinking water and identified three key management elements: clear roles and responsibilities, multi-barrier management, and inter-departmental drinking-water management. This document also contained an action plan for better drinking-water management and, in 2005, the Nova Scotia Minister of Environment and Labour published a report highlighting that all action items had been completed (Nova Scotia Environment and Labour, 2005). The specific drinking-water management elements included as part of the *Nova Scotia Drinking Water Strategy* are broad and can be found as part of Table 16 (see later).

It is also important to note that a separate document, authored by Nova Scotia Environment and Labour (n.d.) and titled *Safe Drinking Water for Public Water Systems: A Diligent Approach*, categorizes multiple barrier management of drinking water in Nova Scotia into three steps: keeping clean water clean (source protection), making it safe (water treatment and system operation), and proving that it is safe (monitoring and testing).

Ontario (ON). After the waterborne disease outbreak in Walkerton, Ontario, *The Walkerton Inquiry* resulted in two reports: Part 1 was associated with the causes of the outbreak, and Part 2 detailed a proposed strategy for improvement (O'Connor, 2002a, 2002b; Hrudey, 2011). In Part 2, 93 recommendations were made to implement a multiple-barrier approach that resulted in tighter drinking-water regulations. The *Ontario Drinking Water Quality Management Standard* was developed to complement the updated

Table 9. Levels of the *Multi-barrier Strategic Action Plan* in Newfoundland and Labrador (Government of Newfoundland and Labrador, 2015).

Level 1	Level 2	Level 3
• Drinking-water distribution • Drinking-water treatment • Source water protection	• Corrective measures • Data management and reporting • Inspection and enforcement • Monitoring • Operator education and certification	• Guidelines, standards, and objectives • Legislative and policy framework • Public involvement and awareness • Research and development

legislative and regulatory guidelines in place in the province and was designed for both small (with some slight modifications) and large systems. This DWMS is mandated throughout the province for all owners and operators of municipal residential drinking-water systems (Ontario Ministry of the Environment, 2007).

The Ontario Ministry of the Environment (2007) emphasized four areas in developing the *Ontario Drinking Water Quality Management Standard*: (1) proactive/preventative, rather than strictly reactive, management strategies to identify and manage risks to public health; (2) the establishment and documentation of management procedures; (3) meeting these procedures; and (4) continuous improvement of the management system.

Implementation of this DWMS is divided into three steps (Plan/Do, Check, Improve), based on the Plan-Do-Check-Act cycle (Figure 1) (Ontario MoE, 2007). The Plan/Do section is subsequently broken down into 18 elements (Table 10).

Prince Edward Island (PE). Prince Edward Island is the smallest province in Canada, with a population of 148,600 (Statistics Canada, 2016). In regard to drinking-water management, the Government of Prince Edward Island (2001) published a document titled, '*Clear from the Ground to the Glass: 10 Points to Purity*'. While the Government of Prince Edward Island (2001) states, 'Our ten-point strategy uses a multiple-barrier approach to protect drinking water from the ground to the glass, including source protection, system design and operation, and monitoring reporting', the ten points do not highlight any specific drinking-water management approaches or recommended management elements.

Quebec (QC). The *Quebec Water Policy* was implemented in 2002 to ensure the sustainable management of water and protection of public health and the environment (Quebec Ministry of the Environment, 2002). According to the Quebec Ministry of Environment (2002), this DWMS revolves around five key orientations with specified key actions (Table 11). These orientations are then implemented through 16 key actions and 57 governmental agreements (Baril *et al.*, 2006).

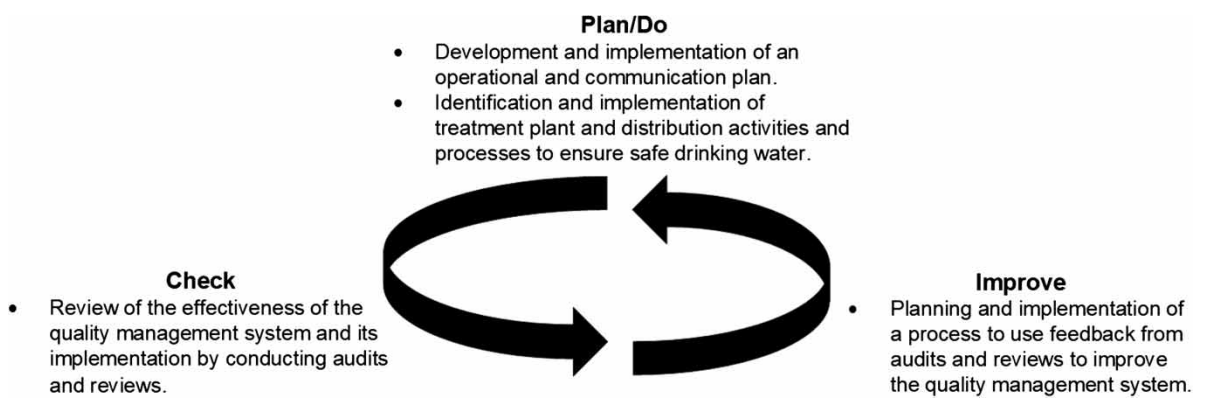

Fig. 1. Three steps of the *Ontario Drinking Water Quality Management Standard* (Ontario Ministry of Environment, 2007).

Table 10. *Ontario Drinking Water Quality Management Standard* plan/do elements (Ontario MOE, 2007).

No.	Element	Description
1	Quality management system	The development and documentation of a QMS (and maintenance of the system) that meets the requirements of the operational plan.
2	Quality management system policy	The development of a QMS policy with three main commitments: maintenance and improvement of the QMS, legislative compliance, and the provision of safe drinking water to the consumer.
3	Commitment and endorsement	The creation of an operational plan that is endorsed by management and the ability to prove its commitment to the QMS.
4	Quality management system representative	The description of specific requirements for selecting a QMS representative (appointment by management) that defines responsibilities and authorities for that role.
5	Document and records control	The establishment and use of document control and management procedures as part of the QMS.
6	Drinking-water system	The development of a process description and flow chart characterizing the entire drinking-water system from source to consumer.
7	Risk assessment	Elements 7 and 8 require the completion (and regular updating) of a risk assessment (using a risk assessment table) for the drinking-water system along with the implementation and documentation of risk management strategies. These modules include the identification of hazards and potential hazardous events, an assessment of the risk associated with hazardous events, ranking of hazardous events according to associated risk, the identification of control measures, the identification of critical control points, the establishment of critical control limits for each critical control point, and documentation of the risk assessment process and outcomes.
8	Risk assessment outcomes	
9	Organizational structure, roles, responsibilities, and authorities	Description (and communication) of the organizational structure of the operating authority that consists of a description of roles, responsibilities and authorities.
10	Competencies	The requirement that conditions in the operational plan are met and includes a documentation of the knowledge, skills, and abilities of all personnel (whose jobs affect drinking-water quality) and identification of necessary activities to ensure that competency requirements are met.
11	Personnel coverage	The development of procedures to ensure adequate coverage of duties affecting drinking-water quality by competent personnel.
12	Communications	The requirement of documented procedures (communication plan) describing how the QMS and QMS procedures are communicated between owners, operators, suppliers, and the public.
13	Essential supplies and services	The management and documentation of essential supplies and services that could potentially impact drinking-water quality.
14	Review and provision of infrastructure	The requirement of documented procedures (and reporting of results) for the annual review of drinking-water system infrastructure.
15	Infrastructure maintenance, rehabilitation, and renewal	The requirement of a summary (and communication of summary) detailing infrastructure maintenance, rehabilitation, and renewal programs for a drinking-water system. It also includes monitoring of the effectiveness of the maintenance program.
16	Sampling, testing, and, monitoring	Elements 16 and 17 require the establishment and implementation of procedures describing water sampling (and sampling plans) and testing and monitoring for process control and finished water quality. These procedures include surface water monitoring activities and details about the calibration and maintenance of the measurement and recording equipment.
17	Measurement and recording, equipment calibration, and maintenance	

(*Continued.*)

Table 10. (*Continued.*)

No.	Element	Description
18	Emergency management	The requirement that operational plans include (and conform to) emergency procedures and contact information, which includes information about communication, response, and recovery procedures (and testing of procedures), emergency training, responsibilities of personnel and management, municipal emergency planning measures, and an emergency contact list.

Table 11. *Quebec Water Policy* orientations and key actions (Quebec Ministry of the Environment, 2002).

No.	Orientation	Key actions
1	Water governance reform	1. Revision of the legal framework pertaining to water 2. Implementation of watershed-based management 3. Acquisition of knowledge and information about water 4. Introduction of economic instruments for governance 5. Strengthening of Quebec's partnerships and relationships
2	Integrated management of the St. Lawrence River	1. Grant the St. Lawrence River special status 2. Integrated management of the St. Lawrence River
3	Protection of water quality and aquatic ecosystems	1. Ensuring safe, quality drinking water 2. Protecting aquatic ecosystems
4	Continued clean-up and improved management of water services	1. Intensifying agricultural clean-up efforts 2. Broadening industrial clean-up efforts 3. Supplementing municipal clean-up efforts 4. Ensuring the sustainability of municipal infrastructures while improving the management of water services
5	Promotion of water-related recreational and tourism activities	1. Expanding access to water and promoting sport fishing 2. Promoting water safety and the quality of life on lakes and watercourses 3. Promoting nautical tourism

The *Quebec Water Policy* was designed to comprehensively incorporate both integrated water resources management and stakeholder involvement and is defined as a non-regulatory, voluntary approach to watershed management (Quebec Ministry of the Environment, 2002; Baril *et al.*, 2006; Hill *et al.*, 2008; Roy *et al.*, 2009; Rizvi & Adamowski, 2013). Integrated water resources management refers to the coordinated optimization and management of both upstream and downstream resources (e.g. water, land, habitats, etc.) to maximize economic and social benefits without compromising the sustainability of the environment (World Summit on Sustainable Development (WSSD), 2002; Rahaman & Varis, 2005). Together, these elements define the drinking-water management approach in the province.

With the 2002 implementation of the *Quebec Water Policy*, 33 priority watersheds were initially chosen by the Government of Quebec to develop an integrated water resources plan. This voluntary plan was designed to serve as a planning tool for determining and prioritizing interventions within a watershed to reach objectives defined by the water stakeholders (Gangbazo, 2004; Hill *et al.*, 2008). More recently, the Government of Quebec extended the integrated water resources plan principles to

the entire province across 40 watershed management zones (Gangbazo, 2011). The planning and implementation of this process involve seven different steps (Table 12).

In 2012, a strategy for the protection and conservation of source water intended for human consumption was proposed by the Government of Quebec (Government of Quebec, 2012). The strategy includes five steps: (1) water sources inventory; (2) source vulnerability assessment/risk assessment; (3) preparation of protection and conservation measures; (4) establishing implementation mechanisms of conservation and protection measures; and (5) establishing monitoring mechanisms.

In 2014, a regulation for drinking-water source protection was implemented (Government of Quebec, 2014). The purpose of this piece of legislation was to set standards for source water intakes, regulate water-quality sampling, and identify and regulate activities that could impact source water. It also included the mandatory implementation of vulnerability assessments of surface water sources for specified factors (e.g. microorganisms, turbidity, fertilizers, etc.) (Government of Quebec, 2014). A guidance

Table 12. Quebec integrated water resources management implementation steps (Gangbazo, 2004; Baril *et al.*, 2006).

No.	Steps	Description
1	Formation of a technical committee	The committee should be composed of all stakeholders having activities in the watershed and potential project funders (from academia, government, business and community).
2	Collection of information about the water system	Collection of information about threats, action possibilities, and water and ecosystem-related issues. It is composed of two parts: watershed description (e.g. activities, land use, etc.) and diagnosis of water and related ecosystem issues.
3	Setting issues and orientations	Definition of water management major concerns or fundamental challenges that must be addressed by watershed organizations. Actors must define the main actions for resolving issues identified. This step allows to provide a strategic overview of the different actions that should be defined and implemented.
4	Setting objectives and choice of indicators	General long-term objectives and specific short-term objectives must be defined at this stage. The objectives could be related to source water state and water uses. The indicators are administrative (performance) and environmental (ecosystem health and recovery).
5	Action plan development	Adoption of solutions (projects or activities) including voluntary or mandatory actions and enforcement programs (i.e. training and awareness programs), which may be conducted to achieve objectives and sustaining gains. The action plan could include: • Monitoring programs (administrative and environmental) • Partners' responsibilities (depending on their commitment) • Budget • Funding sources • Planning.
6	Action plan implementation	Action plan implementation is the responsibility of water stakeholders. Ideally, all governmental programs on water uses, water pollution control and protection or ecosystems restoration must be involved. Watershed organizations must plan additional measures (e.g. public information, raising funds and political commitment) to ensure the long-term viability of the project.
7	Follow-up and action plan assessment	Follow-up and assessment of environmental and socioeconomic impacts of the action plan and communication to the public.

document for the preparation and implementation of a vulnerability analysis was also developed and corresponds to the first step in the 2012 source water strategy discussed previously. Quebec does not have a specific DWMS for smaller utilities, however, the Ministry of Environment has released a design guide for small drinking-water treatment plants (Ellis, 2009).

Saskatchewan (SK). In Saskatchewan, a water management framework has been in place since 1999 (Government of Saskatchewan, 1999). After the waterborne disease outbreak in North Battleford, Saskatchewan in 2002, the province replaced the original drinking-water management framework with the *Safe Drinking Water Strategy* in 2003 in an attempt to '…demonstrate the province's commitment to making the conservation and protection of our water a top priority' (Government of Saskatchewan, 2003, p. 1).

As part of the *Safe Drinking Water Strategy*, the Government of Saskatchewan (2003) identified five guiding principles outlined here and four overarching goals with specific objectives (Table 13). The five guiding principles are: (1) human health as a primary concern; (2) preventing risks to drinking water is a high priority; (3) realistic pricing to acknowledge the value of safe drinking water; (4) accurate and timely information about water problems and solutions is essential; (5) governmental and stakeholder cooperation is key in developing and implementing water management solutions.

Today, the Saskatchewan Water Security Agency is responsible for the planning, implementation and reporting associated with drinking-water governance and management (as of 2012) (Government of Saskatchewan, 2014). However, the Saskatchewan Ministry of Environment, Ministry of Government Relations, the Ministry of Health/Health Regions, the Ministry of Agriculture, and SaskWater also play roles in the management of Saskatchewan drinking water (Government of Saskatchewan, 2014). Despite this extensive agency cooperation between different stakeholders, Saskatchewan does not have a mandatory DWMS in place throughout the province.

Table 13. Saskatchewan *Safe Drinking Water Strategy* goals and objectives (Government of Saskatchewan, 2003).

Goals	Objectives
Waterworks systems provide safe, clean, and sustainable drinking water.	• Waterworks staff are capable and well trained. • Infrastructure produces water that meets Canadian drinking-water standards. • Waterworks systems and operations are financially sustainable.
The drinking-water regulatory system is clear and effective.	• Regulations are clear and ensure that health and drinking-water quality will be protected. • Professional regulatory staff have access to the tools necessary to ensure compliance.
Source waters are protected now and into the future.	• Risks to source water are known. • Watersheds are protected, natural purification and protection processes are maximized, and potential for contamination is minimized.
Citizens and consumers trust and value their drinking water and the operations that produce it.	• Citizens have meaningful access to information about the quality of their water. • Reduced consumption of water. • Consumers value quality water and are willing to pay for it. • Citizens and consumers trust the quality and reliability of their drinking-water systems and are confident in the regulatory system.

Northwest Territories (NWT). Drinking-water management in the Northwest Territories has progressed further than in both Nunavut and the Yukon. Despite the fact that there are only 34 public water systems in the Territory, the waterborne disease outbreaks in Walkerton, Ontario and North Battleford, Saskatchewan pushed the government to begin development of a DWMS in 2001 (Government of the Northwest Territories, 2005). The *Northwest Territories Safe Drinking Water Framework and Strategy* is based on a three-layered multiple-barrier approach designed to incorporate all levels of government (Government of the Northwest Territories, 2014). The barriers are broken down into three categories: keeping water clean, making drinking water safe, proving that drinking water is safe (Table 14).

In 2011, the Government of the Northwest Territories published the *Water Stewardship Strategy* to improve cooperation of water management between stakeholders and address gaps and weaknesses in water stewardship within the territory (Government of the Northwest Territories, 2011). The Government of the Northwest Territories (2015) recently introduced a new website (www.nwtdrinkingwater.ca) to increase transparency for drinking water, treatment processes, and roles and responsibilities of the communities and governmental departments, but does not have a specific DWMS for smaller utilities.

Nunavut (NU). Nunavut has a population of approximately 11,000 people residing in 14 coastal communities (Martin *et al.*, 2007). Drinking-water treatment in Nunavut is generally simple, rarely incorporating any chemical or physical treatments aside from chlorination (Daley *et al.*, 2014). Due to the cold climate and economic situation in Nunavut, traditional distribution systems are rare, with most communities relying on trucked water delivery from a central municipal treatment facility (Martin *et al.*, 2007; Daley *et al.*, 2014). From a governance standpoint, all water resources (and water quality and quantity monitoring) in Nunavut are managed by Aboriginal Affairs and Northern Development Canada, which gives the department provincial-styled responsibilities, while the Nunavut Water Board is responsible for water permits. It is also important to note that the Canadian Federal Government has ownership of the water in Nunavut (NCCEH, 2014). Department of Health and Environmental Health Officers are responsible for enforcing public water supply regulations, however, there is no established approach to drinking-water management for the territory.

Yukon (YT). Drinking-water management in the Yukon is in its relative infancy. In 2003, the Canadian Federal Government transferred water management responsibilities to the Yukon government (Government of Yukon, 2014b). In 2014, the Government of the Yukon, with input from Yukon First Nations

Table 14. *Northwest Territories Safe Drinking Water Framework and Strategy* categories and barriers (Government of the Northwest Territories, 2014).

Keeping NWT water clean	Making drinking water safe	Proving drinking water is safe
• Community water licensing • Testing of source water quality • Coordinated watershed decision making • Effective legislation • Public education	• Standards and guidelines • Trained and certified water treatment plant operators • Water treatment and distribution systems • Effective legislation • Public education	• Testing and monitoring of treated water quality • Public access to water-quality data • Incident tracking and reporting • Public reporting on drinking-water quality • Assessment of water treatment infrastructure and operations • Public education

governments, released the *Yukon Water Strategy and Action Plan* to address water management within the territory (only focused on groundwater) (Government of Yukon, 2014a). This approach consists of six priority areas: (1) better understanding and management of groundwater; (2) planning for water needs now and into the future; (3) improving water management programs; (4) maintaining/improving access to safe drinking water; (5) promoting the sustainable use of water; (6) improving the sharing of information about Yukon's water.

In the Yukon, water licenses are issued by the Yukon Water Board, and Health and Social Services are responsible for the regulation of drinking-water systems (Government of Yukon, 2011). The *Yukon Water Strategy and Action Plan* is a milestone for water management in the territory, however, there is limited information available specifically related to the DWMS and elements in place.

Analysis

There are many distinct differences and small nuances between the reviewed QMSs and DWMSs. In Table 15, the ISO, 9001:2015 QMS, the HACCP QMS, and the DWMSs implemented/recommended by Australia, Canada, New Zealand and the WHO are compared across 41 management elements developed from a review of literature and regulatory documents to standardize the comparison process. The selected elements are broken down into six management categories: (1) Administrative – regulatory requirements, stakeholder involvement, organizational controls; (2) Assessment – analysis of the complete system and all included sub-processes; (3) Mitigation – review, inventory, planning of preventative

Table 15. Comparison of selected QMSs and national drinking-water management approaches.

Category	Elements	HACCP[b,d,f,g]	ISO, 9001 (2015)[c]	Australia[d]	Canada[a]	New Zealand[e]	WHO (2011)[h]
Administrative	Assemble quality-management team(s)	X	–	X	–	–	X
	Commitment to drinking-water quality management	–	–	X	–	–	–
	Communication outreach plan	–	X	X	–	–	X
	Drinking-water quality policy	–	–	X	X	X	–
	Management plan	–	–	–	–	–	–
	Modified method for smaller systems	X	–	X	–	X	–
	Public involvement and awareness	–	X	X	X	–	–
	Regulatory and formal requirements (legally binding)	X	X	X	X	X	–
	Health-based targets	–	–	–	–	–	X
Assessment	Critical control points	X	–	X	–	–	–
	Flow diagram	X	–	X	–	X	–
	Hazard identification/risk assessment	X	–	X	–	X	X
	Hazard (risk) prioritization	–	–	X	–	–	–
	Identification of barriers and/or control measures	–	–	–	–	X	X
	System analysis	X	–	X	–	X	X

(*Continued.*)

Table 15. (*Continued.*)

Category	Elements	HACCP[b,d,f,g]	ISO, 9001 (2015)[c]	Australia[d]	Canada[a]	New Zealand[e]	WHO (2011)[h]
Mitigation	Contingency planning/incident response protocols	–	–	X	–	X	–
	Employee involvement (awareness, competency, training)	X	X	X	X	–	X
	Equipment capability and maintenance verification	–	X	X	–	–	–
	Established critical limits	X	–	–	–	–	–
	General preventative measures (non-specific)	–	–	–	–	X	–
	Multiple barriers	X	–	X	X	–	–
	Watershed (source) management	–	–	X	X	–	–
Monitoring and verification	Operational monitoring	X	X	X	–	–	X
	Control measure monitoring	–	X	X	–	–	X
	Customer satisfaction monitoring	–	X	X	–	–	–
	General monitoring (non-specific)	X	–	–	–	–	–
	Independent monitoring	–	–	–	–	–	X
	Process validation	X	X	–	–	–	–
	Water-quality monitoring	X	–	–	X	–	–
Improvement	Corrective actions	X	X	X	–	X	X
	Inventory of available resources for improvement	–	–	–	–	–	–
	Prioritization of improvements	–	–	–	–	X	–
	Research and development	–	–	X	X	–	–
	Timetable for improvements	–	–	–	–	X	–
Documentation and review	Audit/review of QMS	X	X	X	–	X	X
	Continuous improvement	–	X	X	X	X	–
	Documentation, record-keeping, and reporting (general)	X	X	X	–	–	X
	QMS Improvement Plan	–	X	–	–	–	–
	Identification of links to other quality-assurance systems	–	–	–	–	X	X
	Management of documentation and record-keeping	X	X	–	–	–	–
	Review by senior executive	X	X	X	–	–	–

[a]CCME (2002).
[b]Davison *et al.* (2006).
[c]ISO (2015).
[d]NHMRC (2011).
[e]NZMOH (2015).
[f]Ropkins & Beck (2000).
[g]Sperber (2005).
[h]WHO (2011).

measures, management; (4) Monitoring and verification – review and validation of performance-monitoring practices; (5) Improvement – identification and prioritization of improvements, development; and (6) Documentation and review – record-keeping, auditing, review processes.

Within Canada, the provincial and territorial approaches to drinking-water management were also compared (Table 16) based on the same elements and categories found in Table 15. The results in Table 16 illustrate the differences of drinking-water management approaches that can be found throughout Canada and highlight the frequency of each management element within Canadian provincial/territorial DWMSs. The dark-gray shading represents management elements that are found in less than 30% of all provincial/territorial DWMSs; the light-gray shading represents management elements that are found in less than 50% of all provincial/territorial DWMSs; white (no shading) represents management elements found in greater than 50% of all provincial/territorial DWMSs. The general QMSs and national DWMS approaches/recommendations were excluded from the frequency values found in Table 16 in order to provide a more-representative picture of the provincial/territorial DWMSs and to better highlight common deficiencies and management gaps found in Canada.

Results and discussion

Quantifying the performance of DWMSs and the importance of individual management elements is difficult due to its qualitative nature. However, by comparing the DWMSs with each other, a context to gauge the comprehensiveness of an individual DWMS can be established. With this information, potential management gaps and areas for improvement can be identified and used by DWSS planners, operators and legislators to improve existing, or developing new, DWMSs. After reviewing the frequency of different management elements and the comparisons in Tables 15 and 16, it is evident that there are significant differences between approaches to drinking-water management in different parts of the world and across Canada. While these differences can most likely be attributed to a variety of factors (e.g. legislation, priorities, governance structure) and that some elements may be considered more important than others, the lack of consistency across DWMSs is surprising, given the same goal of providing safe, clean drinking water.

The results in Table 15 illustrate the lack of a comprehensive federal DWMS in Canada, especially when comparing the *CCME Multi-barrier Approach* and the incorporated management elements to the DWMSs in Australia and New Zealand and the *WHO WSP Recommendations*. This is expected, given the broad, oversight-oriented approach to federal drinking-water management and the decentralized governance structure in Canada (Hill *et al.*, 2008). In theory, the *CCME Multi-barrier Approach* is designed to be a broad management template, complemented by provincial/territorial DWMSs. However, in practice, this is not the case.

The results in Table 16 highlight the vastly different approaches to drinking-water management across the provinces and territories. While some provinces such as British Columbia, Ontario and Quebec appear to provide more-comprehensive approaches to drinking-water management and cover many of the identified management elements, provinces and territories with less-developed approaches, such as New Brunswick, Nunavut, Prince Edward Island and the Yukon, may be leaving consumers susceptible to drinking-water quality issues by relying on less-comprehensive or non-existent DWMSs. This vulnerability could be amplified even further in small, rural and First Nations communities where human resources and budgetary constraints already result in significant challenges (Scheili *et al.*, 2015).

Table 16. Comparison of Canadian provincial and territorial drinking-water management approaches and frequency of included elements.

Category	Elements	AB[f]	BC[a,b,c]	MB[m]	NB[d]	NL[g,h]	NS[i]	NT[l]	NU[d]	ON[n]	PE[d,j]	QC[e]	SK[j,k]	YT[d]	Frequency of elements
Administrative	Assemble quality-management team(s)	–	X	X	–	–	X	–	–	X	–	X	–	–	38.5%
	Commitment to drinking-water quality management	–	–	–	–	X	X	–	–	X	–	–	–	–	23.1%
	Communication outreach plan	–	–	–	–	–	X	X	–	X	–	X	–	–	30.8%
	Drinking-water quality policy	X	X	X	–	X	X	–	–	X	X	–	–	–	53.8%
	Management plan	X	–	–	–	–	–	–	–	X	–	X	–	–	23.1%
	Modified method for smaller systems	–	X	–	–	–	–	–	–	X	–	–	–	–	15.4%
	Public involvement and awareness	X	–	–	–	X	–	X	–	X	–	X	X	–	46.2%
	Regulatory and formal requirements (legally binding)	X	–	X	–	–	X	X	–	X	–	–	X	X	53.8%
Assessment	Health–based targets	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0%
	Critical control points	–	–	–	–	–	–	–	–	X	–	–	–	–	7.7%
	Flow diagram	–	X	–	–	–	–	–	–	X	–	X	–	–	23.1%
	Hazard identification/risk assessment	X	X	–	–	–	X	–	–	X	–	X	–	–	38.5%
	Hazard (risk) prioritization	–	X	–	–	–	–	–	–	X	–	–	–	–	15.4%
	Identification of barriers and/or control measures	–	X	–	–	–	–	X	–	X	–	X	–	–	30.8%
	System analysis	X	X	X	–	–	X	X	–	X	–	X	–	–	53.8%
Mitigation	Contingency planning/incident response protocols	–	X	–	–	–	–	X	–	X	–	–	–	–	23.1%
	Employee involvement (awareness, competency, training)	X	X	X	X	–	X	X	X	X	X	X	X	X	92.3%
	Equipment capability and maintenance verification	–	X	–	–	–	–	X	–	X	–	–	–	–	23.1%
	Established critical limits	–	–	–	–	–	–	–	–	X	–	X	–	–	15.4%
	General preventative measures (non-specific)	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0%
	Multiple barriers	–	X	–	–	X	X	X	–	X	–	–	X	–	46.2%
	Watershed (source) management	–	X	X	–	X	X	X	–	X	–	X	X	–	61.5%
Monitoring and verification	Operational monitoring	–	X	–	–	X	X	X	–	X	–	–	–	–	38.5%
	Control measure monitoring	–	–	–	–	X	X	–	–	X	–	X	–	–	30.8%
	Customer satisfaction monitoring	–	X	–	–	X	–	X	–	X	–	–	–	–	30.8%
	General monitoring (non-specific)	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0%
	Independent monitoring	–	–	–	–	–	–	–	–	–	–	X	–	–	7.7%
	Process validation	–	X	–	–	–	X	–	–	X	–	–	–	–	23.1%
	Water-quality monitoring	–	X	–	–	X	X	X	–	X	–	X	X	–	53.8%

(*Continued.*)

Table 16. (*Continued.*)

Category	Elements	AB[f]	BC[a,b,c]	MB[m]	NB[d]	NL[g,h]	NS[i]	NT[l]	NU[d]	ON[n]	PE[d,j]	QC[e]	SK[j,k]	YT[d]	Frequency of elements
Improvement	Corrective actions	X	X	–	–	X	X	–	–	X	–	X	X	–	53.8%
	Inventory of available resources for improvement	X	X	X	–	–	X	–	–	X	–	X	–	–	46.2%
	Prioritization of improvements	X	X	X	–	–	–	–	–	X	–	X	–	–	38.5%
	Research and development	–	–	–	–	X	–	–	–	X	–	–	–	–	15.4%
	Timetable for improvements	X	X	X	–	–	–	–	–	X	–	X	–	–	38.5%
Documentation and review	Audit/review of DWMS	X	X	–	–	–	X	–	–	X	–	X	–	–	38.5%
	Continuous improvement	–	–	–	–	–	X	–	–	X	–	–	–	–	15.4%
	Documentation, record-keeping, and reporting (general)	–	X	–	–	X	X	X	–	X	–	X	–	–	46.2%
	DWMS improvement plan	–	X	–	–	–	–	–	–	X	–	X	–	–	23.1%
	Identification of links to other quality-assurance systems	–	X	–	–	–	–	–	–	–	–	–	–	–	7.7%
	Management of documentation and record-keeping	–	X	–	–	–	–	–	–	X	–	X	–	–	23.1%
	Review by senior executive	–	–	–	–	–	X	–	–	X	–	–	–	–	15.4%

[a]BCMHLS (2010).
[b]BCMOH (2013).
[c]BCOPHO (2015).
[d]Dunn *et al*. (2014).
[e]Gangbazo (2011).
[f]Government of Alberta (2012).
[g]Government of Newfoundland and Labrador (2001).
[h]Government of Newfoundland and Labrador (2015).
[i]Government of Nova Scotia (2002).
[j]Government of Prince Edward Island (2001).
[k]Government of Saskatchewan (2003).
[l]Government of the Northwest Territories (2005).
[m]Manitoba Provincial Planning Regulation (n.d.).
[n]Ontario Ministry of Environment (2007).

It is also important to note the differences found between the majority of DWMSs and the more-generalized QMS approaches in Table 15. These differences can be attributed to the fact that the chosen DWMSs are, by their nature, more specific in terms of elements applying to the actual water treatment process. However, while most DWMSs highlight specifics such as watershed (source) management, regulatory requirements and drinking-water quality policy, they appear to focus less on monitoring, verification, documentation and review than is suggested by the ISO, 9001:2015 and the HACCPs approach.

Recommendations

In order to address the multifaceted nature of drinking-water management and governance in Canada and to ensure high-quality drinking water from catchment to the consumer's tap, the Canadian Federal Government must take a more-proactive role with provincial, territorial and municipal drinking-water management. While the *CCME Multi-barrier Approach* serves as a broad template for the preventative management of DWSSs, it is overly generic and does not provide a defined pathway for implementation. In this context, a guidance document such as the WHO *Guidelines for Drinking-water Quality* (Chapter 4 – WSPs) (WHO, 2011) should be developed and implemented specifically for Canada to serve as a more-useful resource for provincial and territorial governments in the development of improved DWMSs.

Given the nature of Canada's decentralized governance structure, provincial/territorial governments have and will continue to maintain the most direct responsibility for drinking-water management (de Loë & Kreutzwiser, 2007). In order to ensure high-quality, consistent drinking-water across the country, provincial and territorial governments must strive to develop, implement and enforce the use of more-comprehensive catchment to consumer DWMSs, as is already established in Ontario and Quebec. The provincial/territorial governments should also explore the implementation of more-general QMS elements and place a greater emphasis on continuous improvement, monitoring/documentation and review.

With almost 80% of all public drinking-water utilities in Canada serving populations of fewer than 5,000 people, steps must also be taken to ensure that smaller municipalities can meet the financial and human resource demands of more-comprehensive DWMSs (Statistics Canada, 2011; Scheili *et al.*, 2014; Bereskie *et al.*, 2017a). In terms of implementation, this can follow the example set by the *Australian Framework for Management of Safe Drinking Water* (NHMRC, 2011), with smaller systems focusing heavily on preventative management (e.g. more-frequent use of sanitary inspections to identify potential sources of contamination) and approaching formal water-quality testing and monitoring in a more cost-effective manner (WHO, 1996, 2011; NHMRC, 2011).

Conclusion

DWMSs encompass a wide variety of differing policies, procedures and administrative/behavioral controls for ensuring safe drinking water throughout the world. Canada is no exception to this variability, with vastly different approaches to drinking-water management across the country. Although quantifying the effectiveness and impact of management practices is difficult, given their nature, comparing the Canadian state of practice and management elements at the national and provincial/territorial level against the WHO, world leaders in regard to DWMSs and well-established QMSs, a context can be

provided to characterize the comprehensiveness of the existing Canadian provincial and territorial DWMSs.

The results of this comparison show DWMSs ranging from comprehensive (e.g. Ontario) to outdated (e.g. Prince Edward Island) and non-existent (e.g. Nunavut) and highlight specific management elements (i.e. independent monitoring, continuous improvement, senior-executive review, etc.) and categories (i.e. documentation and review and monitoring and verification) lacking in Canadian provincial/territorial DWMSs. The information from this review can be valuable to stakeholders, legislators and decision-makers looking to improve DWSSs through more efficient and effective management practices from other DWMSs or less-specific QMSs.

Future studies related to reviewing and comparing DWMSs should include more international DWMSs and general QMSs for comparison. This can help to potentially identify more categories and elements that should be included as part of a comprehensive DWMS. As the use and documentation associated with DWMSs continue to expand, more information will be available regarding the impact of including and excluding specific management elements. Furthermore, future research should incorporate the development of a performance metric, potentially integrating water quality, customer satisfaction and utility reliability, to quantify the effectiveness of individual management elements and, subsequently, overall DWMS performance. In this same context, the impacts and effectiveness of DWMSs specifically in small, rural and First Nations communities should be investigated to provide additional information for decision-makers looking to improve DWSS performance in these vulnerable areas.

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References

Alberta Environment (2009). *Alberta Environment's Drinking Water Program: A Source to Tap, Multi-Barrier Approach*. Edmonton. Available at: http://environment.gov.ab.ca/info/library/8156.pdf (accessed 1 April 2016).

Bakker, K. (2007). *Eau Canada: The Future of Canada's Water*. University of British Columbia Press, Vancouver.

Bakker, K. & Cook, C. (2011). Water governance in Canada: innovation and fragmentation. *International Journal of Water Resources Development 27*, 275–289. http://doi.org/10.1080/07900627.2011.564969.

Baril, P., Maranda, Y. & Baudrand, J. (2006). Integrated watershed management in Quebec (Canada): a participatory approach centered on local solidarity. *Water Science and Technology 53*(10), 301–307.

Bartram, J., Fewtrell, L. & Stenström, T. (2001). Harmonised assessment of risk and risk management for water-related infectious disease: an overview. Water Quality: Guidelines, Standards and Health. Available at: http://www.who.int/water_sanitation_health/dwq/iwachap1.pdf (accessed 7 November 2015).

Baum, R., Amjad, U., Luh, J. & Bartram, J. (2015). An examination of the potential added value of water safety plans to the United States national drinking water legislation. *International Journal of Hygiene and Environmental Health 218*, 677–685. doi:10.1016/j.ijheh.2014.12.004.

Bereskie, T., Rodriguez, M. J. & Sadiq, R. (2017a). Drinking water management and governance in Canada: an innovative plan-do-check-act (PDCA) framework for a safe drinking water supply. *Environmental Management 60*, 243–262. doi.org/10.1007/s00267-017-0873-9.

Bereskie, T., Haider, H., Rodriguez, M. J. & Sadiq, R. (2017b). Framework for continuous performance improvement in small drinking water systems. *Science of the Total Environment 574*, 1405–1414. doi.org/10.1016/j.scitotenv.2016.08.067.

British Columbia Ministry of Health (BCMOH) (2013). Small Water System Guidebook. Available at: http://www2.gov.bc.ca/assets/gov/environment/air-land-water/small-water-system-guidebook.pdf (accessed 1 April 2016).

British Columbia Ministry of Health Living and Sport (BCMHLS) (2010). Comprehensive Drinking Water Source-To-Tap Assessment Guideline. Available at: http://www2.gov.bc.ca/assets/gov/environment/air-land-water/cs2ta-intro.pdf (accessed 1 April 2016).

British Columbia Office of the Provincial Health Officer (BCOPHO) (2015). Progress on the Action Plan for Safe Drinking Water in British Columbia, Victoria. Available at: http://www2.gov.bc.ca/assets/gov/environment/air-land-water/pho-drinkingwater2015-web.pdf (accessed 1 April 2016).

Canadian Council of Ministers of the Environment (CCME) (2002). From Source to Tap: The multi-barrier approach to safe drinking water. Available at: http://www.hc-sc.gc.ca/ewh-semt/alt_formats/hecs-sesc/pdf/water-eau/tap-source-robinet/tap-source-robinet-eng.pdf (accessed 19 January 2015).

CCME (2004). From Source to Tap: Guidance on the Multi-Barrier Approach to Safe Drinking Water. Available at: http://www.ccme.ca/files/Resources/water/source_tap/mba_guidance_doc_e.pdf (accessed 19 January 2015).

Cianfrani, C. A. & West, J. E. (2014). *ISO 9001:2008 Explained & Expanded.* American Society for Quality, Quality Press, Milwaukee.

Conservation Council of New Brunswick (2016). Water Policy in New Brunswick. Available at: https://www.conservation-council.ca/our-programs/freshwater-protection/water-policy-in-new-brunswick/ (accessed 1 April 2016).

Daley, K., Castleden, H., Jamieson, R., Furgal, C. & Ell, L. (2014). Municipal water quantities and health in Nunavut households: an exploratory case study in Coral Harbour, Nunavut, Canada. *International Journal of Circumpolar Health 73*, 1–9. http://doi.org/10.3402/ijch.v73.23843.

Davison, A., Deere, D., Stevens, M., Howard, G. & Bartram, J. (2006). Water Safety Plan Manual. Available at: http://cdrwww.who.int/entity/water_sanitation_health/dwq/manual.pdf (accessed 21 March 2016).

de Loë, R. & Kreutzwiser, R. D. (2007). Challenging the status quo: the evolution of water governance in Canada. In: *Eau Canada: The Future of Canada's Water.* Bakker, K. (ed.). University of British Columbia Press, Vancouver.

Dunn, G., Bakker, K. & Harris, L. (2014). Drinking water quality guidelines across Canadian provinces and territories: jurisdictional variation in the context of decentralized water governance. *International Journal of Environmental Research and Public Health 11*, 4634–4651. doi:10.3390/ijerph110504634.

Dunn, G., Harris, L. & Bakker, K. (2015). Microbial risk governance : challenges and opportunities in fresh water management in Canada. *Canadian Water Resources Journal 40*(3), 237–249. http://doi.org/10.1080/07011784.2015.104364.

Ellis, D. (2009). Design guide for small drinking water treatment plants, Québec, Ministère du Développement durable, de l'Environnement et des Parcs (PDF).

Exall, K., Marsalek, J. & Schaefer, K. (2006). Water reuse in Canada: opportunities and challenges. In: *Integrated Urban Water Resources Management.* Hlavinek, P., Kukharchuyk, T., Marsalek, J. & Mahrikova, I. (eds). Springer, Berlin, New York, pp. 253–262. http://doi.org/10.1007/1-4020-4685-5_26.

Gagnon, G. (2014). Drinking Water Safety Plans. Available at: http://www.cwn-rce.ca/assets/Uploads/Drinking-Water-Safety-Plan-Report-2015.pdf (accessed 19 January 2015).

Gangbazo, G. (2004). *Élaboration d'un plan directeur de l'eau: guide à l'intention des organismes de bassins versants.* Ministry of Environment, Québec.

Gangbazo, G. (2011). *Guide pour l'élaboration d'un plan directeur de l'eau: un manuel pour assister les organismes de bassin versant du Québec dans la planification de la gestion intégrée des ressources en eau.* Ministry of Environment, Québec.

Government of Alberta (2012). A guidance framework for the production of drinking water safety plans. Available at: http://environment.gov.ab.ca/info/posting.asp?assetid=8489&searchtype=asset&txtsearch=drinkingwatersafety (accessed 7 November 2015).

Government of New Brunswick (2009). Know Your H_2O: Domestic Water Quality Monitoring. Available at: http://www2.gnb.ca/content/dam/gnb/Departments/env/pdf/Water-Eau/KnowYourH2O.pdf (accessed 11 November 2016).

Government of Newfoundland and Labrador (2001). Source to Tap: Water Supplies in Newfoundland and Labrador, St John's. doi:10.1002/ejoc.201200111.

Government of Newfoundland and Labrador (2010). *Drinking Water Safety in Newfoundland and Labrador: Annual Report 2010.* Available at: http://www.env.gov.nl.ca/env/waterres/reports/drinking_water/annual_report_2009-10.pdf (accessed 7 April 2016).

Government of Newfoundland and Labrador (2015). *Drinking Water Safety in Newfoundland and Labrador: Annual Report 2015, St. John's.* Available at: http://www.env.gov.nl.ca/env/waterres/reports/drinking_water/annual_report_2015.pdf (accessed 1 April 2016).

Government of Nova Scotia (2002). *A Drinking Water Strategy for Nova Scotia*. Available at: https://www.novascotia.ca/nse/water/docs/NSWaterStrategy.pdf (accessed 13 November 2016).

Government of Prince Edward Island (2001). Clear from the ground to the glass: 10 Points to Purity. Available at: http://www.gov.pe.ca/photos/original/10points2purity.pdf (accessed 13 November 2016).

Government of Quebec (2012). Strategy of protection and conservation of water sources intended for human consumption (Projet de stratégie de protection et de conservation des sources destinées à l'alimentation en eau potable). Public consultation document.

Government of Quebec (2014). Regulation for water intake and sources protection (Règlement sur le prélèvement des eaux et leur protection). Loi sur la qualité de l'environnement, chapitre Q-2, r. 35.2 Gazette Officielle du Québec, No. 31.

Government of Saskatchewan (1999). Water Management Framework. Available at: http://www.saskh20.ca/PDF/Water%20Management%20Framework%201999.pdf (accessed 7 April 2016).

Government of Saskatchewan (2003). Saskatchewan's Safe Drinking Water Strategy. Available at: http://www.saskh2o.ca/pdf/ltsdws_report2003.pdf (accessed 7 April 2016).

Government of Saskatchewan (2014). *Annual Report for 2014–2015: State of Drinking Water Quality in Saskatchewan*. Available at: https://www.wsask.ca/Global/AboutWSA/AnnualReportsandPlans/DrinkingWaterAnnualReport/WSA-Drinking-Water-Report-14-2015.pdf (accessed 6 January 2016).

Government of the Northwest Territories (2005). Managing Drinking Water Quality in the Northwest Territories. Available at: http://www.maca.gov.nt.ca/operations/water/docs/waterframework.pdf (accessed 7 November 2015).

Government of the Northwest Territories (2011). Northern Voices, Northern Waters: NWT Water Stewardship Strategy. Available at: http://www.enr.gov.nt.ca/sites/default/files/strategies/nwt_water_stewardship_strategy.pdf (accessed 11 November 2016).

Government of the Northwest Territories (2014). GNWT Report on Drinking Water. Available at: http://www.nwtdrinking-water.ca/wp-content/uploads/MACA-Drinking-Water-Report-2014.pdf (accessed 11 November 2016).

Government of the Northwest Territories (2015). 2015 Water Quality Summary. Available at: http://www.nwtdrinkingwater.ca/wp-content/uploads/2015_Primer_Final.pdf (accessed 11 November 2016).

Government of Yukon (2011). Best Management Practices for Works Affecting Water in Yukon. Available at: http://www.env.gov.yk.ca/publications-maps/documents/bestpractes_water.pdf (accessed 11 November 2016).

Government of Yukon (2014a). *History of Water Management in Yukon*, Whitehorse, YT. Available at: http://www.env.gov.yk.ca/publications-maps/documents/FS_history_water_mgmt.pdf (accessed 11 November 2016).

Government of Yukon (2014b). Yukon Water Strategy and Action Plan. Available at: http://www.env.gov.yk.ca/publications-maps/documents/Yukon_Water_Strategy_Action_Plan.pdf (accessed 13 September 2016).

Gunnarsdóttir, M. J. & Gissurarson, L. R. (2008). HACCP and water safety plans in Icelandic water supply: preliminary evaluation of experience. *Journal of Water and Health 6*, 377. doi:10.2166/wh.2008.055.

Gunnarsdóttir, M. J., Gardarsson, S. M., Elliott, M., Sigmundsdottir, G. & Bartram, J. (2012). Benefits of water safety plans: microbiology, compliance, and public health. *Environmental Science and Technology 46*, 7782–7789.

Hill, C., Furlong, K., Bakker, K. & Cohen, A. (2008). Harmonization versus subsidiarity in water governance: a review of water governance and legislation in the Canadian Provinces and Territories. *Canadian Water Resources Journal 33*, 315–332. doi:10.4296/cwrj3304315.

Hrudey, S. E. (2011). Safe Drinking Water Policy for Canada – Turning Hindsight into Foresight. C.D. Howe Institute Commentary No. 323. doi: 10.2139/ssm.1799531.

Hrudey, S. E., Payment, P., Huck, P. M., Gillham, R. W. & Hrudey, E. J. (2003). A fatal waterborne disease epidemic in Walkerton, Ontario: comparison with other waterborne outbreaks in the developed world. *Water Science and Technology 47*, 7–14.

Hrudey, S. E., Hrudey, E. J. & Pollard, S. J. T. (2006). Risk management for assuring safe drinking water. *Environment International 32*, 948–957. doi:10.1016/j.envint.2006.06.004.

Hubbert, D. (2013). Identifying Drinking Water Regulatory Frameworks, University of Victoria. Available at: http://hdl.handle.net/1828/4811 (accessed 22 December 2015).

Hulsmann, A. & Smeets, P. (2011). Towards a Guidance Document for the implementation of a Risk Assessment for small water supplies in the European Union, Nieuwegein. Available at: https://circabc.europa.eu/sd/d/d091f8a9-e4ba-4800-89c8-09574a6f3d8e/TowardsBestPracticesDocument.pdf (accessed 1 June 2016).

International Organization for Standardization (ISO) (2015). *ISO 9001: Quality Management Systems – Requirements*. International Organization for Standardization, Geneva, Switzerland.

Jayaratne, A. (2008). Application of a risk management system to improve drinking water safety. *Journal of Water and Health 6*, 547–557. doi:10.2166/wh.2008.061.

Kafetzopoulos, D. P., Psomas, E. L. & Kafetzopoulos, P. D. (2013). Measuring the effectiveness of the HACCP food safety management system. *Food Control 33*, 505–513. doi:10.1016/j.foodcont.2013.03.044.

Langley, G. J., Nolan, K. M. & Nolan, T. W. (1994). The foundation of improvement. *Quality Progress 27*, 81–86.

Legislative Assembly of Manitoba (2005). The Water Protection Act, c. W65. Available at: https://web2.gov.mb.ca/laws/statutes/ccsm/w065e.php (accessed 7 April 2016).

Legislative Assembly of Manitoba (2011). Bill 46: The Save Lake Winnipeg Act 2011 Legislative Assembly of Manitoba, 5th Session, 39th Legislature. Available at: https://web2.gov.mb.ca/bills/39-5/b046e.php (accessed 7 April 2016).

Lodgaard, E. & Aasland, K. E. (2011). An examination of the application of plan-do-check-act cycle in product development. *Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol.* 10: Design Methods and Tools pt. 2. Lyngby/Copenhagen.

Manitoba Provincial Planning Regulation (n.d.). Guide to Developing a Drinking Water Plan. Available at: http://www.gov.mb.ca/imr/mr/plups/pdf/dwg.pdf (accessed 7 April 2016).

Manitoba Water Stewardship (2003). The Manitoba Water Strategy. Available at: https://www.gov.mb.ca/conservation/waterstewardship/waterstrategy/pdf/index.html?print&print&print (accessed 7 April 2016).

Manitoba Water Stewardship (2007). Best Practices Manual for Small Drinking Water Systems. Available at: http://www.gov.mb.ca/waterstewardship/odw/reg-info/operations-monitor/best_practices_for_small_drinking_water_systems-manual.pdf (accessed 14 October 2015).

Manitoba Water Stewardship (2011a). Safe Drinking Water. Available at: https://www.gov.mb.ca/waterstewardship/odw/public-info/fact_sheets/pdf/factsheet_drinking_water_program.pdf (accessed 7 April 2016).

Manitoba Water Stewardship (2011b). Manitoba Water Quality Standards, Objectives, and Guidelines. Available at: https://www.gov.mb.ca/waterstewardship/water_quality/quality/pdf/mb_water_quality_standard_final.pdf (accessed 7 April 2016).

Martin, D., Bélanger, D., Gosselin, P., Brazeau, J., Furgal, C. & Déry, S. (2007). Drinking water and potential threats to human health in Nunavik: adaptation strategies under climate change conditions. *Arctic 60*, 195–202. http://doi.org/10.1016/j.neuroimage.2009.09.064.

Martinez-Costa, M., Choi, T. Y., Martinez, J. A. & Martinez-Lorente, A. R. (2009). ISO 9000/1994, ISO 9001/2000 and TQM: the performance debate revisited. *Journal of Operations Management 27*, 495–511. doi:10.1016/j.jom.2009.04.002.

Moen, R. (2009). Foundation and history of the PDSA Cycle. In: *Asian Network for Quality Conference*, 15–18 September, Tokyo. Available at: https://www.deming.org/sites/default/files/pdf/2015/PDSA_History_Ron_Moen.pdf (accessed 21 October 2016).

Moen, R. & Norman, C. (2006). Evolution of the PDCA cycle. Available at: http://cissp. tjscott.net/standards/moen.norman.pdca.origins.pdf (accessed 8 November 2015).

Murphy, H., Thomas, M., Medeiros, D., McFadyn, S. & Pintar, K. (2016). Estimating the number of cases of acute gastrointestinal illness (AGI) associated with Canadian municipal drinking water systems. *Epidemiology and Infection 144*(7), 1371–1385. doi:10.1017/S0950268815002083.

National Collaborating Centre for Environmental Health (NCCEH) (2014). Small Drinking Water Systems: Who Does What in Nunavut? Available at: http://www.ncceh.ca/sites/default/files/SDWS_Who_What_Nunavut.pdf (accessed 7 April 2016).

National Health and Medical Research Council (NHMRC) (2011). *Australian Drinking Water Guidelines Paper 6: National Water Quality Management Strategy*. National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra. doi:1864965118.

National Research Council (2006). *Drinking Water Distribution Systems: Assessing and Reducing Risks.* National Academies Press, Washington, DC. Available at: http://www.nap.edu/download.php?record_id=11728# (accessed 25 May 2016).

Nova Scotia Environment and Labour (2005). *A Drinking Water Strategy for Nova Scotia: Final Report*. Available at: https://novascotia.ca/nse/water/docs/NSWaterStrategyReport.pdf (accessed 11 November 2016).

Nova Scotia Environment and Labour (n.d.). *Safe Drinking Water for Public Water Systems: A Diligent Approach*. Halifax, NS. Available at: https://novascotia.ca/nse/water/docs/DrinkingWaterDueDiligenceFull.pdf (accessed 11 November 2016).

NZMOH (2008). Drinking-water Standards for New Zealand 2005 (Revised 2008) (Vol. 2005). New Zealand Ministry of Health, Wellington, NZ. Available at: http://www.health.govt.nz/publication/drinking-water-standards-new-zealand-2005-revised-2008-0 (accessed 30 March 2016).

NZMOH (2014). *Small Drinking-Water Supplies: Preparing A Water Safety Plan.* New Zealand Ministry of Health, Wellington, NZ. Available at: http://www.health.govt.nz/system/files/documents/publications/small-drinking-water-supplies-jan14-v2_0.pdf (accessed 30 March 2016).

NZMOH (2015). *Guidelines for Drinking-Water Quality Management for New Zealand.* New Zealand Ministry of Health, Wellington, NZ. Available at: http://www.health.govt.nz/system/files/documents/publications/guidelines-drinking-water-quality-management-for-new-zealand-2015-oct15.pdf (accessed 7 November 2015).

O'Connor, D. R. (2002a). *Report of the Walkerton Inquiry: The Events of May 2000 and Related Issues, Part two*. Queen's Printer for Ontario, Toronto.

O'Connor, D. R. (2002b). *Report of the Walkerton Inquiry: The Events of May 2000 and Related Issues, Part one*. Queen's Printer for Ontario, Toronto.

Ontario Ministry of the Environment (2007). Implementing Quality Management: A Guide for Ontario's Drinking Water Systems. Available at: https://dr6j45jk9xcmk.cloudfront.net/documents/1592/4-1a-1a-quality-management-system-part-1-en-pdf.pdf (accessed 1 April 2016).

PaiMazumder, D., Sushama, L., Laprise, R., Khaliq, M. N. & Sauchyn, D. (2013). Canadian RCM projected changes to short- and long-term drought characteristics over the Canadian prairies. *International Journal of Climatology 33*, 1409–1423. http://doi.org/10.1002/joc.3521.

Perrier, E., Kot, M., Castleden, H. & Gagnon, G. A. (2014). Drinking water safety plans: barriers and bridges for small systems in Alberta, Canada. *Water Policy 16*, 1140–1154. doi:10.2166/wp.2014.207.

Quebec Ministry of Environment (2002). *Quebec Water Policy*. Available at: http://www.mddelcc.gouv.qc.ca/eau/politique/policy.pdf (accessed 1 April 2016).

Rahaman, M. M. & Varis, O. (2005). Integrated water resources management: evolution, prospects and future challenges. *Sustainability: Science, Practice & Policy 1*, 15–21. doi:10.1016/S0011-9164(99)00099-5.

Reid, D. C., Abramowski, K., Beier, A., Janzen, A., Lok, D., Mack, H., Radhakrishnan, H., Rahman, M. M., Schroth, R. & Vatcher, R. (2014). Implementation of Alberta's drinking water safety plans. *Water Quality Research Journal of Canada 49*, 5. doi:10.2166/wqrjc.2013.063.

Rizak, S. & Hrudey, S. E. (2008). Drinking water safety- challenges for community managed systems. *Journal of Water and Health 6*, 33–41. doi:10.2166/wh.2008.033.

Rizvi, Z. & Adamowski, J. (2013). First nation capacity in Québec to practise integrated water resources management. *International Journal of Water 7*, 161–190. doi:10.1504/IJW.2013.054859.

Ropkins, K. & Beck, A. J. (2000). Evaluation of worldwide approaches to the use of HACCP to control food safety. *Trends in Food Science and Technology 11*, 10–21. doi:10.1016/S0924-2244(00)00036-4.

Roy, D., Oborne, B. & Venema, H. D. (2009). *Integrated Water Resources Management (IWRM) in Canada: Recommendations for Agricultural Sector Participation*. Winnipeg, Manitoba. doi:10.1016/j.pce.2008.07.001.

Saunders, J. O. & Wenig, M. (2007). Whose water? Canadian water management and the challenges of jurisdictional fragmentation. In: *Eau Canada: The Future of Canada's Water.* Bakker, K. (ed.). University of British Columbia Press, Vancouver, pp. 119–142.

Scheili, A., Rodriguez, M. J. & Sadiq, R. (2014). Seasonal and spatial variations of source and drinking water quality in small municipal systems of two Canadian regions. *Science of the Total Environment 508*, 514–524. http://doi.org/10.1016/j.scitotenv.2014.11.069.

Scheili, A., Rodriguez, M. J. & Sadiq, R. (2015). Development, application, and sensitivity analysis of a water quality index for drinking water management in small systems. *Environmental Monitoring and Assessment 187*, 685. doi:10.1007/s10661-015-4908-5.

Simms, G. & de Loë, R. C. (2010). *Challenges for Water Governance in Canada: A Discussion Paper. Governance for Source Water Protection in Canada Report No. 2*. Waterloo. Available at: http://www.governanceforwater.ca/sites/default/files/WPGG_Report_No2_WEB.pdf (accessed 5 October 2016).

Sinclair, M. & Rizak, S. (2004). Drinking-Water quality management: the Australian framework. *Journal of Toxicology & Environmental Health: Part A 67*, 1567–1579. doi:10.1080/15287390490491873.

Sperber, W. H. (2005). HACCP and transparency. *Food Control 16*, 505–509. doi:10.1016/j.foodcont.2003.10.012.

Statistics Canada (2011). Survey of Drinking Water Plants. Available at: www.statcan.gc.ca/pub/16…/16-403-x2013001-eng.pdf (accessed 1 November 2016).

Statistics Canada (2016). Table 051-0001 - Estimates of population by age group and sex for July 1, Canada, Provinces and territories, CANSIM (database). Available at: http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/demo02a-eng.htm (accessed 6 April 2016).

Taylor, M. (2002). *Development of Drinking-Water Management in New Zealand Since 1992*. Wellington, NZ. Available at: http://www.moh.govt.nz/notebook/nbbooks.nsf/0/6d2e4dfe48b2d0b1cc25783600721d2e/$FILE/nzdw-management.pdf (accessed 30 March 2016).

Terziovski, M., Power, D. & Sohal, A. S. (2003). The longitudinal effects of the ISO 9000 certification process on business performance. *European Journal of Operational Research 146*, 580–595. doi:10.1016/S0377-2217(02)00252-7.

United States Environmental Protection Agency (USEPA) (2016). Protecting Drinking Water Quality through Promotion of Water Safety Plans. Available at: https://www.epa.gov/international-cooperation/protecting-drinking-water-quality-through-promotion-water-safety-plans (accessed 23 May 2016).

Vinson, N. G. (2012). Towards estimating the economic burden of waterborne illness in Canada: what do we know, where do we go? Available at: http://nparc.cisti-icist.nrc-cnrc.gc.ca/eng/view/accepted/?id=319c22ff-b36b-402b-a67d-b05d5171f3a7 (accessed 19 November 2016).

World Health Organization (WHO) (1996). Fact Sheets on Environmental Sanitation. Available at: http://helid.digicollection.org/en/d/Js13461e/ (accessed 21 March 2016).

World Health Organization (WHO) (2004). *Guidelines for Drinking-Water Quality,* 3rd edn. WHO, Geneva. Available at: http://www.who.int/water_sanitation_health/dwq/gdwqvol32ed.pdf (accessed 21 March 2016).

World Health Organization (WHO) (2009). *Water Safety Plan Manual: Step-by-Step Risk Management for Drinking-Water Suppliers.* WHO, Geneva. Available at: http://apps.who.int/iris/bitstream/10665/75141/1/9789241562638_eng.pdf (accessed 19 January 2015).

World Health Organization (WHO) (2011). *Guidelines for Drinking Water Quality,* 4th edn. WHO, Geneva. Available at: http://apps.who.int/iris/bitstream/10665/44584/1/9789241548151_eng.pdf (accessed 22 February 2016).

World Summit on Sustainable Development (WSSD) (2002). Report of the World Summit on Sustainable Development. In: *Johannesburg World Summit on Sustainable Development*. United Nations, New York. Available at: http://www.unmillenniumproject.org/documents/131302_wssd_report_reissued.pdf (accessed 31 May 2016).

Yokoi, H. (2006). Study on the introduction of hazard analysis and critical control point (HACCP) concept of the water quality management. *Water Science and Technology 53*, 483–492.

Yusa, A., Berry, P., Cheng, J. J., Ogden, N., Bonsal, B., Stewart, R. & Waldick, R. (2015). Climate change, drought and human health in Canada. *International Journal of Environmental Research and Public Health 12*, 8359–8412. http://doi.org/10.3390/ijerph120708359.

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