Development and implementation of Water Safety Plans in Canadian water systems

by

Kaycie Lane

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Abstract

Current, persistent water quality and quantity concerns in small, rural, Northern and Indigenous water systems in Canada necessitate a change in water management strategies. Analysis of drinking water advisories across water systems reveals the predominance of operational concerns in water systems that are not addressed by the current regulatory structure mandating water quality sampling. Regionalized water governance and fragmented policy making do not account for all stakeholders in a water system and do not contribute to consumer confidence in the provision of safe water in Canadian water systems. This situation is exacerbated in small and geographically remote communities with limited access to the resources or the capacity to adequately address operational and water quality concerns. Focus needs to be placed on improving management of water systems to improve not only capacity to meet water quality guidelines, but to solve operational concerns through a more proactive strategy.

This dissertation examines the applicability of a water safety planning approach, a proactive risk management strategy, to water systems in Canada. Implementation and adoption of water safety plans relies heavily on water system environment: the attitudes and preconceived ideas about water safety through which stakeholders evaluate new management tools. This research focuses on understanding factors that form barriers to water safety planning implementation in both municipal and First Nation water systems. This research begins with a review of water safety planning literature and the drinking water advisory as the current water safety tool in Canada. Based on the benefits and challenges identified in this method, a water safety plan tool was developed specifically for this thesis and tested by consulting water system stakeholders. This tool was reviewed by both municipal and First Nation water systems. Additionally, focus was placed on determining strategies for presenting the information generated through the water safety planning process and examining strategies for adding water quality data to the water safety plan. The water safety plan tool shows promise as a management method for water systems, but successful and sustainable implementation will require a shift in water system culture from reactive water quality monitoring to proactive operational practices.

List of Abbreviations Used

AESRD – Alberta Environment and Sustainable Resource Development

APC – Atlantic Policy Congress of First Nations Chiefs

BWA – Boil water advisory

DNC – Do not consume

DNU – Do not use

DWA – Drinking water advisory

EHO – Environmental Health Officer

FNHIB – First Nation Health and Inuit Branch

GCDWQ – Guidelines for Canadian Drinking Water Quality

HACCP – Hazard and critical control points

INAC – Indigenous and Northern Affairs Canada

ISC – Indigenous Services Canada

IWA – International Water Association

MAC – Maximum acceptable concentration

MTA – Municipal Transfer Agreement

OCAP - Ownership, Control, Access and Possession

OECD - Organisation for Economic Co-operation and Development

PCA – Principal Component Analysis

PCoA – Principal Coordinate Analysis

PDF – Probability density function

QMRA – Quantitative Microbial Risk Assessment

SCADA – Supervisory control and data acquisition

UPGMA - Unweighted pair group method with arithmetic means

WHO – World Health Organization

WSP – Water Safety Plan

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1 Chapter One – Introduction

1.1 Introduction

This thesis explores the application of water safety planning methodologies in the context of rural, remote and Indigenous water supply systems in Canadian water systems. The focus of this chapter is to frame the current situation in Canadian water supply systems and highlight the need for improved risk assessment and management tools. First, a review of a current water management tool, the drinking water advisory is examined to understand management practices that currently exist in Canadian water systems. Based on this knowledge, further exploration of rural and remote (sometimes termed "small") systems characteristics was undertaken, understanding that the majority of vulnerable water systems are small systems, either by population served or by other identified characteristics of small water systems. Next, a review of the benefits and challenges associated with an alternative water safety tool, the water safety plan, across both Canada and global jurisdictions is presented. Furthermore, technicalities of the risk assessment methodologies used in water safety planning are reviewed to frame how risk assessment procedures can be improved with water quality monitoring data in future studies. Finally, the subsequent chapters of this thesis are outlined, presenting the studies completed to answer the research questions and objectives formulated for this thesis.

1.2 Drinking Water Advisories as a water safety measure

In Canada, the most commonly used reporting metric of water safety is the drinking water advisory (DWA), a tool that informs the public and government agencies when there are concerns in a water system (Health Canada, 2018, Galway, 2016). There are two primary types of drinking water advisories: precautionary advisories (concerns with operations or water quality that do not directly impact public health) and emergency drinking water advisories (most often involving the detection of microbial parameters in water samples). Drinking water advisories are further classified as boil water advisories or orders (BWAs), do not consume (DNC) or do not use (DNU), with BWAs making up the majority of DWAs issued (Health Canada, 2018, Environment and Climate Change Canada, 2017).

While relatively straightforward to utilize and communicate information to consumers, the prevalence of drinking water advisories across Canada in recent years is cause for concern. Eggerston reported a total of 1766 drinking water advisories across Canada in 2008, and the seven years later reported 1838 advisories (Eggerston, 2008, Eggerston, 2015), a very clear indication that the prevalence of drinking water advisories remains high. In addition to the prevalence of DWAs, studies have pointed to the duration of DWAs as a concern. Galway reported an average duration of 294 days in 2016 in Ontario First Nations, and Thompson et. al., reported an average duration of 169 days across all First Nations (Galway, 2016, Thompson et.al., 2017). Given both the extent and duration of DWAs across Canada, the utility of this tool is diminished, as it does not help prioritize individual system improvements and only provides basic information about a water system. DWAs have been used as a proxy for safe water (Galway, 2016, Black and McBean, 2018), particularly in First Nation communities, but the evidence provided by research studies of DWAs indicates that revision is needed to ensure water safety.

One of the key difficulties involved in using the DWA as a water safety measure is the lack of consistent reporting methods across both provincial agencies and federally for First Nation communities. A review of the DWA as a communication tool in the United States showed that methodologies used for issuing advisories are inconsistent (Miller and Watson, 2011). The same concern was voiced when reviewing First Nations DWAs as reported by provincial bodies: every province is different, leading to an incomplete data set at the federal level (Thompson et.al., 2017). This is further explored in Chapter Two of this thesis: a review of DWA reporting mechanisms in Nova Scotia, New Brunswick and Newfoundland and Labrador revealed only one common element reported in all three jurisdictions. Reporting inconsistencies limit the amount of useful information that can be agglomerated to find common causes of DWAs and thereby improve water safety.

Several studies have attempted to predict the occurrence of future DWAs in water systems using advanced modeling techniques such as neural networks and decision tree analysese. Previous studies used data mining as well to understand the cause of DWAs in Ontario First Nation systems (Harvey et.al., 2015). While prediction of DWAs is a useful exercise, all of these studies focused on First Nation water systems, where issues are extensively documented from previous incidents. Furthermore, while predictive tools help proactive decision making, there are multiple factors or reasons that lead to a DWA that are not captured by current reporting agencies and were not included in predictive modeling. Current predictive modeling provides a water system with data about future DWAs based only on similar, previous DWAs. Utilizing DWA data to prevent future DWAs is a start towards proactive water system management but is insufficient to ensure the safety of a water system due to its lack of focus on operational and managerial concerns in a water system.

One possible solution is to integrate the data provided by a DWA with water safety planning, a risk management methodology supported by the World Health Organization (WHO) (Bartram et.al., 2009). A case study of the 2014 Toledo, Ohio DWA found that had water safety planning been utilized, the DWA could have been prevented (Jetoo et.al., 2015). Post-advisory analysis showed that use of the eleven modules in the WHO WSP Manual (Bartram et.al., 2009), highlighted key vulnerabilities in the Toledo water system that were largely related to operating procedures and lack of coherent communication between regulatory agencies (Jetoo et.al., 2015). This example shows that a DWA could have been avoided all together, had a risk management framework, such as a water safety plan, been in place to prevent the algal bloom from impacting the entire water supply system. Evidence of this nature suggests that a DWA on its own does not reveal the underlying cause for the issuance of the DWA and cannot critically identify the multitude of hazardous situations that trigger a DWA in an emergency situation.

1.3 Rural and Remote Water Systems Focus

While Canada is considered a developed country in 2019, it is the only country part of the Organization for Economic Cooperation and Development that does not have nationally enforceable drinking water quality standards (Bakker and Cook, 2011). There are national water quality guidelines, but these guidelines are only enforceable at a provincial level (Kot et. al., 2011), which has led to a decentralized and fragmented governance in the drinking water sector (Bakker and Cook, 2011, de Loe, 2017). This fragmentation has had negative impacts on the ability of individual communities to adequately deal with water resources and to handle new issues that arise (Bakker and Cook 2011), particularly in rural and remote water supply systems (Moffatt and Struck, 2011). Rural systems must meet the same regulations as larger, urban municipal water systems, but often lack the capacity or resources to respond to new challenges in a water system (Moffatt and Struck, 2001, Kot et. al., 2011, Boag et. al., 2010, Butterfield and Camper, 2004, Pons et. al., 2014, WHO, 2012). Studies have demonstrated that a historically “safe” water system with good water quality cannot be guaranteed to remain safe in the future (Jalba, and Hrudey, 2006); this is of particular concern in rural and remote systems.

The health implications of consuming contaminated drinking water have been documented in rural and small drinking water systems in Canada. According to a 2011 report, 15% of the drinking water systems in Canada are classified as small systems (serving less than 5000 people) but represent a disproportionally high portion of the water systems that have experienced outbreaks of waterborne illness (Moffatt and Struck, 2011). In 2005, 288 disease outbreaks were found to be related to drinking water sources, approximately 50% of which were in private or registered water systems (Schuster et. al., 2005). In 2008 there were 1766 drinking water advisories in place in Canada (excluding First Nations water systems) and some communities had more than one drinking water advisory in place (Eggerston, 2008). Reporting formats for both drinking water advisories and infectious disease outbreaks is far from consistent and often not mandatory or easily accessible (Schuster et. al., 2005, Eggerston, 2008, Murphy et. al., 2015) which suggests that these figures are an underestimation of the actual disease burden from drinking water being imposed on small, rural water systems. Assessments of microbial contamination in rural water system have shown that these remote systems are particularly vulnerable to contamination and often have fewer protective barriers in place than larger, urban water systems (Butterfield and Camper, 2004).

Not only do rural community water systems lack physical or chemical barriers to microbial contamination; rural systems often lack capacity – whether financially, operationally or personnel – to adequately maintain the safety of a water system. The Guidelines for Canadian Drinking Water Quality (GCDWQ) promote a multi-barrier approach to protecting customers from potential outbreaks of waterborne illness (Health Canada, 2014). The multi-barrier approach includes all possible components of the water supply system: source water protection plans, specified treatment technologies for log removal of pathogens, procedures for sampling in a distribution system and training and certification of water treatment facility operators (Health Canada, 2014). However, while trained operators can be a barrier to waterborne contamination (Moffatt and Struck, 2011), evaluations of rural water system capacity have shown that operator training opportunities are limited in remote systems and operator turnover is high (Kot et. al., 2011, Pons et. al., 2014). Furthermore, rural water supply systems experience several issues that are not common in comparable urban systems: geographic remoteness, financial constraints, backup power systems, lack of redundant treatment technologies, high staff turnover rates and overall concerns with being able to adequately maintain an acceptable water quality (Kot et.al., 2011, Pons et. al., 2014, Murphy et. al., 2015, Boag et. al., 2010, Butterfield and Camper, 2004, Kot et. al., 2015, Omar et. al., 2017, WHO, 2012). These concerns, coupled with the decentralized water governance strategy in Canada (Bakker and Cook, 2011) make it difficult for a rural water system to adapt to changes within the water supply system.

Small water supply systems are best described by the challenges they face in providing safe water to a community, not by the population served (WHO, 2012). A small water system is most often defined as a system serving less than 5000 customers (Health Canada, 2017), but this definition is limiting, particularly since small systems may be municipal, private, public, semi-public or otherwise designated by a provincial authority. However, based on the issues listed previously, small systems are better characterized by capacity: the ability to meet water system challenges effectively. The World Health Organization Water Safety Planning manual for small systems defines small systems by capacity, in part due to the community-specific nature of a water safety plan (WSP). Not only size defines small systems: culture, both from a regulatory standpoint and from a local perspective, influences daily operations of a water system (Omar et.al., 2017, Kot et.al., 2015, Summerill et. al., 2010a, Summerill et. al., 2010b, String and Lantagne, 2016), especially when considering adopting a WSP approach. Therefore, this thesis will consider small systems those which have limited capacity to meet either regulatory water quality standards or maintain adequate barriers to protect consumer health due to size, geographic location, age of the system and/or personnel constraints. The term "rural water system" is used in place of small water systems in order to better characterize the water systems evaluated in this thesis.

1.4 Water Safety Planning

1.4.1 Water Safety Plans in the Global Context

Water safety plans have been applied globally in 93 different countries (WHO &IWA, 2017), and the benefits and challenges associated with this risk assessment method are well documented. Benefits of water safety plans are numerous and include decreases in disease outbreaks, better overall understanding of water system hazards, improved communication and collaboration, better monitoring and record keeping, and better operational procedures. Challenges include the sustainability of the WSP approach, the need for external and internal auditing procedures, the need for strong management and supporting programs that aid in the development and continuing effectiveness of WSPs.

One of the best documented benefits to completing a WSP, particularly in rural water systems, is an increased knowledge about the water system holistically (WHO, 2012, Hubbards et.al., 2013, Loret et.al., 2016, Setty, et.al., 2017, Viljoen, 2010). Rural systems are often decentralized, run by multiple stakeholders and suffer from resource constraints (WHO, 2012, Kot et.al., 2011); this leads to fragmented knowledge of how a water system operates and delivers water safely to customers. Water safety plans focus on describing a water supply system and hazard identification as the initial steps to implementation (WHO, 2012) and this process generate a collective knowledge surrounding all aspects of the water system that has not been previously compiled in the system. Water safety plans generate more knowledge about a water supply system than data collection alone, not just from a water operator perspective, but from a community perspective, taking into account both equity and climate-change considerations (WHO, 2017, WHO, 2019, Hubbards et.al., 2013, Loret et.al., 2016, Setty et.al., 2017, Viljoen, 2010). Knowledge is also transferred across all stakeholders involved in the WSP, making the WSP an effective communication tool across a broad spectrum of experience and expertise (WHO, 2012, Bartram et.al., 2009). This was seen in Australia in a case study completed by Byleveld et. al. in 2008, demonstrating that improved communication resulted from implementing a water safety plan (Byleveld et. al., 2008).

Water safety plans also improve monitoring and record keeping as well as management and operational procedures. A WHO 2018 report demonstrated how WSPs drive operational and maintenance improvements, showing that there is increased operator training, operational cost savings and enhanced treatment performance as a result of WSP adoption (WHO, 2018). Furthermore, other operations and maintenance benefits include avoiding incident management costs, reduced raw water losses, fewer failures in disinfection processes and less treatment plant downtime (WHO, 2018). These benefits have been verified by other researchers: Ferrero et.al. 2019 further investigated the importance of training programs and auditing procedures for WSPs, Rondhi et.al., 2015 examined sustainability of WSPs in Sub-Saharan Africa, and Godfrey and Howard, 2004 looked at WSP implementation in piped water supplies in developing countries. All of these studies noted the importance of training and auditing WSPs and verified the presence of better monitoring and record keeping and better operational and management procedures as a result of WSP implementation (Ferrero et.al., 2019, Rondhi, et.al., 2015, Godfrey and Howard, 2004).

While there is a strong body of literature outlining the benefits of WSPs, research is still needed to meet identified challenges to sustainable WSP implementation. There is a clear need for internal and external audits of WSPs, supporting programs and strong management procedures (WHO & IWA, 2017). In addition, water system culture can be a barrier to WSP buy-in and small system often have different needs in the WSP process and often lack the capacity to move a WSP forward effectively (WHO & IWA, 2017, WHO, 2012, Summerill et.al., 2010a, Summerill et.al., 2010b). Several studies have provided evidence for these challenges through global case studies and provide suggestions for future WSP implementation.

1.4.2 Water Safety Plans in the Canadian Context

Although the 2017 Global Status Report on WSPs identifies Canada as a country with at least ten implemented water safety plans (WHO & IWA, 2017), only the province of Alberta has developed and required a drinking water safety plan as part of water regulations (AESRD, 2011, Reid et.al., 2014). There is evidence that the Ontario Drinking Water Quality Management Standard provides a similar level of risk assessment as a water safety plan (Post et.al., 2017), but an explicit water safety plan has not been developed in this province. Risk assessment in the context of this thesis refers to the analysis and assignation of risk to possible hazardous events in water system components, evaluating both the likelihood and consequence that a hazardous event results in inadequate water quality reaching a customer. However, this leaves three territories and eight provinces that do not have a water safety plan approach in place to safeguard human health from waterborne disease and contamination of drinking water supplies. The Atlantic region (Nova Scotia, New Brunswick, Prince Edward Island and Newfoundland and Labrador) does not current have or require WSPs and this approach has not been investigated beyond exploratory studies (Kot et.al., 2015).

The Alberta WSP is the first WSP implemented in North America, with all systems regulated by the AESRD required to complete and maintain a WSP by the end of 2013 (Reid et.al., 2014). Eighty percent of the water systems in Alberta fall under the ESRD and the WSP is considered part of the multi-barrier approach. The Alberta Drinking WSP is built on pre-existing regulatory requirements (Reid et.al., 2014) which present an interesting avenue of exploratory research. The WSP is an approach that can help a water system meet regulations but does not have to be enmeshed with regulations to be successful according to WHO WSP documentation (Bartram et.al., 2009, WHO, 2012, WHO, 2016). The drinking WSP is not designed to work in isolation, however, and requires communication between treatment facility operators and other stakeholders in the water system (Reid et.al., 2014). The WSP methodology in Alberta is implemented using an Excel document that asks for a large quantity of information to be filled in about previously identified hazards and was compiled by the ESRD based on hazard prevalence across Alberta and the applicability of each hazard to the provincial regulations.

The Alberta Drinking Water Safety Plan consists of four tables of possible hazardous events: source, treatment, distribution and consumer, with the ability to add system specific hazards should the need arise (Reid et.al., 2014). While extensive, reviews of this approach have noted that such a lengthy hazard identification process can be inhibitive, particularly to small systems, with operators suffering from “survey fatigue” (Post et.al., 2017, Perrier et.al., 2014). Although workshops were held province-wide to train operator how to use the WSP tool (Reid et.al., 2014), barriers to successful implementation, particularly in small systems, exist and have yet to be overcome (Perrier et.al., 2014). WSPs developed in other provinces can use the Alberta case study to identify the best path forward based on individual province regulations and system needs, keeping in mind that a WSP is a continuous cycle of risk assessment and mitigation (WHO, 2012, Bartram et.al., 2009).

1.4.3 Risk Methodologies for Water Safety Planning

Water safety plans are designed to evaluate risk using a risk matrix approach (Bartram et. al., 2009). For each hazardous event identified in the water safety plan process, a risk level is assigned by describing the likelihood of the hazardous event and the consequence or impact of the event using a predetermined numeric scale. The scores associated with likelihood and consequence of an event are multiplied to obtain a risk matrix of risk score (WHO, 2012, WHO, 2016, Bartram et. al., 2009). Risk level (low, medium, high or very high) are assigned based on the risk score. Risk matrices were chosen for the WSP method as they are relatively easy to adapt to different industries, can be modified by and individual water supply system to be system-specific and are a fast and effective way to prioritize hazardous events (Bartram et. al., 2009, WHO, 2012, WHO, 2016). This approach has been effective in small water system applications of water safety plans as it requires only entry-level risk management skills and is highly adaptable to system requirements (WHO, 2012, Hokstad et. al., 2009).

However, risk analysts have critiqued the risk matrix approach for its poor resolution, ambiguous definitions of likelihood and consequence and errors in accurately determining appropriate risk levels, all of which can contribute to suboptimal resource allocation (Cox Jr., 2008). Since a risk matrix is relatively easy to use, it has been employed in the airline industry, in environmental contamination studies, to assess national security threats and several other industries (Cox, Jr., 2008, McBean, 2019), but wide application of this method does not correspond to accuracy. A 2008 analysis of the risk matrix method showed that using a risk matrix to categorize risk is not always better than or as good as purely random decision making (Cox Jr., 2008). Furthermore, risk matrices, while able to prioritize hazardous events by risk level, do not accurately reflect the real-life trade-offs that would be incurred by decision-makers and stakeholders in a water system if actions were to be taken to mitigate risk (Cox Jr., 2008). Risk matrices provide baseline information about a hazardous event, but do not provide detailed strategies for mitigating risk, and misinterpretation of the risk matrix can result.

In a rural systems context where there is a paucity of water quality data available, a risk matrix provides a simplified method for risk assessment. However, in a data rich setting – which can be found in some rural water systems with online monitoring and automated data collection – a risk matrix does not necessarily provide a more accurate method for assessing risk in a system (Cox Jr., 2008); the WSP risk matrix uses semi-quantitative scoring methods unrelated to water quality. Several methods for evaluating risk in a WSP were examined by TECHNEAU in 2009 to evaluate risk assessment expertise required, data availability and needs for each analysis technique and to demonstrate how hazard identification fits into the larger landscape of risk assessment (Hokstad et. al., 2009). This report examined coarse risk analysis, hazard and operability analysis, quantitative microbial risk assessment (QMRA), failure modes effects and criticality analysis, fault tree analysis, reliability block diagrams, human reliability analysis, Markov analysis, event tree analysis and Bayesian networks (Hokstad et.al., 2009). There is no one recommended method for all water supply systems due to the data requirements and the risk analysis expertise unique to each method (Hokstad et. al., 2009), which accounts for the choice of a risk matrix as the standardized risk analysis method in a water safety plan. However, the steps in the WSP process remain the same until risk analysis or estimation is performed: determine the scope, describe the system, identify hazardous events and estimate risk by evaluating probabilities and consequences (Hokstad et.al., 2009, WHO, 2012, Bartram et. al., 2009).

While the risk matrix method does have pitfalls, the only other risk analysis method well documented in the water safety plan case study literature is the quantitative microbial risk assessment (QMRA). Few case studies have used traditional risk analysis methods for calculating probabilities of occurrence (Rosen et. al., 2008, Nilsson, 2006, Smeets et.al., 2010, Howard et. al., 2006) and even fewer have examined the consequence or impact (excluding disability adjusted life year calculations) to quantify water quality and quantity concerns. To date, there is also little to no evidence of comparisons between the risk matrix method and other risk analyses techniques in the water industry. Especially as data collection and water quality monitoring improve, effort needs to be placed on determining if data provides a better estimation of probability of occurrence and consequence of hazardous events than the risk matrix method. If risk analysis performed on water quality data can be reliably compared to a risk matrix in a WSP or used to enhance a WSP, it would provide an incentive to many heavily regulated facilities to begin the process of adopting the WSP methodology.

1.5 Research Objectives and Thesis Structure

1.5.1 Hypothesis

This thesis hypothesizes rural and remote water systems in Canada benefit from the implementation of water safety plan frameworks. Furthermore, the second hypothesis proposes a water safety plan provides more useful information to water regulators and policy makers than current water tools. Finally, the third hypothesis proposes water safety plan risk methodologies can be improved with the addition of quantitative water quality data.

1.5.2 Research Questions

1. What tools are currently used in Canada to ensure water safety? How do these tools compare to a water safety plan methodology?
2. For small, remote or Indigenous communities in Canada, does a water safety plan method improve water safety security and management?
3. Can we use "indicator parameter" data (such as turbidity, pH, chlorine residual, etc.) already collected in small water systems to provide a better characterization of risk in water safety plans than the current semi-quantitative risk matrix approach?

1.5.3 Research Objectives

Based on these research questions, the following objectives were outlined to provide clear studies to be undertaken in this thesis. Objective One focuses on the review of drinking water advisories and water safety plans to best understand how these management tools fit into the water governance landscape in Canada. Objective Two focuses on the development and validation of a WSP structure for the water systems included in this thesis. Objective Three takes the water safety plan developed in Objective Two to water systems across Atlantic Canada and focuses on talking to stakeholders in each water system to determine needs for successful water safety plan implementation. Objective Four uses data from the rural systems included in Objective Three and compares the results from the WSP risk matrix to the probability of occurrence of a hazardous event based on water quality monitoring data.

1.5.3.1 Objective One: Review of DWAs and WSPs

Using current literature studies and documentation of both drinking water advisories and water safety plans, a thorough review of these methodologies was conducted. The review was completed through the lens of Canadian water governance and management practices to best understand the benefits of each tool and the barriers present when providing safe water. Objective One addresses research question one by evaluating the current tool used in Canada (DWA) and an alternative tool (WSP) as water management methodologies in rural and remote water systems.

1.5.3.2 Objective Two: Development and Review of a WSP Structure for Rural and Remote Systems

Water safety plans are designed as community-specific tools: in the context of the water systems included in this thesis, this necessitated the development of a water safety plan applicable to the water systems included in Objective Three. Using templates for WSPs globally and the WHO Small Systems Manual (WHO, 2012), an operator-informed WSP was developed, as questionnaire to be completed by the primary drinking water operator in a water system. This survey-based tool uses fault trees to show how hazardous events are related and focuses on asking water system stakeholders questions about daily operations, without emphasizing risk scoring methods.

1.5.3.3 Objective Three: Test WSP Structure in Small, Remote and Indigenous communities to build evidence base

Using the WSP developed in Objective Two, fourteen water systems, both municipal and Indigenous, were visited over the course of three years to review the WSP. The purpose of these visits was to engage with water treatment facility operators, water quality sampling staff, utility managers and other relevant stakeholders to discuss the water safety planning process, complete example modules, and formulate strategies for successful future implementation of this risk assessment framework. Data from each system was also collected where applicable at the time of the visit for use in Objective Four.

1.5.3.4 Objective Four: Compare the WSP Risk Matrix to Quantitative Probability of Occurrence

Using data, where available, from the fourteen water systems included, two methods for determining probability of occurrence of an adverse water quality event were chosen. These calculations of probability of occurrence were compared to the traditional risk matrix approach by translating the descriptions of likelihood available in WSP templates to numeric probabilities. The purpose was to determine how closely the risk matrix aligns with water quality data, showing if underestimation or overestimation of risk is occurring in these water systems.

1.6 Thesis Structure

This thesis contains several studies utilized to complete the proposed objectives and prove the hypotheses presented above and was conceived as a paper-based thesis. Chapter Two examines the drinking water advisory in more detail to determine how current reporting measures for water safety can be improved to complete Objective One. Chapter Three provides a proposed theoretical water safety plan structure for use in Nunavut based on a literature review of Arctic jurisdictions and two WSP templates to understand the specific hazardous events applicable to the Arctic context. Chapter Four uses the knowledge gained from this study to develop and review an operator-informed water safety plan for use in Atlantic Canadian rural water systems, completing Objective Two. Chapters Five and Six take a look at the status of water systems retrospectively, before water safety planning was attempted and after the operator-informed water safety plan was completed. These chapters cover Objective Three, with Chapter Five focusing specifically on municipal systems and Chapter Six focusing on Indigenous systems. Objective Four is met in Chapter Seven, which provides a look at how the risk matrix approach for chlorine disinfection compares to the probability of occurrence of low chlorine residual in water systems. Chapter Eight provides an examination of how the data produced by the operator-informed WSP can be visualized and analyzed to provide more information about a water system to further build evidence for water safety plan implementation. Finally, Chapter Nine provides conclusions and recommendations based on the work completed in this thesis.

2 Chapter Two – Evaluating the use and intent of drinking water advisories in Atlantic Canada

2.1 Abstract

Drinking water advisories (DWAs) are used as a tool for identifying water safety concerns in Canada and many jurisdictions. Evidence from previous research demonstrates a lack of improvement in water system operations over time, with an increase in the total number of DWAs in place over time. As a result of, DWAs are becoming a chronic issue for many water systems without operational and process improvements. This study explores DWA characteristics in four provinces in Atlantic Canada, including frequency and duration, focusing on municipal and private water systems. The reasons DWAs are issued are predominantly operational concerns and are precautionary in nature, showcasing a lack of risk mitigation procedures and proactive management in water systems. Furthermore, seasonality was identified in DWA issuance in Nova Scotia, and reasons for DWA issuance are largely unchanged over time, but neither of these identified concerns has led to a change in DWA reporting or issuance procedures. Additionally, lack of a common reporting format is identified in this study, leading to the proposal of a template of minimum characteristics for future DWA reporting. Overall, this study highlights deficiencies in the DWA issuance process as a water safety measure and suggests alternative methods for risk management in water systems to alleviate the persistence and prevalence of DWAs in Canada.

2.2 Introduction

In Canada, the drinking water advisory (DWA) is used as a tool to communicate concerns with water quality safety both to consumers and government agencies that regulate drinking water systems (Environment and Climate Change Canada, 2018). Drinking water advisories can be precautionary (related to operational challenges, treatment failures or adverse water quality results) or emergency advisories (issued as a result of microbial contamination) (Environment and Climate Change Canada, 2018). Previous studies have shown that the majority of the advisories issued are precautionary (Black and McBean, 2018, Post et.al., 2018, Murphy et. al., 2016, Galway, 2016). Drinking water advisories are most often issued for operational or process related concerns; according to a 2018 report specifically on Boil Water Advisories (BWAs), 83% of all advisories are related to these issues, with only 4% of BWAs issued as a result of *E. coli* presence in drinking water (Environment and Climate Change Canada, 2018).

Several studies have shown the prominence of operational concerns in First Nation DWAs specifically: 40% of advisories are related to operational concerns in these water systems (Thompson et.al. 2017).

The prevalence of precautionary DWAs is not the only concern revealed by previous studies. The lack of a consistent and uniform DWA reporting method is a common theme observed in literature. Each province or territory has a different agency in charge of reporting advisories and the information presented with each advisory lacks a uniform format (Miller and Watson, 2011, Post et.al., 2018, Murphy et.al., 2016). Inconsistencies in reporting format, both across provinces and over time, make it difficult to compile an accurate and complete data set for analysis (Murphy et.al., 2016, Harvey et.al., 2015, Eggerston, 2008). As a result, several previous studies have censored DWA data sets, limiting the effectiveness of drinking water advisory characterization (Post et.al., 2018, Thompson et.al., 2017). Complete data sets for either municipal, registered or First Nation water systems are virtually nonexistent.

Several studies have examined DWAs in specifically in First Nation water systems given the federal government's 2015 initiative to end all DWAs in First Nation communities by 2021 (Indigenous Services Canada, 2019). With the current focus the government has placed on removing DWAs in First Nation water systems, several studies have evaluated trends over time (Indigenous Services Canada, 2018). First Nation water systems have experienced a disproportionately high number of long-term drinking water advisories compared to municipal and registered water systems (Murphy et.al, 2016, Thompson et.al., 2017, Bradford et.al., 2017). Of the 420 First Nation communities included in a study of advisories from 2004 to 2014, 1773 advisories were reported (Thompson et.al. 2017). Galway's study in 2016 found a mean advisory duration of 294 days, while Thompson et al. (2017) found a mean duration of 169 days in 2017 (Galway, 2016, Thompson et.al., 2017). The study performed by Galway examined 402 advisories in Ontario First Nations from 2003 to 2014. The common observed characteristic is the presence of a large number of advisories, in effect for a long duration, impacting both health and well-being in these First Nation water systems.

Analysis of DWAs has primarily revolved around historical data modeling to formulate predictive tools. Murphy et.al., 2016, used data from First Nation water systems in a decision tree model to constructive a predictive algorithm for future advisories with a 79% accuracy rate. Harvey et.al., 2015 used data mining to model First Nation water system DWAs with an accuracy rate of 71% overall. Additionally, the addition of water quality monitoring data (free chlorine, pH, temperature, etc.) has been proposed as a mitigation measure for DWAs; if implemented, up to 36% DWAs could be removed (Black and McBean, 2018). While the two predictive models have an accuracy rate of over 70%, the operational issues contributing to DWAs are not being addressed; as it is broadly acknowledged that the underlying issues causing DWAs need to be resolved to effectively reduce the total number of advisories in place over time (Murphy et.al, 2016, Harvey et.al., 2015, Post et.al, 2018, Black and McBean, 2018).

The focus on First Nation water systems is important for Canada to fully address its commitment to the Truth and Reconciliation Commission to improve First Nations water systems (Truth and Reconciliation Commission of Canada, 2015). In addition, emphasis is needed to address water systems that are private, on-site systems also struggling to provide safe drinking water. Small, private or registered water systems face drinking water advisories as often or more frequently than municipal or centralized water systems and often lack to proper resources to adequately address the reason an advisory was issued (Eggerston, 2018, Eggerston, 2015, Kot et.al., 2011). Small, privately owned or even small, remote, municipal water systems frequently lack the technical expertise, financial resources and advanced water quality knowledge needed to address these concerns (Kot et.al., 2011, Boag et.al., 2010, Butterfield and Camper, 2004). The combination of one or more of these factors leads to create inequalities associated with access to *public* drinking water. For clarity, the term “registered water system” is used in this study to describe these water systems.

This study examines the characteristics of drinking water advisories in the Atlantic Canadian provinces for both municipal and registered water supply systems. The objective was to understand DWAs over time, considering both the duration of advisories and trends in issuance. Furthermore, the reason for DWA issuance over time was examined to understand changes needed in water systems to remove current DWAs. In addition, patterns in DWA issuance including seasonality and populations impacted were examined. Using the results from these analyses, this study also focused on understanding changes needed to improve DWA reporting and examined how DWAs can inform alternative water management strategies.

2.3 Background

While relatively straightforward to utilize and communicate information to consumers, the prevalence of drinking water advisories across Canada in recent years is cause for concern. Eggerston reported a total of 1766 drinking water advisories across Canada in 2008, and the seven years later reported 1838 advisories (Eggerston, 2008, Eggerston, 2015), a very clear indication that the prevalence of drinking water advisories remains high. These studies demonstrated that while there is a shift in where drinking water advisories are located, overall, the number of advisories in place is relatively unchanged (Eggerston, 2015). Other studies have reported similar numbers: Thompson et.al. reported 1773 individual DWA events in First Nations from 2004 to 2014, focusing exclusively on First Nation communities, where water-related issues are disproportionately high in comparison to other water systems (Bradford et.al.,2017).

In addition to the prevalence of DWAs, studies have pointed to the duration of DWAs as a concern. Galway reported an average duration of 294 days in 2016 in Ontario First Nations, and Thompson et. al., reported an average duration of 169 days across all First Nations (Galway, 2016, Thompson et.al., 2017). In Atlantic Canada in particular, there are 34 First Nation water systems and 82.4% have experienced at least one DWA in the past ten years (Thompson et.al., 2017). Given both the extent and duration of DWAs across Canada, the utility of this tool is diminished, as it does not help prioritize individual system improvements and only provides basic information about a water system. DWAs have been used as a proxy for unsafe water (Galway, 2016, Black and McBean, 2018), particularly in First Nation communities, but the evidence provided by research studies of DWAs indicates that revision is needed as safe water is not assured using the DWA alone.

One of the key difficulties involved in using the DWA as a water safety metric is the lack of consistent reporting methods across both provincial agencies and federally for First Nation communities. A review of the DWA as a communication tool in the United States showed that methodologies used for issuing advisories are inconsistent (Miller and Watson, 2011). The same concern was voiced when reviewing First Nations DWAs as reported by provincial bodies: every province is different, leading to an incomplete data set at the federal level (Thompson et.al., 2017). Unfortunately, major incidents or events in a water system are the leading reason why there is collaboration between health departments and drinking water systems (Miller and Watson, 2011); until a failure occurs, there is no communication. Furthermore, when communication occurs, it is inconsistent across provinces. Reporting inconsistencies limit the amount of useful information that can be agglomerated to find common causes of DWAs and thereby improve water safety.

One of the key features that needs to be reported for every DWA is the reason the DWA was issued. However, while the majority of provincial jurisdictions report reason, the reasons given are not in a standardized format. From the data available, DWAs are primarily precautionary, used for operational concerns related to pipe breaks, aging infrastructure and a lack of management procedures or accountability (Thompson et.al., 2017, Black and McBean, 2018). According to a 2018 report specifically on boil water advisories (BWAs) , 83% of all BWAs are due to equipment and process-related problems, with only 4% of advisories in effect due to *E. coli* presence (Environment and Climate Change Canada, 2018). Of the 1766 DWAs studied across First Nations from 2004 to 2014 by Thompson et. al., 2017, forty percent were due to operational issues. This translates to 40% of DWAs that cannot be resolved by increased or altered water quality sampling. The prevalence of operational concerns is expressed in several other studies of DWAs (Galway, 2016, Environment and Climate Change Canada, 2018, Post et.al., 2018) providing evidence that water quality sampling alone is insufficient to address several of the operational concerns in water systems. Whereas micro-organisms and pathogens, chlorine and turbidity can be measured in water quality samples, the same cannot be said of operational concerns which include pipe breaks, treatment failure and power failures. The DWA itself cannot address or prevent these concerns and more proactive risk management is needed to prevent operational issues from becoming a precautionary DWA.

Several studies have attempted to predict the occurrence of future DWAs in water systems using advanced modeling techniques. Probabilistic neural networks were used by Post et.al., 2018 to uncover the key attributes that lead to drinking water advisories, focusing on occurrence, duration, frequency and cause. Murphy et.al., 2016 demonstrated that data mining techniques using DWA datasets can predict up to 79% of future DWAs. This study was performed specifically in First Nation water systems and used a decision tree methodology (Murphy et.al., 2016). Previous studies used data mining as well to understand the cause of DWAs in Ontario First Nation systems (Harvey et.al., 2015). While prediction of DWAs is a useful exercise, all of these studies focused on First Nation water systems, where issues are extensively documented from previous incidents. A small municipal system may have never experienced a DWA, and thus has little historical data available on DWA cause or duration. Furthermore, while predictive tools help proactive decision making, there are multiple factors or reasons that lead to a DWA that are not captured by current reporting agencies and were not included in predictive modeling. Predictive modeling provides a water system with data about future DWAs based only on similar, previous DWAs. Utilizing DWA data to prevent future DWAs is a start towards proactive water system management but is insufficient to ensure the safety of a water system.

One possible solution is to integrate the data provided by a DWA with water safety planning, a risk management methodology supported by the World Health Organization (WHO) (Bartram et.al., 2009). A case study of the 2014 Toledo DWA found that had water safety planning been utilized, the DWA could have been prevented (Jetoo et.al., 2015). In 2014, the presence of an algal bloom in Lake Erie and the detection of the toxin microcystin triggered a DWA in Toledo. Post-advisory analysis showed that use of the eleven modules in the WHO WSP Manual (Bartram et.al., 2009), highlighted key vulnerabilities in the Toledo water system that were largely related to operating procedures and lack of coherent communication between regulatory agencies (Jetoo et.al., 2015). This example shows that a DWA could have been avoided all together, had a risk management framework, such as a water safety plan, been in place to prevent the algal bloom from impacting the entire water supply system. Evidence of this nature suggests that a DWA on its own does not reveal the underlying cause for the issuance of the DWA and cannot critically identify the multitude of hazardous situations that trigger a DWA in an emergency situation. This analysis reveals that while DWAs provide valuable information on water system operations superficially, it is unable to extensively characterize the water system from source to tap in the way that a WSP can.

2.4 Methods

2.4.1 Data Collection

In order to better understand drinking water advisories and their utility as a water management and planning tool, DWA data was reviewed from 3 of the 4 Atlantic Provinces: Nova Scotia, New Brunswick and Newfoundland and Labrador. No data is currently reported publicly from Prince Edward Island and as a result this province was excluded from analysis of the Atlantic region.

2.4.1.1 Nova Scotia

Data from Nova Scotia was collected from the Nova Scotia Environment website, where both municipal and registered system DWAs are reported on a weekly basis. A municipal system is one that holds a municipal water works approval for "collection, production treatment, storage, supply or distribution of potable water to the public" (Nova Scotia Environment, 2019). A registered (private) system is a public water supply system such as an apartment building, school, rural development, campground, etc. not connected to a municipal water system (Nova Scotia Environment, 2019). Both types of systems are considered public water systems: a water system operating for more than 60 days per year, serving at least 15 service connections or 25 people (Nova Scotia Environment, 2019).

Historical DWA data from Nova Scotia was made available to the public in October 2019. Data was downloaded from: https://data.novascotia.ca/Environment-and-Energy/Boil-Water-Advisories/7t68-

9xmm for data issued between 2001 to 2019 (Nova Scotia Environment and Energy, 2019). Data was transferred by the researcher from portable document format to a comma separated variable Excel file and subsequently analysis in the R software language. Prior to 2019, data on DWAs was generated on a weekly basis in portable document format and needed to be saved as individual documents, similar to the method employed in Newfoundland and Labrador.

2.4.1.2 New Brunswick

New Brunswick data is available online through the Office of the Chief Medical Officer of Health (Department of Public Health, https://www2.gnb.ca/content/gnb/en/departments/ocmoh/ health_advisories/past_boil_orders.html) and is updated as drinking water advisories occur. The data on this website was emailed to researchers by the Department of Public Health, and then copied the data to a table format in Excel. Data was available from January 1st, 2006 to Summer 2019 when the data was compiled.

2.4.1.3 Newfoundland and Labrador

Newfoundland and Labrador reports are uploaded weekly to the Municipal Affairs and Environment website under the Water Research Portal, similar to the Nova Scotia format (Municipal Affairs and Environment, 2019, https://www.mae.gov.nl.ca/waterres/quality/drinkingwater/advisories.html). The Water Research Portal provides detailed information on the issuance and removal of DWAs, both by community and date in portable document format. As past reported are not available on this platform, data from Newfoundland and Labrador was only collected from Spring to Summer 2019. Data was obtained online and translated to an Excel document for analysis in R software.

2.4.2 Data Analysis

Data from each Atlantic province was analyzed to determine (1) what characteristics are being reported in each jurisdiction, (2) duration of DWAs over time, (3) the reason a DWA is issued and (4) if any patterns exist in the data over time that are useful for water management decision making. The purpose behind each goal is to determine what features in these water systems make a system or community vulnerable and thus susceptible to future water quality concerns. Substantial literature reporting DWA prevalence has been reviewed above; however, more studies are needed to link the reasons behind the occurrence of a DWA or to identify system characteristics that make a water system vulnerable. This study focuses on the reason a DWA was issued over time to determine changes in water system operations and monitoring.

2.5 Results

2.5.1 Reported characteristics of DWAs

Review of the reporting mechanisms utilized in Nova Scotia, New Brunswick and Newfoundland and Labrador indicate there is no common accepted format for reporting drinking water advisories in the Atlantic Provinces. The only features all three reports have in common are the start date of the advisory and the reason the advisory was issued. Duration date (start date – end date) can only be calculated for Nova Scotia and New Brunswick. Furthermore, water system size (as represented by population, the number of people served by a water system) is only available in Newfoundland and Labrador, although Nova Scotia differentiates between registered water systems and municipal water systems. Neither of these statistics are available for New Brunswick. No system contains all the characteristics analyzed, which leads to a fragmented data set for analysis at a federal level.

2.5.1.1 DWA trends over time

The largest data set available for this study came from Nova Scotia. Figure 2.1 shows the number of drinking water advisories issued each week over a ten-year study period. The red bars represent the number of drinking water advisories issued each week, while the blue bars represent the number of drinking water advisories removed each week. Seasonality is represented on the graph by the colored bands across the background, each band representing three months. Winter is represented in blue, spring is represented in green, summer is represented in red and fall is represented in yellow.

Evidence from Nova Scotia presented in Figure 2.1 demonstrates that drinking water issuance over time shows periodicity and predictability over time. In Figure 2.1, each bar represents a month of DWA data. More drinking water advisories were removed than were issued in 70 months out of 132 months total. There are ten months where the number of DWAS issued is equal to the number removed. However, in 52 of the months, the number of new drinking water advisories issued was higher than the number of advisories removed. In 39% of the months where data was collected, more DWAs were issued than removed, indicating that overall, the situation in the province is not improving. Most reports available on drinking water advisories indicate number of DWAs removed; the results in Figure 2.1 indicate that keeping track of DWAs issued each month is important as it gives a net output for how well water systems are being managed. Based on the data presented herein, it is clear that DWAs are a largely unresolved issue

Figure 2.1: Trend in registered system DWA occurrence over time in Nova Scotia (Panel A). Trend in DWAs in New Brunswick from 2009-2019 (Panel B). Seasonality is represented on the graph by the colored bands across the background, each band representing three months. Winter is represented in blue, spring is represented in green, summer is represented in red and fall is represented in yellow.

Panel B of Figure 2.1 shows DWAs over time in New Brunswick, summarized by month. The fewest number of DWAs issued by month was zero and the highest was eleven DWAs. There are eight months where no DWAs were issued out of 96 months total in the data set. In fifty-five months, more DWAs were removed than issued. In the remaining thirty-two months, more DWAs were issued than removed, representing 33% of the total data set. Overall, the summer and fall months predominantly had more DWAs issued than removed, similar to the trend observed in Nova Scotia (areas colored in red and yellow respectively). To further explore DWAs issuance, Figure 2.2 shows the number of DWAs issued versus removed in Nova Scotia (Panel A) and New Brunswick (Panel B). Figure 2.2 confirms overall the number of months with more DWAs issued than removed is similar to the number of months where DWAs removed is greater than issued.

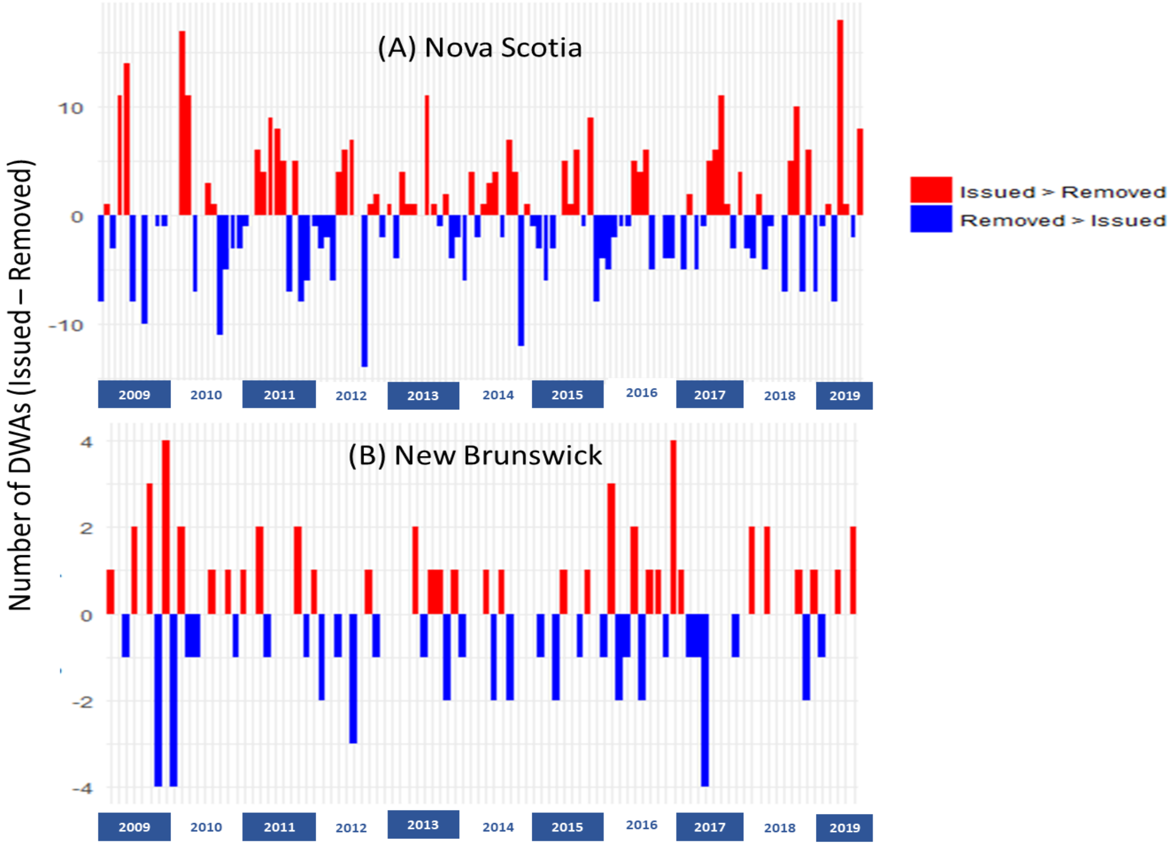


Figure 2.2: In both Nova Scotia and New Brunswick, there are few months where the number of DWAs issued are equal to the number removed. Each bar in this figure represents a month of data. Bars in blue represent months where more DWAs were removed than issued and bars in red represent months where more DWAs were issued than removed.

Figure 2.3 reveals the presence of clear seasonality in the issuance of drinking water advisories in Nova Scotia. The majority of new DWAs are issued in the summer and fall months, between May and October. In the winter months DWA issuance is the smallest. The trend for removing DWAs is less clear but follows the same pattern. In Nova Scotia the high prevalence of drinking water advisories in the summer corresponds to when summer businesses such as campgrounds, hotels and restaurants are closing at the end of the summer tourist season. Water quality testing in these registered systems is only required once a year (Health Canada, 2014a). Seasonality is seen in Panel B in New Brunswick, with the majority of months with more DWAs issued than removed found in summer and fall months.

Seasonality of DWAs is examined in Figure 2.3. Month is represented numerically on the x-axis, duration is represented in days on the y-axis and Panel A shows data from Nova Scotia, with Panel B representing data from New Brunswick. Figure 3 shows most DWAs in Nova Scotia are issued in the summer months, represented in red, with DWA removal following a similar trend. In New Brunswick, seasonal trends are not well defined; however, the longest duration DWAs are issued in June, July, August and September. Seasonality plays an important role in Nova Scotia, predominantly due to registered system characteristics. Seasonal businesses and a yearly sampling requirement lead to a large portion of total coliform and E. coli testing in late summer months, accounting for the sharp increase in DWAs issued during the summer.

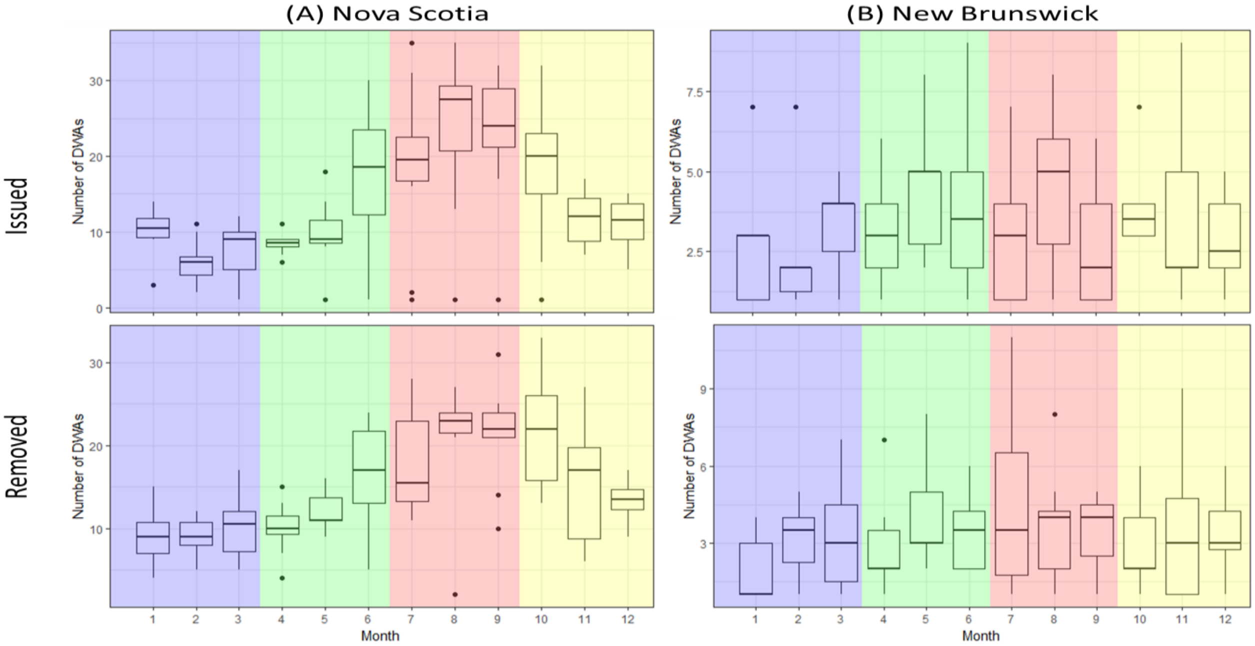


Figure 2.3: An evaluation of DWA issuance and removal by month revealed clear seasonality in DWA issuance in Nova Scotia. The majority of DWAs are issued in summer and fall months, with the most DWAs issued in August.

2.5.1.2 Reasons DWAs are issued

To further understand drinking water advisories in the Atlantic provinces, Figure 2.4 presents the reasons that drinking water advisories are issued. In Figure 2.4, emergency DWAs are represented in red and precautionary DWAs are represented in blue. Figure 2.4 shows that drinking water advisories in New Brunswick and Newfoundland and Labrador are primarily issued due to operational concerns. Municipal systems in Nova Scotia share this characteristic, however, registered system DWAs are predominantly emergency DWAs, issued due to the presence of total coliforms.

In Newfoundland and Labrador, less than 1/8 (12.5%) of all drinking water advisories are emergency advisories. The remaining 87.5% of DWAs issued in 2019 were operational concerns, ranging from concerns with chlorine disinfection effectiveness to the presence of disinfection procedures and water quantity issues (loss of flow in the distribution system or change in source water inflow). DWAs are predominantly issued as a result of a failure within the chlorine disinfection system. In New Brunswick, 26 emergency DWAs were issued out of 324 total DWAs over a ten-year period. Therefore, 92% of DWAs in New Brunswick were precautionary DWAs related to operational concerns. Water main breaks and power outages are the two most frequent reasons DWAs are issued. Available reasons in Newfoundland and Labrador focus mainly on disinfection as a barrier to preventing microbial contamination while New Brunswick reporting reveals concerns with infrastructure failure and water quantity concerns.

In New Brunswick and Newfoundland, several of the systems included in this study are small or remote systems, most likely on point of use or point of entry water treatment rather than centralized drinking water supplies. As a result, the high number of precautionary DWAs in these provinces may be explained by a lack of knowledge how to operate these point treatment options effectively, a lack of access to replacement components and financial constraints, as is typically seen in many small systems (Kot et.al., 2011). Nova Scotia makes the distinction between registered and municipal systems, whereas, New Brunswick and Newfoundland and Labrador do not. Without this distinction, it is hypothesized that the reason precautionary advisories are prominent in these two provinces is due to the small or remote nature of these water systems, necessitating point of use or point of entry treatment that cannot be easily maintained by a homeowner.

In Nova Scotia, approximately 50% of municipal DWAs are precautionary DWAs. In registered systems, there were 1442 emergency DWAs representing 76.9 % of advisories issued. Of the 1876 DWAs reported in Nova Scotia, only 28 were in municipal systems, indicating 98.5% of all DWAs issued in Nova Scotia were in registered systems. The main reason DWAs are issued in registered systems is the presence of total coliforms in a water sample. Figure 2.4 clearly demonstrates the unequal water quality and health risk experienced in registered systems. Registered systems experience the majority of DWAs in Nova Scotia, with DWAs issued as a result of unsafe water quality.

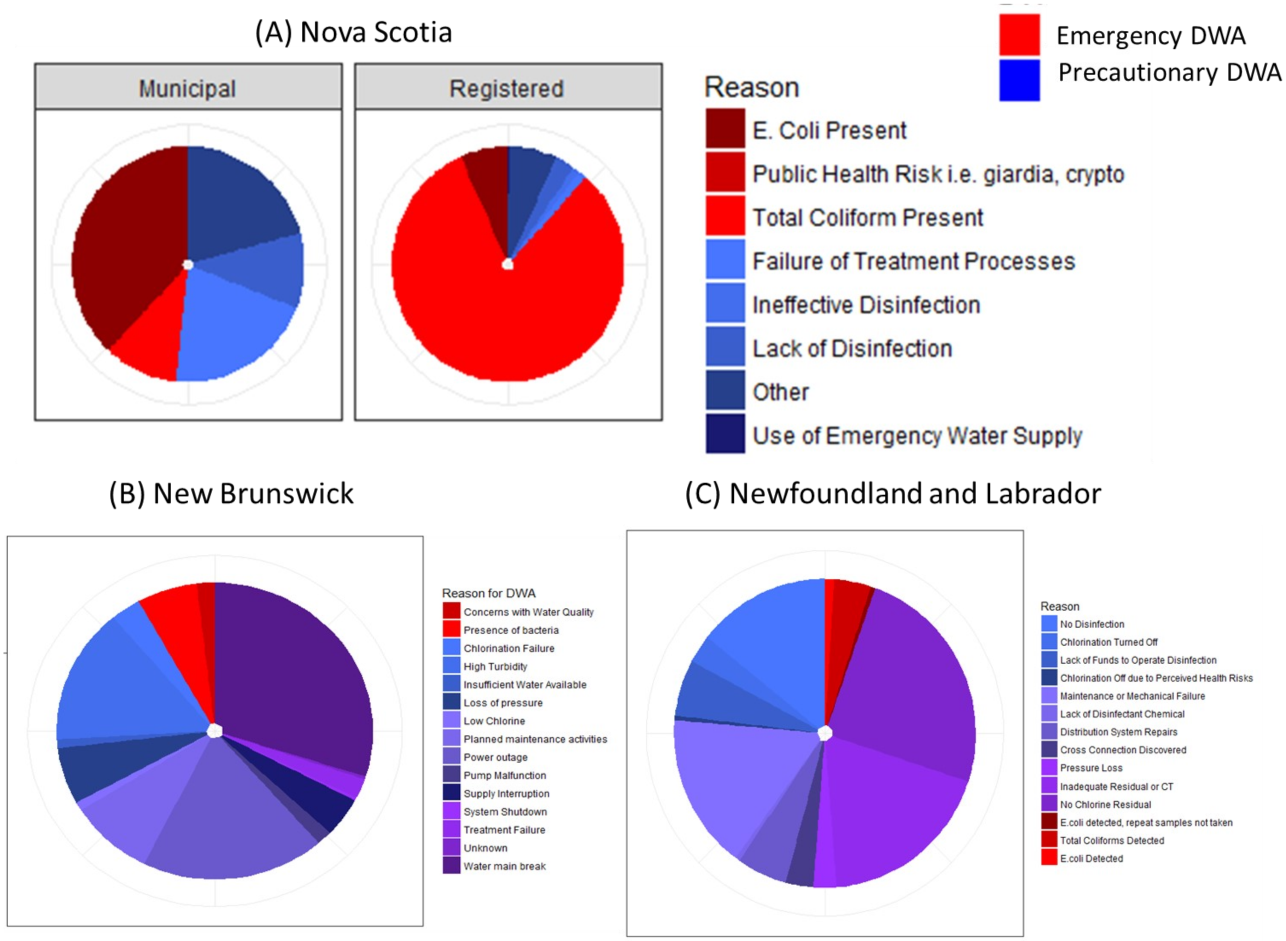


Figure 2.4: Data from the Atlantic provinces reveals operational concerns are the primary reason that drinking water advisories are issued in municipal water systems. DWAs considers emergency DWAs are represented in red and precautionary DWAs are represented in blue.

2.5.1.3 Population impacted by DWA

The number of people served by a water system was only available from Newfoundland and Labrador. Small systems in Figure 2.5 represent water systems that serve a population of less than 5000 people. Figure 2.5 reveals drinking water advisories are predominantly issued in small water systems, with large systems having DWAs for one specific reason (D1, distribution system undergoing repairs). The only reason a DWA was issued for a large system represented a precautionary measure with the water distribution system was undergoing repairs. The number of advisories in small systems was largest for reasons E2 (No free chlorine residual detected in the water distribution system) and E1 (Water entering the distribution system or facility, after a minimum 20 minute contact time does not have a free chlorine residual of at least 0.3 mg/l or equivalent CT value), both representing water with a low disinfectant chlorine residual. Reason C1 represents the absence of disinfection as a result of repair of mechanical failure and reason A represents a water system with no disinfection system in place. As seen previously in Figure 2.4, the four predominant reasons that DWAs are issued in small systems are due to operational concerns, specifically related to disinfection. Population data was only available from Newfoundland and Labrador, however, given the distinction between registered and municipal systems in Nova Scotia, the situation is similar as registered systems service include hotels, campgrounds and daycares (Nova Scotia Environment, 2019).

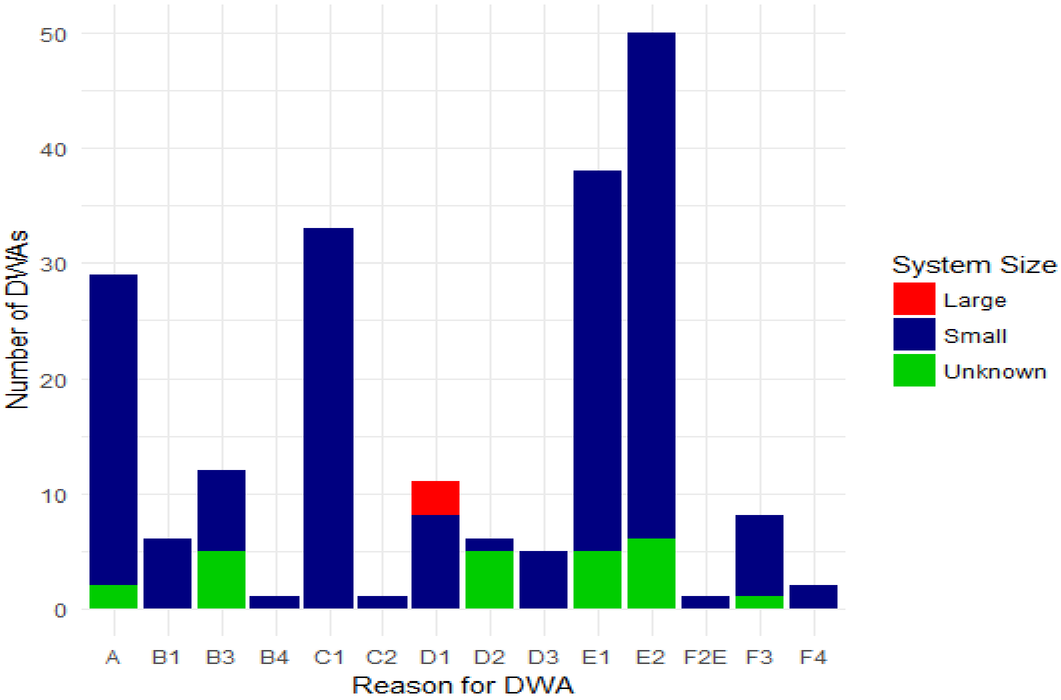


Figure 2.5: Data from Newfoundland and Labrador suggests that DWAs predominantly occur in small systems. The reasons for presents here DWAs are defined specifically for Newfoundland and Labrador (Municipal Affairs and Environment, 2019).

2.5.1.4 Duration of DWAs

Finally, review of data from Nova Scotia and New Brunswick demonstrated the presence of long-term drinking water advisories in both municipal and registered water systems. Duration data is presented in Figure 2.6 showing boxplots for duration of a DWA on the x-axis in days and the reason for the DWA on the y-axis. Failure of treatment systems in Nova Scotia municipal systems contribute to the longest lasting DWAs. In New Brunswick, insufficient water quantity and high turbidity contribute to the longest DWAs. Figure 2.6 reveals DWAs in place for as few as three days, but also highlights several DWAs that have been in place for over 1000 days. Furthermore, the tails of the boxplots presented in Figure 2.6 indicate that there are water systems where a drinking water advisory has been in place for more than 4000 days. Registered systems experience DWAs that are years long, while the majority of DWAs in municipal systems are under 30 days in length. This data highlights long-term drinking water advisories in non-First Nation water systems, revealing evidence that rural and remote systems in Nova Scotia also deal with long-standing water quality concerns.

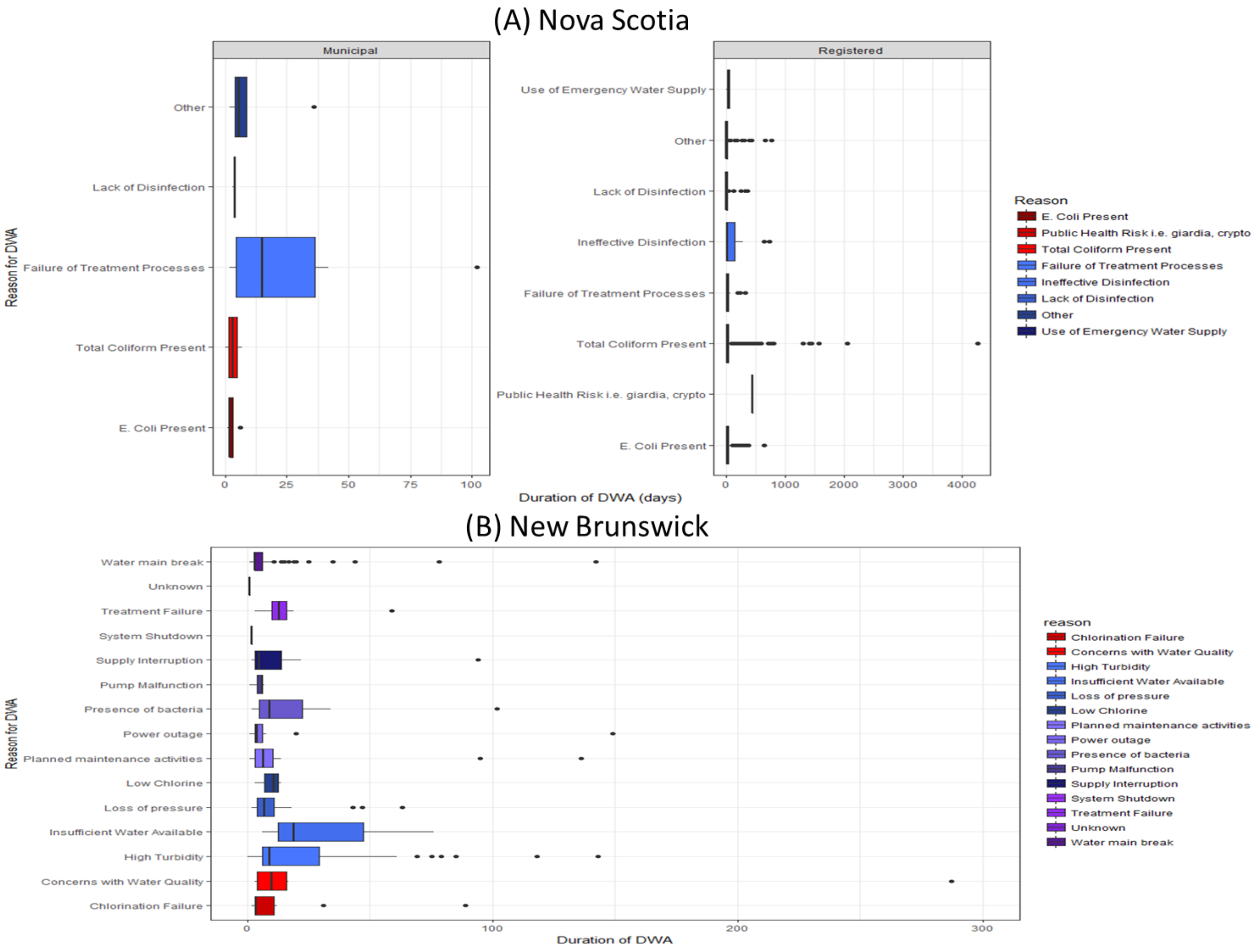


Figure 2.6: Review of drinking water advisories in New Brunswick and Nova Scotia revealed the presence of long term DWAs in registered water systems in Nova Scotia. DWAs are in place for more than 100 days in several instances, with the tails of the boxplots indicating DWAs in place for over 4000 days, or more than ten years.

2.6 Discussion

2.6.1 Current Data Gaps

Across the three provinces in the Atlantic region, there is no common reporting format for DWAs. This leads to an incomplete data set where all relevant DWA characteristics cannot be accurately compared to discern commonalities. Post et.al., 2018 noted that DWA data sets needed to be censored in order to have a complete set of variables to construct probabilistic neural networks for First Nation drinking water advisories. Several other studies of First Nation DWAs have noted the same concern, particularly when trying to model future events or understand factors driving DWA issuance (Murphy et.al., 2016, Harvey et.al, 2015). This study demonstrates that lack of consistent reporting for DWA is not a First Nation concern alone. In fact, Dunn et.al., 2017 notes this lack of common reporting and data collection is an underlying concern with water governance in Canada overall (Dunn et.al., 2017). Limited data across provincial borders leads to an inability to understand the main drivers behind waterborne disease and operational and process-related concerns in Canadian water systems, resulting in no clearly defined national trends (Dunn et.al., 2017). A common reporting format that is publicly available for consumers to consult is needed to strength the DWA as a water safety tool.

Communication of a DWA is also a concern highlighted by the different reporting mechanisms observed in this study and in the literature. Unfortunately, most communication between government agencies responsible for the provision of safe water only occurs when an issue arises, such as the issuance of a DWA (Miller and Watson, 2011). While the data utilized in this study was publicly available online through the corresponding provincial authorities, the Newfoundland and Labrador data was collected over a short study periods, as there is no historical data available. Without constant monitoring of DWA issuance, trends over time cannot be recorded.

To alleviate this reporting concern, Table 2.1 provides a template of information that need to be included in drinking water advisory reporting formats across provinces. Using the data currently reported from the Atlantic provinces, this table combines the current DWA characteristics from each jurisdiction and adds two additional characteristics: type of system (municipal, private or First Nation) and water quality parameters measured that led to the issuance of the advisory. Table 2.1 provides information about location, duration, population, reason, and type of advisory from previous reporting formats. Type of system was added to allow for differentiation between water systems; in future studies this can be used to determine which issues are unique to each system type to better design system-specific solutions. System size contains information not only about population served but also the number of connections to a water distribution system for clarity.

The data presented in Table 2.1 is categorical data; accurately understanding trends in DWA data over time relies on proper sample sizes from a full data set to understand how water systems differ. Water safety planning is a system-specific approach: each water system is evaluated based on the unique hazards present in the system (WHO, 2012, Bartram et.al, 2009). A first step towards improving the DWA as a water safety tool is to add this element to DWA reporting. This ensures when describe DWAs from localized water systems, readers understand these systems are a subset of a larger, complete data set at a federal level. Instead of grouping all DWAs as the same or generalizing conclusions across several types of systems, a full dataset collected using the format in Table 2.1 better highlights concerns in specific system types and generates more information to inform water governance policy.

Table 2.1: Based on the inconsistencies present in current DWA reporting formats, this table presents a recommended format for communicating DWAs across provinces to allow for a federal database of DWA knowledge to be developed.

Location	Start Date	End Date	Reason	Comments	Type of System	Population/ System Size	Type of Advisory	Water Quality Parameters Measured to issue advisory
System A, County A, Nova Scotia	September 19th, 2019	September 29th, 2019	Reason_Code: Water main break in distribution system	Water main break occurred in service lateral on Street Avenue on September 19th.	Municipal	3000 people, 345 connections	Boil Water Advisory	Flow rate, pressure in laterals
System B, County B, Nova Scotia	September 16th, 2019	Still in place	Reason_Code: Presence of microbial contamination	Sampling staff measured presence of E.coli in water system on September 16th	Private	15 people, 10 connections	Boil Water Advisory	E.Coli (MPN), Chlorine Residual
System A, County B, New Brunswick	September 3rd, 2019	September 4th, 2019	Reason_Code: Disinfection turned off	Disinfection system was turned off by staff due to lack of chemical available to provide adequate disinfection	Private	35 people, 20 connections	Boil Water Advisory	Chlorine residual, free chlorine, chlorine dose, contact time (CT)

Table 2.1 represents an initial strategy recommending information to be included in DWA reporting mechanisms. At a national level, this information is critical to understanding trends in DWA issuance. At a provincial level, this information is the minimum information recorded for each DWA. Additional characteristics can be added according to provincial regulatory agencies, such as sample location, laboratory analysis location and tests, how the advisory was communicated to the public and source water type. In order to avoid a data collection burden on the agencies reporting this information currently, Table 2.1 recommends the minimum characteristics that should be reported; future studies may reveal the need to include other characteristics.

2.6.2 DWAs in the context of water risk management

Analysis of DWAs in Atlantic Canada reveals a clear seasonality when most DWAs are issued. From Figure 2.1, in Nova Scotia, DWA issuance increased towards the end of June and increases over the later summer of months of August and September. Previous DWA studies have noted this seasonality as well

(Black and McBean, 2018, Galway, 2016, Post et.al., 2018, Murphy et.al., 2016). When framing the DWA as a safety tool, there is clear room for improvement in how a DWA informs seasonal risk, particularly considering changes in source water quality in summer months. Several studies have shown how fluctuations in seasonal organic content of lakes or temperatures in aquifers can lead to noticeable impacts in finished water quality delivered to consumers (White & Driscoll 1987, Granger et.al., 2014). Since the DWA is a reactionary tool that uses endpoint monitoring, a DWA cannot inform a consumer about changes in source water quality and how that impacts consumers. Despite understanding seasonality of DWAs, little has been done to mitigate seasonality's effects on registered systems. Knowledge of changes in source water characteristics with seasonality is crucial and communicating and educating water systems about this concern is needed.

The need for increased education extends to mitigating operational concerns in water systems to prevent future precautionary advisories. In all Atlantic municipal water systems, the majority of reasons for DWA issuance are operational or related to process control in water treatment and distribution systems. This result has been reported specifically in First Nation communities in several studies (Post et.al., 2018, Black and McBean, 2018, Thompson et.al., 2017), in Ontario specifically (Galway, 2016), and across water systems in Canada (Environment and Climate Change Canada, 2018). While removing First Nation DWAs is an acknowledged and pressing concern (Indigenous Services Canada, 2018), there is also clear evidence that municipal and registered water systems also lack sufficient resources to remove DWAs by addressing the root causes of the advisory. This is not to marginalize the concerns in First Nation systems, where advisories have been in place for as long as twenty five years; this study demonstrates that DWA concerns are prevalent across water systems in Canada, pointing to a need for a shift in how water is managed in Canada.

In addition to the concerns presented with DWA issuance and removal, there is also no current evidence available in the Atlantic provinces that suggests DWAs are being communicated and adhered to by the general public. A 2011 study from British Columbia demonstrated for 31 water systems, over 30% of the time, the water authority officials were not aware if a drinking water advisory was being adhered to (Grover, 2011). Furthermore, over 50% of the time, there was no knowledge about compliance with the DWA or it was known that the DWA was not being complied with (Grover, 2011). Given the lack of historical data available from both Nova Scotia and Newfoundland and Labrador, it is difficult to discern how the general public would be expected to know if a water advisory had been issued for a water system previously. Without historical data or data surrounding public compliance, DWA efficacy is relatively unknown for the Atlantic provinces as the DWA is designed as a tool to communicate water safety risk to customers. Grover, 2011 identified risk communication, message fatigue and public compliance with boil water advisories as key challenges that need to be addressed when using a boil water advisory. Without further studies, it is currently unknown whether the general public complies with DWAs.

A case study of the Toledo DWA in 2014 demonstrated how a water safety plan could have prevented the issuance of a drinking water advisory for this large city (Jetoo et.al., 2015). Water safety plans are risk management tools promoted by the World Health Organization since 2004 that focus on proactive risk management (Bartram et.al., 2009, WHO, 2012). Jetoo et.al., 2015 analyzed the events that led to the Toldeo DWA and concluded that the crisis could have been averted with simple risk management procedures. The study concluded that institutional concerns were the most critical threats to the Toledo system: a lack of operator training, standard operating procedures and system monitoring accountability, threats that would lead to a precautionary DWA in Canada (Jetoo et.al., 2015). A multi-stakeholder, collaborative approach was recommended in the Toledo DWA case study, and the study advised adoption of proactive measures that limit the translation of future operational issues to the issuance of a DWA (Jetoo et.al., 2015). This case study presents a potential method for achieving safe drinking water based on a DWA case that could have been averted given proper attention to operational concerns. DWAs do not consider risks from source, through treatment and distribution in the methodical way water safety plans are designed to. In the context of Canadian DWAs and water management, the water safety plan provides one potential method for achieving safer water than the DWA alone.

2.7 Conclusions

The drinking water advisory as a water safety tool lacks necessary information about water system risk. Analysis of DWAs in three provinces demonstrated the clear seasonality of DWA issuance, DWAs are largely issued for operational and process-related reasons and there is a disproportionate DWA burden in small water systems. In addition, the number of drinking water advisories is approximately equal the number of advisories removed in most of the months recorded in Nova Scotia and New Brunswick, which indicates a system that is need of fundamental improvement.

A DWA characteristic analysis demonstrated the predominance of operational concerns and the need for interventions to improve water systems. Review of drinking water advisory data demonstrated the lack of a consistent reporting format across provinces. Inconsistent reporting of DWAs is a symptom of a larger concern for water governance in Canada: the DWA is a metric for water safety but provides incomplete knowledge to make decisions about water system safety at both a provincial and federal level. As a result, a new reporting format was proposed to collect the minimum information needed to begin understanding national trends in water system safety. In particular, proactive risked-based management tools, such as water safety plans, are needed to resolve the operational concerns observed in Canadian water systems.

3 Chapter Three - Water Safety Plans as a Tool for Drinking Water Regulatory Frameworks in Arctic Communities

Kaycie Lane, Amina K. Stoddart and Graham A. Gagnon

3.1 Abstract

Arctic communities often face drinking water supply challenges that are unique to their location. Consequently, conventional drinking water regulatory strategies often do not meet the needs of these communities. A literature review of Arctic jurisdictions was conducted to evaluate the current water management approaches and how these techniques could be applied to the territory of Nunavut in Canada. The countries included are all members of the Arctic Council and also included other Canadian jurisdictions considered important to the understanding of water management for Northern Canadian communities. The communities in Nunavut face many challenges in delivering safe water to customers due to remoteness, small community size and therefore staffing constraints, lack of guidelines and monitoring procedures specific to Nunavut, and water treatment and distribution systems that are vastly different than those used in southern communities. Water safety plans were explored as an alternative to water quality regulations as recent case studies have demonstrated the utility of this risk management tool, especially in the context of small communities. Iceland and Alberta both currently have regulated water safety plans (WSPs) and were examined to understand shortcomings and benefits if WSPs were to be applied as a possible strategy in Nunavut. Finally, this study discusses specific considerations that are necessary should a WSP approach be applied in Nunavut.

3.2 Introduction

Meeting current drinking water regulations has proved a major challenge, particularly for Arctic communities, such as the communities located in Nunavut. In the capital of Iqaluit, a traditional piped distribution system is in use, facilitated by the use of a Utilidor system for maintaining an acceptable temperature in pipes that would otherwise freeze. However, in most communities in Nunavut, water is delivered by hauling trucks rather than conventional piped methods, a system for which few guidelines have been developed nationally (Health Canada, 2014). A map of the communities present in the territory of Nunavut is provided for reference purposes (Figure 3.1).

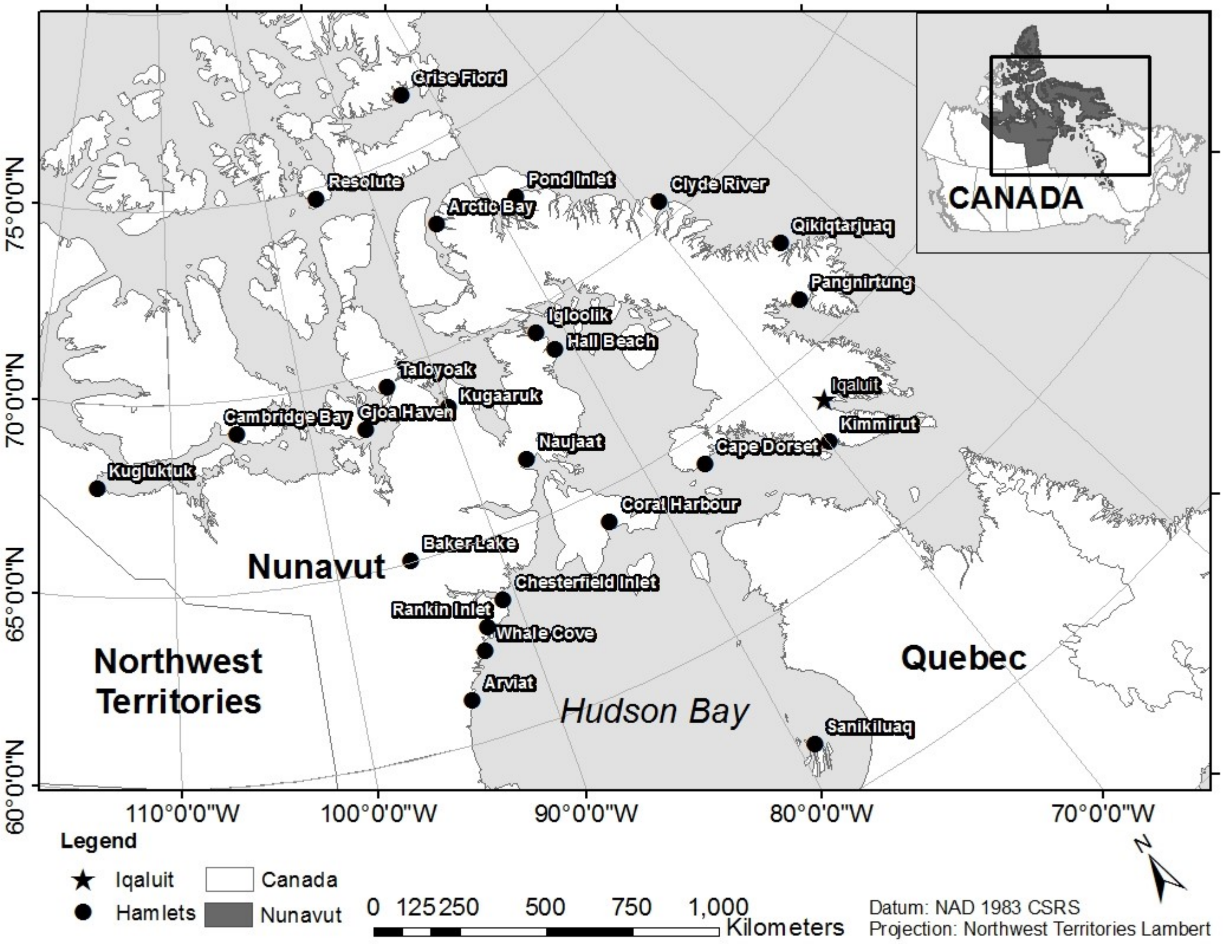


Figure 3.1: A map of the locations of the remote communities in Nunavut.

The current approach in the water industry relies heavily on the use of water quality guidelines, specifying parameters to be measured and compared to acceptable concentration levels at the end of a treatment train in a drinking water supply system (Baum et. al., 2015, Bartram et.al., 2009, Jalba and Hrudey, 2005). However, stringent regulations on a suite of chemical and microbiological parameters at the end of a treatment facility are often not practical for small and remote communities (Summerill et. al., 2010, Kot et.al., 2011, Butterfield and Camper, 2004, Boag et.al., 2010). Furthermore, a regulatory approach that is driven by sampling for contaminants opposed to preventing the occurrence of contamination does not identify underlying systemic issues that may be present in the water supply system. In addition, there may be parameters not included in water quality guidelines in southern communities because they are not commonly present at these latitudes but are present and, more importantly, a risk in northern communities. For example, sources of microbial contamination may or may not be present in the north or are transmitted via different pathogenic pathways; a study by Iqbal et. al. (2015) demonstrated the prevalence of *Cryptosporidium* and *Giardia* in the Qikiqtani Region in Nunavut and cited zootonic transmission through seals and whales as possible methods of transmission (Iqbal et. al., 2015). In southern climates, Cryptosporidium and giardia are most often transmitted to human populations via surface water sources through cattle populations and other domesticated farm animals (WHO, Protozoan Parasites).

Previous reports from Arctic communities have demonstrated the prevalence of gastrointestinal illness in remote communities (Pardhan-Ali et. al., 2012). A study performed in the Northwest Territories calculated prevalence of gastrointestinal illness in communities as a result of waterborne disease and concluded that campylobacteriosis, giardiasis and salmonellosis are common in these communities, because of contamination sources not found in southern communities (Pardhan-Ali et. al., 2012). A study of transmission pathways for *Cryptosporidium* and *Giardia* in Nunavut also confirms a higher prevalence of gastrointestinal illness associated with waterborne pathogens in Northern communities (Iqbal et. al., 2015). Furthermore, the study attempted to understand the species of these pathogenic organisms that are present in the North; current data on the longevity of these pathogens in Arctic climates is limited by insufficient knowledge of the specific species of *Cryptosporidium* and *Giardia* present in the arctic (Iqbal et. al., 2015).

Water safety plans (WSPs) are a water quality management tool that have been introduced to drinking water systems to provide a risk analysis tool that applies a proactive approach instead of the current reactive regulatory approach (Kot et. al., 2014, Bartram et.al., 2009, WHO, 2012, WHO, 2016). Current regulatory structures that require testing for specific chemical, microbiological and aesthetic parameters rely on sampling that occurs at set points within the treatment facilities and distribution systems themselves, not at every potential hazardous location for feasibility reasons. However, this generates an approach that pinpoints the hazardous event after it has already occurred. A WSP attempts to curb this reactionary approach to drinking water management by locating and managing hazardous situations; not by measuring the full suite of parameters in a federal or provincial guideline (Bartram et.al., 2009, WHO, 2012). WSPs attempt to prevent hazards from occurring by promoting good maintenance practices, active engagement of the community served by the water supply and by using identified hazards to help meet water quality guidelines (Baum et. al., 2015, WHO, 2012, WHO & IWA, 2018). Water quality guidelines can still be used and met with a water safety plan; the key difference is knowledge is generated about the system via risk management practices.

Arctic communities are often unable to meet many of the federal regulations for microbiological and chemical contaminants due to small size and lack of access to communities. Kot et. al. 2014, highlighted specific reasons why regulations may be difficult to meet in these small Arctic communities: a lack of capacity to sample specific parameters, lack of knowledge of proper sampling procedures, and parameters that are not applicable to small communities (Kot et. al., 2014). Previous studies conducted within the past twenty years have highlighted the following unique issues in Arctic communities: problems with trucked water supply, overcrowding and inadequate housing (Daley et. al., 2014), and use of untreated water sources for consumption and hygienic purposes. In addition, Harper et. al. 2014, demonstrated that the incidence of gastrointestinal illness is higher on average in northern communities in Canada than the national average for the country as a whole. Thus, the need for unique and robust drinking water regulations is still required.

The objective of this study was to examine strategies for drinking water regulation in Arctic communities. As a case study, the Canadian territory of Nunavut was used to assess the applicability of water safety plans as an approach to water governance.

3.3 Methods

Currently in Nunavut, many policies regarding water quality and water utility operation are under revision to determine which methods are used in Arctic regions globally to safeguard public health. In conducting this review of Arctic policies, the countries included on the Arctic Council were chosen for comparison. In addition, provinces and territories in Canada which have Arctic regions or policies specific to communities located north of 60 degrees latitude were considered. Canadian policies were examined to determine provincial and territorial strategies for meeting and implementing the Guidelines for Canadian Drinking Water Quality (GCDWQ) which are set at the federal level but legally enforceable only at the provincial and territorial level (Health Canada, 2014, Kot et.al., 2011, Bakker and Cook, 2011).

The review of Arctic policies presented examined several key components of the drinking water quality policies and practices in the chosen locations. Management practices were considered by examining which governmental entity or document details water quality policies; many times, there is no Ministry dedicated specifically to water management and the responsibility of managing water can fall under “environmental” or “public health” branches of the government. Treatment requirements, where available, were examined to determine minimum regulations for drinking water utilities. These minimum requirements facilitate an understanding of advisable treatment methods that may be applicable in Nunavut or advisable treatment requirements (for example, 0.2 mg/L chlorine residual required in the distribution system after treatment). Disinfection was a focus as it is considered a safeguard for public health (Health Canada, 2014).

In addition, consideration was given to the type of source waters present in Arctic regions. Ground water and surface water sources often require different methods of treatment to ensure that delivered water quality is free of possible pathogenic organisms (Health Canada, 2014). Regulated drinking water quality parameters were also considered; specifically, which chemical and physical versus microbiological parameters are measured and monitored and with which frequencies. These review topics were chosen to facilitate comparisons between Nunavut and other Arctic Regions for future regulations consideration. Sources of relevant information were varied, including previous peer-review studies and regulatory documents stipulating water quality standards.

3.4 Strategies and Legislation in Arctic Jurisdictions

The Arctic Council identifies eight countries as having Arctic communities or regions: Iceland, Alaska (United States), Denmark (Greenland), Norway, Sweden, Finland, Russia and Canada (Yukon, Nunavut and Northwest Territories and the provinces of Manitoba, Quebec and Newfoundland and Labrador). A review of the current drinking water legislation, guidelines and administration of water management was conducted to ascertain similarities in water governance policies and water management strategies. The comparison of the Arctic jurisdictions considered is presented in Table 3.1.

Table 3.1: A comparison of global arctic jurisdiction water quality regulations and practices. Emphasis was put on understanding how water management is conducted and whether there are provisions in legislation or regulation specifically for small systems.

	Iceland	Norway	Sweden	Finland	Russia	Alaska, USA
Governing Body	The Ministry of Industry and Innovation	The Ministry of the Environment	Ministry of Agriculture, National Food Administration	Ministry of Social Affairs and Health		Division of Environmental Health
Governing Document	Icelandic Drinking Water Regulations, The Foodstuffs Act, 1995				Russian Federation Water Code	Alaska Drinking Water Regulations
Source Water Type	95% Groundwater 5% Surface water	90% Surface water 10% Groundwater	50% Surface water	70% Groundwater	70% Surface water 30% Groundwater	80% Groundwater 20% Surface Water or Rainwater
Common Treatment Methods	There are no specifications for treatment of groundwater. Surface water is treated with filtration and UV disinfection.	No requirements specified	Typical waterworks include flocculation, coagulation, sedimentation, filtration, disinfection and storage components	No requirements specified	No requirements specified	Filtration required for surface water sources. Disinfection required for all sources.
Water Quality Parameters	EU Drinking Water Directive	EU Drinking Water Directive	EU Drinking Water Directive	EU Drinking Water Directive	Russian Federation Water Code	US EPA Safe Drinking Water Act
Special Considerations by Community Size	YES	YES	YES	YES	Not Specified	YES
Water Safety Plan (WSP)	YES	NO	NO	NO	NO	NO
Primary References	Gunnarsdottir et. al., 2012a	Ministry of Health Care and Services, 2012	Swedish Water and Wastewater Association, 2000	Finnish Institute of Drinking Water/ Prizztech Ltd., 2008	Organisation for Economic Co-operation and Development, 2006, Dudarev et. al., 2013	State of Alaska: Department of Environmental Health, 2016

3.4.1 European Union Drinking Water Directive

The European Union (EU) outlined the Drinking Water Directive (Council Directive 98/83/EC on the quality of water intended for human consumption [2001] OJ L330/32) to define minimum requirements for drinking water quality for members in the council of the EU in 1998 (European Commission: Environment, 2015). The Directive applies to all distribution systems within an EU member state that serve more than 50 people or supply more than 10 m^3 water/day. The Directive also applies to drinking water from tankers, bottles and containers and water that is used in the food industry and for other commercial activities served by a utility (European Commission: Environment, 2015).

The Directive sets guidelines for parameters that must be monitored in drinking water treatment facilities; specifically, the Directive provides guidance on 48 microbiological and chemical parameters to be monitored regularly to ensure water cleanliness (European Commission: Environment, 2015). These parameters were generated from the World Health Organization (WHO) Guidelines for Drinking Water Quality and from the European Commission's Scientific Advisory Committee (European Commission: Environment, 2015). Members of the EU must regulate the parameters defined by the Directive and cannot lower the prescribed maximum acceptable concentrations of regulated substances. Member countries can, however, regulate other parameters, in addition to those prescribed in the Directive, that are specifically relevant to their country. Member countries are also required to provide documentation and regular information to consumers. Drinking water quality must be reported to the European Commission every 3 years for evaluation of compliance with the Directive but only for water utilities that serve greater than 5000 people (European Commission: Environment, 2015).

3.4.2 Iceland

Iceland has regulated drinking water quality through the Icelandic Drinking Water Regulation in accordance with the EU Drinking Water Directive since 2001. The Icelandic Drinking Water Regulation outlines source water protection requirements for the largely ground water (~95%) sources (Gunnarsdottir et. al., 2012a) present in the nation. These groundwater sources are typically not treated prior to distribution, whereas, in contrast the surface water source or ground water under the direct influence of surface water are typically treated by filtration (Gunnarsdottir et. al., 2012a). Treatment, when applied is most often achieved by UV disinfection; it is of note that no residual chlorine is required for the distribution systems in Iceland which is 100% piped (Gunnarsdottir et. al., 2012a).

Water utilities in Iceland have had a legal obligation since 1995 to implement a WSP as outlined in *The Foodstuffs Act, 1995.* Implementation began in 1997, and by 2008, approximately 80% of the population was served by a utility with a WSP in place (Gunnarsdottir et. al., 2012a). Compliance with water safety plan requirements is governed by a Local Competent Authority (Gunnarsdottir et. al., 2012a). Larger utilities (i.e. those serving >5000 customers) are required to implement a Hazard Analysis and Critical Control Point model, while small utilities (~~i.e.~~ those serving 500-5000 customers) may implement a smaller five-step model. The smallest communities (serving 100-550 customers) may use a sanitary checklist to complete the requirements of the WSP (Gunnarsdottir and Gissurarson, 2008).

3.4.3 Norway

The Ministry of the Environment acts as the governing body in Norway for the implementation of the EU Drinking Water Directive (Ministry of Health Care and Services, 2012). Every three years, the Ministry submits a report to the EU Commission to fulfill the monitoring requirements of the directive. Norway currently does not employ a water safety planning approach and any initiatives for source water protection are under the jurisdiction of the Ministry of the Environment. Source water in Norway comes primarily from surface water source (~90%) and secondarily from groundwater (~10%). Microbial parameters are therefore a concern in Norway as more than 80% of the population is served by a drinking water system serving more than five thousand people (Ministry of Health Care and Services, 2012).

3.4.4 Sweden

At the federal level, the Ministry of Agriculture oversees drinking water quality and compliance with the EU Drinking Water Directive. The Ministry of the Environment oversees source water protection plans in Sweden aided by the Swedish Water and Wastewater Association in regards to water utility organization (The Swedish Water and Wastewater Association, 2000). Many of the regulations and policies generated in reference to water policy come from the Swedish Water and Wastewater Association as well.

In Sweden, about 50% of the population is served by publicly owned waterworks that are based on surface water withdrawal. The remaining population is served by either traditional or artificial (infiltrated) groundwater (The Swedish Water and Wastewater Association, 2000). Per the Waterworks Association policies, a typical water utility for surface water includes the following types of treatment:

screening, flocculation, sedimentation, a rapid sand filter, and disinfection while in storage before the water is released to the distribution system (Swedish Water and Wastewater Association, 2000).

3.4.5 Finland

The Finnish Ministry of Social Affairs and Health issued regulations and recommendations in 2000 for drinking water quality based on the Decree Relating to the Quality and Monitoring of Water Intended for Human Consumption (Finnish Institute of Drinking Water/ Prizztech Ltd., 2008). The Finnish Decree adheres to the same distribution system sizes presented in the EU Drinking Water Directive (systems supplying 50 or more people a day or supplying >10 m^3/day) and uses the Drinking Water Directive as a guiding document to establish regulations for chemical, physical and microbiological parameters within the water supply system (Finnish Institute of Drinking Water/Prizztech Ltd., 2008). The Ministry of Social Affairs and Health is responsible for reporting compliance to the EU Commission every three years (Finnish Institute of Drinking Water/Prizztech Ltd., 2008).

Approximately 70% of the water used in utilities comes from groundwater in Finland (Katko et. al., 2006). Groundwater is regarded as a source less prone to pathogenic activity; hence, microbiological parameters in Finland are divided into two categories for monitoring and compliance. Microbes that are subject to quality standards include enterococci and *E. coli*; quality recommendations including clostridium perfringens and coliform bacteria (Katko et. al., 2006). This twofold definition of microbial risks in Finland highlights the need to consider microbial activity specifically for the region the regulations are being applied to; different source waters in other Arctic regions may be more susceptible to other types of microbial activity that need to be taken into consideration.

3.4.6 Russia

Russian federal law stipulates that local governments are responsible for the maintenance, organization and development of municipal water supplies under the General Principals of Local Self-Governance (Organisation for Economic Co-operation and Development, 2006). Water utilities are operated as unitary enterprises and must be based on contractual agreements delineated by the federal government. The Russian Federation Water Code was developed initially in 1995, and was most recently updated in 2006 (Organisation for Economic Co-operation and Development, 2006). The Water Code regulates use and protection of water resources and maintains the quality of source waters to meet environmental and sanitary regulations under the Ministry of the Environment and the Ministry of Healthcare, respectively (Organization for Economic Co-operation and Development, 2006).

In the Russian Federation, approximately 70% of the population is served by surface water and 30% by groundwater (Dudarev et. al., 2013). While Russia does have a large percentage of the world's fresh water supply, most is inaccessible due to permafrost and groundwater is often considered underused (Dudarev et. al., 2013). Surface water is more commonly used, especially in the Arctic regions. The study by Dudarev et. al., 2013 showed that approximately 40% of the distributions systems in Northern Russia do not comply with hygienic standards, and that 16% of systems do not employ disinfection in treatment facilities. Treatment processes in Russia currently have no standardized requirements based on treatment technology or facility sizing (Dudarev et. al., 2013) and no current water management or safety planning in legislative documentation although reorganization of water facilities has been highlighted as an important need in the Russian Federation (Organisation for Economic Co-operation and Development, 2006).

3.4.7 Alaska, USA

The Division of Environmental Health in Alaska, implements the federal drinking water regulations stipulated by the United Stated Environmental Protection Agency as laid out in the National Primary Drinking Water Regulations (State of Alaska: Department of Environmental Health, 2016). These regulations are legally enforceable standards designed to protect public health by setting maximum contaminate levels for microbiological, chemical and physical parameters (USEPA, 2016). In the Alaskan Drinking Water Regulations specifically, there is a focus on the following microbial parameters: *Cryptosporidium*, *Giardia*, heterotrophic plate counts, *Legionella*, total coliforms (including both *E. coli* and fecal coliforms), turbidity measurements and enteric viruses. No WSPs are currently formalized in Alaska; however, the state implements Endorsed Drinking Water Protection Plans based on the size of the water system (State Department of Alaska: Natural Resources Department, 2016).

Approximately 80% of public water systems in Alaska draw from ground water sources as of a 2008 report (Alaska Department of Environmental Conservation, 2008). Since ground water is the primary source in Alaska, usually only the minimum Environmental Protection Agency requirements of filtration and disinfection are applied (USEPA, 2016). For surface water sources and ground water sources under the influence of surface water, the Environmental Protection Agency stipulates log-removal requirements for *Giardia* and viruses specifically as well as turbidity measurements after treatment (USEPA, 2016).

3.4.8 Yukon, Canada

In the Yukon, the Department of Health and Social Services is responsible for compliance with drinking water standards. The Yukon Drinking Water Regulations specify treatment regulations for disinfection treatment methods (Environment Yukon, 2015) in the Yukon Territory and no regulations beyond disinfection are outlined. However, all public water systems are required to have and emergency response and contingency plan in place (Commissioner of Yukon, 2015). Testing of physical and chemical parameters must be conducted once per year under the Yukon Drinking Water Regulations.

The majority of communities in the Yukon use groundwater as their source. In the Yukon, the Department of the Environment in responsible for monitoring the health of both surface and ground water sources (Government of Yukon, 2011). As described in the Drinking Water Regulations for the Yukon, bacteriological parameters that must be analyzed include total coliforms, *E. coli* and turbidity with monitoring frequency dependent upon system size. Chlorine residuals are required for public systems, with a residual chlorine measurement of 0.4 mg/L ~~s~~et specifically for a trucked distribution system. Disinfection requirements stipulate that no water may enter a trucked distribution system unless it has been treated by chlorine (Commissioner of Yukon, 2007). Piped distribution systems are also required to have a chlorine residual unless another form of disinfection is used.

3.4.9 Northwest Territories, Canada

Standards for drinking water systems in the Northwest Territories are set through the *Public Health Act* and *Water Supply System Regulations*, which use the GCDWQ as the legally binding standard for drinking water quality (Government of the Northwest Territories, 2014). Environmental Health Officers are responsible for ensuring that community governments are following sampling protocols (Government of the Northwest Territories, 2014). The Water Supply System Regulations require sampling and analysis of bacteriological parameters; these include total coliforms, *E. coli* and turbidity. Monitoring frequency for these parameters are dependent on source water type and size of the treatment facility (Government of the Northwest Territories, 2014).

3.4.10 Quebec, Canada

In Quebec, there are different treatment and management requirements for communities located north of the 55th parallel. These are governed by the *Regulations Respecting the Quality of Drinking Water* which consider treatment system size and community location. Surface water sources or sources under the influence of surface water are required to use filtration and disinfection unless the facility can provide evidence of consistently low turbidity, no production of disinfection by-products and is unlikely to be impacted by changes in source water quality.

Monitoring and sampling frequencies are dependent on system size, with smaller systems having to sample less frequently for microbiological parameters. Treatment systems supplying less than 20,000 people must maintain records for turbidity and free residual disinfectant. Of note are systems serving less than or equal to 500 people and/or are north of the 55th parallel; no turbidity measurements and no disinfection equipment is required. Furthermore, record keeping requirements are relaxed and alarms can be limited to the disinfection process if applicable.

3.4.11 Newfoundland and Labrador, Canada

Water regulation legislation in Newfoundland and Labrador consists of the Water Resource Act and the Municipal Affairs Act, with the Department of Health and Community Services in charge of public community water supplies. Drinking water quality data for parameters such as chlorine residual, *E. coli* and total coliforms are reported monthly to the Department of Environment and Conservation (Newfoundland and Labrador: Health and Community Services, 2014). Environmental Health Offices are responsible for collecting these samples in public water supplies (Newfoundland and Labrador: Health and Community Services, 2014).

According to the annual report published in 2014, about 60% of source water in Newfoundland comes from surface water sources (Department of Environment and Conservation, 2014). No percentages were reported for Labrador. As of 2014, treatment standards for Newfoundland were under development with the province applying a Multi-Barrier Strategic Action Plan similar to the approach in the GCDWQ (Department of Environment and Conservation, 2014). Monitoring of bacteriological parameters (*E. coli* and total coliforms) is required monthly. No sampling procedures are specifically detailed for small communities although it is known that approximately 70% of public water systems serve less than 500 people (Department of Environment and Conservation, 2014).

3.4.12 Nunavut, Canada

The Nunavut Water Board is an institution of the public government that controls licensing for water use in the territory. Indigenous and Northern Affairs Canada manages water resources in Nunavut and this responsibility is set by the *Department of Indian Affairs and Northern Development Act*. Responsibilities related to drinking water include compliance and enforcement of terms and conditions of water licences issued by the Nunavut Water Board and provisions of the *Nunavut Waters and Nunavut Surface Rights Tribunal Act*. As stipulated in the *Public Water Supply Regulations*, samples for bacteriological, physical, chemical and radiological parameters should be collected in a frequency and manner determined by the Chief Medical Health Officer. Physical parameters are to be sampled daily, chemical parameters at least once every 2 years and microbiological samples by community size on a monthly basis.

Treatment requirements include specifying types of filters allowable if filtration is used, guidelines for fluoridation where applicable and disinfection residuals requirements specifically for chlorine disinfection. These chlorine disinfection residuals and contact time guidelines apply to both ground and surface water sources with wells and storage containers. For water haulage trucks, the *Public Water Supply Regulations* make some stipulations with respect to cleanliness, including the ability to be drained and flushed as well as clean storage space for hoses to prevent contamination of nozzles. For a visual comparison of the Canadian jurisdictions to practices in relation to Nunavut please reference Table 3.2.

Table 3.2: A comparison of Canadian arctic jurisdiction water quality regulations and practices. Focus was concentrated on determining whether small systems had different sampling requirements and determining the current regulations for microbial water quality parameters. For clarity, monitoring frequency defines how often samples are collected for each category of water quality parameter.

	Yukon	**Northwest Territories**	**Newfoundland and Labrador**	**Northern Quebec**	**Nunavut**
Governing Body or Document	Department of the Environment	*Public Health Act* and *Water Supply System Regulations*	Department of Health and Community Services	*Regulations Respecting the Quality of Drinking Water*	Nunavut Water Board
Microbiological Water Quality Parameters	*E. coli* Total coliforms Turbidity	*E. coli* Total coliforms Turbidity	*E. coli* Total coliforms	*E. coli* Total coliforms Turbidity	*E. coli* Total coliforms
Treatment Requirements	Disinfection	Not specified	Under development	Filtration and Disinfection unless approved otherwise	Disinfection for source waters with wells and reservoirs
Specific Considerations by Community Size	YES	Not specified	Not specified	YES	YES
Source Water Types	Mainly Ground water sources	Not specified	60% Source Water 40% Groundwater	Not specified	Not specified
Monitoring Frequency	Physical and Chemical – Yearly for all GCDWQ Microbiological – dependent upon system size	Dependent upon source water type and treatment technology	Microbiological – Monthly	Dependent upon community size	Physical – Daily Chemical – Every 2 Years Microbiological – Monthly
Primary References	Commissioner of Yukon, 2007	Government of the Northwest Territories, 2014	Newfoundland and Labrador: Health and Community Services, 2014	Regulation respecting the quality of drinking water, CQLR c Q-2, r 40	Nunavut Water Board, 2016

3.5 Application of WSPs in Arctic Jurisdictions

Applying a water safety plan to Nunavut and other Arctic jurisdictions would require provisions that specifically address problems unique to these communities. As an example, the communities in Nunavut currently use a trucked water distribution system with disinfection as the primary method of treatment, a system dissimilar to southern communities. Unique water quality parameters would need to be explored and documented to understand greatest risks and hazards present. In addition, the ability of each community to implement and sustain a water safety plan would be critical to the functionality of a WSP approach long-term. Without the capacity to continually improve the water safety plan by re-assessing hazards and implementing new monitoring plans and control measures, the sustainability of the WSP in these communities is not assured.

3.5.1 Water Safety Plans

Water safety planning is an approach promoted by the World Health Organization (WHO) that aims to develop a preventative framework that protects and manages water supplies from source to consumption (WHO, 2012, Bartram et.al., 2009, WHO, 2016). Water safety plans (WSPs) are designed to be adaptable and flexible; they are designed with community structure and socioeconomic variables considered as critical inputs. An effective WSP structure enhances the capabilities of the water supply and identifies areas of improvement that are feasible for a community by using tools that determine the cost effectiveness of the improvements needed in a community (World Health Organization, 2012). A WSP is meant to be a “living document”; it evolves and improves as the plan is used by the community (World Health Organization, 2012).

The WHO has developed a document that defines six steps that can be used to develop a WSP for small communities. Small communities are often defined by small populations and rates of flow but the true determining factors that make systems “small” are the ways in which water is managed and treated and the challenges that are unique to the systems utilized by the community (World Health Organization, 2012). The WHO defines a water supply system as the source water, treatment and distribution components of water management in a small system. The division of the water system into these components allows development of the WSP to be community specific in the way that current drinking water regulations do not (World Health Organization, 2012).

First, a community must “buy in” to the WSP: if a community does not have engaged members and stakeholders, the WSP will not be effective because the community is not informed and active in the WSP implementation process (World Health Organization, 2012). The second step involves understanding and categorizing the water supply in the community so that the source water is clearly defined. This will assist community members in identifying sources of possible pollution and contamination of the water source (World Health Organization, 2012).

Next, hazards, hazardous events, risks and existing control measures for these events must be evaluated; then a community can begin the development and implementation of an improvement plan for the water supply system (World Health Organization, 2012). The improvement plan is incremental and identifies the improvements that are the most critical and/or the improvements that are available given the capital reserves of the community (World Health Organization, 2012). After these improvements have begun, it is important that the changes are monitored to determine whether improvements are effectively alleviating the risks identified. If improvements are not effective, then the WSP needs revisions. Continual evolution of the WSP is critical to the effectiveness of the plan since it ensures that the system is being continually evaluated for error and new sources of contamination (World Health Organization, 2012). Finally, documentation of the improvements, monitoring outcomes and the WSP plan structure are important to ensuring continuity within the community so that an understanding of the WSP and the hazards faced by the community are transferred to community members as management staff and stakeholders transfer leadership (World Health Organization, 2012).

The key principles governing WSPs include the following: community understanding and commitment to a WSP, a focus on preventative risk management, a framework that is flexible and adaptable with incremental improvements and a regular review of the WSP to gauge effectiveness (World Health Organization, 2012). In addition, there is a need for a focus on disease-causing organisms and an approach with multiple barriers to prevent pathogens and microbiological agents from contaminating drinking water and impacting public health (World Health Organization, 2012). Customer input is ~~also~~ important and records of customer complaints can be an effective method to involve the consumer in the WSP. Understanding sudden changes in the environmental conditions are also important to a WSP since they can introduce new hazards into the water supply (World Health Organization, 2012).

Currently, 93 countries in the world have experience with WSPs, either at the national level or as specific community case studies (WHO & IWA, 2017). Since the introduction of WSPs as a possible water regulation structure, the following countries have adopted this approach or at a national level to varying degrees: the UK, Iceland, New Zealand, and Australia (Baum et. al., 2015), with the province of Alberta in Canada being the only province to implement a WSP. At the national level, countries with risk based approached have demonstrated an improvement in microbial water quality; there have been fewer outbreaks of waterborne disease reported (Baum et. al., 2015). Case studies have been conducted in countries such as Uganda, Senegal, Nepal, Bangaldesh, the Pacific Isalnds, and Sri Lanka and frameworks have been developed specifically for the communities included in the case study. Many countries, such as the United States, have implemented sanitary surveys as a part of new regulations. To date, there is little information available comparing a WSP approach to the traditional regulatory approach of sampling and comparing parameters to water quality standards.

The adoption of a WSP approach in Nunavut would facilitate assessment of water supplies from source to distribution and allow for identification of hazards and risks on a case-by-case basis, or community level. While several jurisdictions currently employ WSPs, both Iceland and Alberta regulate their use and are useful to discuss as part of this review to provide both a Northern and Canadian context for water safety plan applications.

3.5.2 Applying the Iceland WSP Framework to Nunavut

The WSP approach has been applied with success in Iceland since 1997. Gunnarsdottir et. al., (2012b) investigated the effectiveness of WSPs in Iceland in terms of regulatory compliance, microbial water quality and public health factors. The study found a statistically significant improvement in microbial water quality including fewer instances of non-compliance and fewer heterotrophic plate counts exceeding 10 colony forming units per mL of sample (Gunnarsdottir et. al., 2012a). From a public health perspective, implementation of WSPs have reportedly resulted in a significant decrease in incidence of diarrhea and a reduction in the likelihood of developing a clinical case of diarrhea (Gunnarsdottir et. al., 2012b). One of the main goals of a WSP is to improve public health in water supply systems (WHO, 2012, Bartram et.al., 2009) and the Icelandic approach shows promise for water safety plans as an alternative to regulating a large suite of physical, chemical and microbiological parameters.

The current sanitary checklist (for communities ≤500 people) addresses five sections: water catchment area, well-zone, reservoirs, pump stations and main pipe, distribution system and connection and fire hydrants (Gunnarsdottir, personal communication, Feb 2016). The identified hazards within each of these headings were analyzed to determine which hazards could be applicable in Nunavut. Since wells are used in Iceland but Nunavut has mainly surface water sources, when comparing hazards between the two jurisdictions, general source water risks were considered for both the water catchment area and well zone sections since these hazards could be applicable in both the case of surface or ground water. The small systems checklist was available to the authors at the time of the study and was considered the best model for ascertaining applicability of the Iceland approach to Nunavut.

Of the hazards presented in the WSP for small systems in Iceland, the most relevant sections include source water risks and reservoir risks (presented in Table 3.3). While communities in Nunavut do not usually use wells, the source water hazards presented in the Iceland WSP remain valid despite a different in source between the two regions. Iceland relies mainly on groundwater sources for drinking water supply; Nunavut contains many surface water sources, especially where permafrost inhibits groundwater extraction. The Iceland WSP contained provisions for maintenance plans, risks of vandalism, contamination of reservoirs, ablation and motor oil contamination from snowmobiles. Many of these hazards are applicable for Nunavut due to its arctic location, a benefit of the Icelandic model. However, the WSP for small systems would not be an ideal model for Nunavut regarding distribution and fire hydrant sections. While the Icelandic WSP approach is adaptable to system sizes (Gunnarsdottir et. al., 2012b), 100% of the distribution system is piped in Iceland. Critical control points would be needed for water hauling trucks and for surface water hazards in order for a similar WSP model to be applied in Nunavut.

Table 3.3: Applicability of the Iceland small system drinking water safety plan to hamlets in Nunavut by section of the WSP template. Source water hazards from the Iceland model were the most applicable to the hamlets of Nunavut.

Section of WSP	Number of Applicable Hazards	Total Possible Hazards	Percentage of Applicable Hazards
Water catchment area	8	12	67%
Well zone	7	9	78%
Reservoirs, pump stations and main pipe	4	7	45%
Distribution system and connections	3	7	33%
Fire hydrants	0	5	0%

3.5.3 Applying the Alberta WSP Framework to Nunavut

The Alberta Environmental Protection and Enhancement Regulation (Alta Reg 118/1993, Part 2) stipulates that waterworks must have a water safety plan and that the WSP must use a template (provided as an Excel document) by the province. After reviewing the identified hazards in the Alberta framework for applicability in the Nunavut context, about 50% of the risks from the Alberta Framework would be logical hazards to also assess in Nunavut, given the treatment systems described in the

Operation and Maintenance Manuals for each community (where available from the Nunavut Water Board). While the current Alberta WSP contains hazards that are possible at a variety of different water treatment facilities, from conventional treatment to membrane filtration, the plan does not differentiate based on size of a water supply system. Previous research conducted on the effectiveness of the new Alberta WSP template in small communities showed that community readiness is also a factor in water safety plan implementation (Kot et. al., 2017). Communities must have the capacity to implement a WSP and the resources and support necessary to complete the plan to obtain the greatest benefits for their water supply systems (Kot et. al., 2017).

The Alberta WSP framework contains four sections: Source, Treatment, Network and Customer. Within each of these sections there are associated hazards which can be assessed at each drinking water treatment facility for risk level. The percentage of each WSP section applicable to Nunavut can be seen in Table 3.4.

Table 3.4: Applicability of the Alberta Drinking Water Safety Plan to hamlets in Nunavut by section of the WSP template. Source water hazards in Alberta showed the highest applicability to Nunavut while the Treatment and Network sections are considered incomplete if applied to hamlets in Nunavut.

Risk Section	Applicable Questions	Total Questions	Percentage Applicable
Source	27	38	71%
Treatment	31	84	37%
Network	20	48	42%
Customer	10	20	50%

Of the sections, Treatment is the least relevant, which is logical considering the treatment processes that are most commonly used in Nunavut. Alberta's framework contains questions regarding flocculation, coagulation, sedimentation and advanced forms of disinfection that are not common in Nunavut (Nunavut Water Board, personal communication, 2016) and furthermore would not be feasible options for treatment (due to chemical supply, operator knowledge, plant footprint and size, etc.). In addition, the Treatment Risks address issues with pump stations and storage of water before and during pre-treatment. The Treatment section would be most useful for the chlorination systems used in Nunavut as well as the filtration systems available in some communities.

The majority of the Source Risks Questions from the Alberta Framework that are applicable deal with reservoir storage. Most of the relevant questions deal with microbiological contamination of the source water as a result of improper procedures of control and security; these include contamination as a result of wildlife activity and cross contamination due to the location of a sewage treatment lagoon, situations applicable in Nunavut (Krkosek et. al., 2012). Network hazards available in the Alberta Framework mostly deal with piped systems which are not available in the North; however, the framework does address the issue of reservoir circulation. Customer hazards that could be used in Nunavut apply specifically to bulk water delivery and hygienic storage of water within households, which has been previously described as a sanitary issue (Daley et al., 2014).

3.6 A Nunavut WSP Model

3.6.1 Trucked Water Considerations

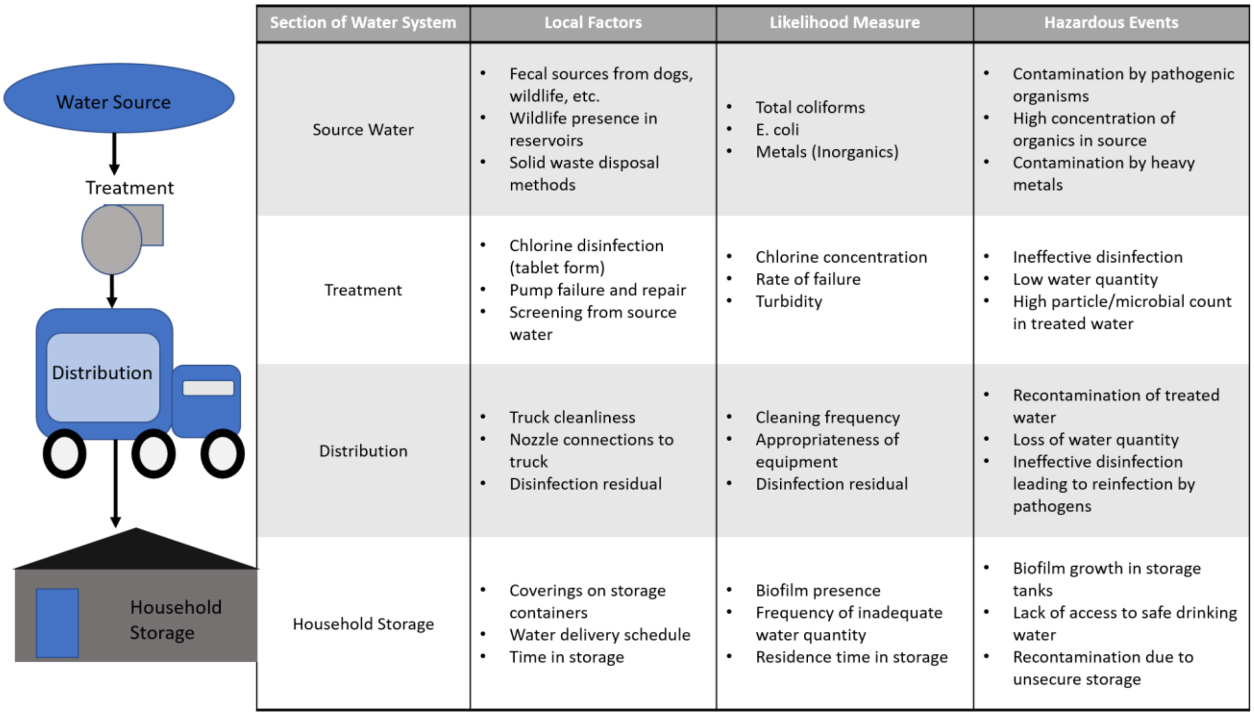
For most communities in Nunavut, water is pumped from a holding reservoir to a water hauling truck and chlorinated in the truck, then delivered to home storage tanks ~~at~~ in each household within a community. There are concerns with this specific method of water delivery as southern jurisdictions have few barriers developed for the potential hazards that could occur in these types of systems. Some of these identified hazards include chlorination method and contact time, biofilm growth and accumulation in home storage tanks, and effectiveness of treatment methods as adequate barriers to protect public health. The WHO publishes a set of guidelines specifically for this type of distribution system which may be useful in the hazard identification process (WHO, 2012).

Of note during the review of northern Canadian water management systems was the Manitoba Bulk Water Hauling Guidelines. In Manitoba, bulk water haulers must have permits to sell and convey drinking water under the Public Water Act (Manitoba Health, 2013). Bulk water is considered water that is potable and intended for human use that is delivered to households or businesses in an approved vehicle that meets the standards of the Bulk Water Hauling Guidelines (Manitoba Health, 2013). Drinking water tanks used by bulk water haulers are approved exclusively for water hauling and may not be used for any other purpose. In addition, any hoses, nozzles and equipment used in conjunction with the water hauler must be of food grade materials to prevent water contamination (Manitoba Health, 2013). Under the Drinking Water Safety Act, water may only be hauled from approved sources. Many of the provisions listed in these guidelines would be key control points to include in Nunavut drinking water management strategies in the future.

3.6.2 Development of a Framework Specific to Communities in Nunavut

Community specificity is a key component of the WSP approach (WHO, 2012); while models used in other jurisdictions may be assessed for applicability in the planning stage of WSP implementation, ultimately a set of hazards and a monitoring method would need to be developed for Nunavut. A possible WSP framework for communities in Nunavut is presented in Figure 3.2. Four sections of the water supply system have been chosen: Source Water, Treatment, Distribution System and Household Storage. The local factors detail possible hazards that would exist in communities that would need to be included in a Nunavut WSP. The likelihood measure describes how a water utility operator would be able to determine the probability that this hazard is present in their particular community. The hazardous events that would result from these factors describe the risk a WSP would hope to mitigate using monitoring and preventative practices applicable to the specific situation present in each community.

As an example, in Figure 3.2, risks at the household level must address the security of household storage tanks, from animal incursion or possible recontamination by environmental pollutants or organic matter. In addition, there are concerns that biofilm growth in storage tanks could be a contributing factor to gastrointestinal illness (Daley et. al., 2014). The WSP would assess the likelihood of this hazardous event by either measuring biofilm growth, *E. coli* presence/absence testing, or water retention time or even by visual inspection of the storage unit. This process can be applied to all the proposed local factors in the Nunavut WSP framework to begin the implementation of a WSP approach in water systems in Nunavut.



Section of Water System	Local Factors	Likelihood Measure	Hazardous Events
Source Water	• Fecal sources from dogs, wildlife, etc. • Wildlife presence in reservoirs • Solid waste disposal methods	• Total coliforms • E. coli • Metals (Inorganics)	• Contamination by pathogenic organisms • High concentration of organics in source • Contamination by heavy metals
Treatment	• Chlorine disinfection (tablet form) • Pump failure and repair • Screening from source water	• Chlorine concentration • Rate of failure • Turbidity	• Ineffective disinfection • Low water quantity • High particle/microbial count in treated water
Distribution	• Truck cleanliness • Nozzle connections to truck • Disinfection residual	• Cleaning frequency • Appropriateness of equipment • Disinfection residual	• Recontamination of treated water • Loss of water quantity • Ineffective disinfection leading to reinfection by pathogens
Household Storage	• Coverings on storage containers • Water delivery schedule • Time in storage	• Biofilm presence • Frequency of inadequate water quantity • Residence time in storage	• Biofilm growth in storage tanks • Lack of access to safe drinking water • Recontamination due to unsecure storage

Figure 3.2: Elements of a water safety plan framework for the unique characteristics present in hamlets in Nunavut. Local factors that would impact source water quality and treatment are presented in relation to likelihood measure (parameters that could be used to determine probability of failure) and hazardous events (identified risks that could potentially occur in a water supply system).

The proposed WSP structure for Nunavut would need development mainly for the distribution, and household storage sections. Hazard identification for source water and treatment modules has been conducted previously in several WSP models (Iceland, Alberta, New Zealand, Australia, etc.) and has a clear starting point. However, community engagement with local operators and stakeholders would be critical to understanding community perceptions of safe water practices so that the hazards described for the communities in Nunavut would reflect local conditions. For example, in the distribution module, disinfection residual is identified as a local factor and likelihood measure; however, community understanding of the need for a disinfection residual may cause homeowners to alter their water quality or obtain another source that is considered "cleaner" aesthetically. Community education will therefore also be an important component of implementing a WSP. The WHO manual for developing a WSP in small systems has iterated this fact; if a community does not comprehend the purpose of the WSP monitoring measures and identified hazards, the WSP is more likely to fail over time (WHO, 2012).

The elements identified in Figure 3.2 form the information basis of the WSP; a structure applicable and easily usable in the remote communities in Nunavut is necessary. Hazard identification documentation is vital to the WSP process but is not sufficient to ensure the sustainability of the approach. Presentation of the hazard information needs to engage the community in a manner that correctly assesses hazard likelihood and consequence: multiple stakeholders must be involved to avoid human error and information bias, the WSP tool must accurately define levels of risk and the structure requires flexibility to add and delete hazards as the water supply system improves over time.

The model presented for Nunavut is an initial understanding of hazard identification for communities; it is not considered all-inclusive and would need further development with the aide of local territorial authorities. Monitoring in the WSP structure is the other critical component of any WSP approach applied in communities. Reviewing Arctic jurisdiction sampling practices demonstrated that disinfection residual, *E. coli*, turbidity and total coliforms measured in most locales; however, other parameters may be better suited due to remoteness, operator knowledge and practicality. Biofilm presence in household storage tanks would be a new addition to the monitoring parameters the government of Nunavut already requires and should be considered, especially if a WSP approach were to be adopted. Without monitoring of the likelihood measures proposed in the Nunavut WSP framework, indication accuracy of hazardous events is diminished.

3.7 Conclusions

Review of Northern jurisdictions and water management policies in Arctic countries have demonstrated that community size, remoteness (access to resources) and understanding a trucked water distribution system are all critical factors in the development of a water management strategy for Nunavut. The current regulatory environment predicated on regulation of set water quality parameters, may not be the most effective available method for the small water systems in Nunavut because of methods of treatment and distribution. A water safety plan approach may be more suitable to Nunavut due to the unique challenges these water systems face and would give water systems more ownership over their water supplies and a better method to protect public health through hazard identification and monitoring. While the Iceland and Alberta drinking water safety plans provide a starting point for hazard identification in the WSP framework development process, ultimately, hazards specific to the conditions in Nunavut require further consideration, especially with regard to distribution system methods and household storage practices. The possible framework presented here represents beginning steps that may be taken to further the discussion of the applicability of a water safety plan approach in Nunavut.

4 Chapter Four – Development of an operator-informed water safety plan tool

4.1 Abstract

Water safety plans (WSPs) represent a risk management strategy for the drinking water industry that focus on hazard identification and risk assessment as opposed to traditional endpoint sampling practices. However, while there are multiple resources available to construct a water safety plan and case studies of water safety plan success, this method has not been applied in Nova Scotia. Furthermore, upon review of water safety plan examples from global jurisdictions, there is a lack of uniform design and implementation of water safety plans, as WSPs are specific to individual water systems. Subsequently, this study aimed to design and test a new variation of water safety planning methods in small water systems in Nova Scotia to determine if the revisions and improvements included in this new method addressed identified concerns with the WSP method. Case studies from global jurisdictions were compared to identify variations in hazard identification. The WSP developed for this study uses an integrated fault tree structure with a series of operator-informed questions to classify the risk level for a set of identified hazardous events. Testing the WSP in three small Nova Scotian water supply systems demonstrated that the risk matrix method used in the WSP manuals needs revision to ensure consistency in risk level assignment. Continuing studies of WSP implementation in Nova Scotia are required to determine what degree adoption of this approach should be recommended.

4.2 Introduction

Since 2004, global jurisdictions have developed and implemented water safety plans, a type of water management tool endorsed and supported by the World Health Organization (WHO)(WHO, 2012). Water safety plans (WSPs) were developed for the drinking water industry based on the hazard and critical control point frameworks that had been effectively demonstrated in the food industry as a proactive tool to mitigate hazards before hazardous situations occurred (WHO, 2012, Gunnarsdottir et. al. 2012). A water safety plan emphasizes hazard identification and the use of semi-quantitative risk scoring to pinpoint potential high-risk situations in a water supply system (consisting of source water protection, treatment process operational procedures and monitoring of the distribution system). This method focuses on proactive management of a water supply system; the current widely accepted method of regulating water quality parameters and comparing to a regulatory standard is considered reactionary as it does not the identify the cause of the issue (Bartram et.al., 2009).

According to a joint 2017 report from the WHO and International Water Association (IWA), WSPs have been adopted by 93 different jurisdictions, either as a regulatory tool at a national or provincial level, or as a case study in a specific community (WHO & IWA, 2017). The report indicates that most jurisdictions have begun implementation but longevity and sustainability of the WSP method is still largely unknown as there are few jurisdictions with active monitoring plans and auditing procedures (WHO & IWA, 2017). In the report, Canada was identified as a country with more than ten WSPs currently developed; however, only the province of Alberta requires drinking water safety plans (WHO &IWA, 2017, AERSD, 2014, Reid et.al., 2014). Atlantic Canadian provinces (New Brunswick, Newfoundland and Labrador, Nova Scotia and Prince Edward Island) currently have very little experience with WSPs. This study will focus on WSP implementation and development in Nova Scotia, drawing from global experiences, as a new method for managing water supply systems.

The focus for the development of a WSP in Nova Scotian water supply systems centers on the needs of small and rural systems. In Canadian regulations, small communities are most often categorized as having less than 5000 people serviced by the water supply system (Health Canada, 2014), but according to the WHO WSP Manual for small systems, small communities are better characterized by the unique challenges the community faces to provide safe drinking water to customers (WHO, 2012). Subsequently, this research categorizes small communities not only by the number of customers served but by characteristics typically seen in small systems: geographic remoteness, lack of capacity financially and in resources, and inability to respond to hazardous situations adequately (Kot et.al., 2011, Boag et.al., 2010, Butterfield and Camper, 2004). The WSP developed in this study focuses on providing a management tool that recognizes and addresses issues faced specifically by small water supply systems.

In addition to the 2017 Global Status on Water Safety Plans Report, the WHO has also published several manuals and guidelines detailing the development process for a WSP, many of which can be found on the WSP Portal (wsportal.org) (WHO, 2012). Among the resources available are several templates for WSP development for a new jurisdiction and examples from case study communities. However, review of several templates from case studies and nationally required WSPs reveals that although a water safety plan should be a "living document", there are few WSPs that allow for feedback and instantaneous interactions between the plan and the stakeholders completing the plan. The majority of templates are paper-based, focused on filling out a table of hazardous events. In addition, a water professional is required to learn how to perform hazard identification and how to use a risk matrix to evaluate risks within water systems, often requiring external professional expertise to complete the risk assessment. Paper-based methods place a time constraint on a water professional or treatment plant operator by requiring extensive additional paperwork requirements. Furthermore, if hazard identification has been completed, a template of all possible hazardous events present in water system would still fail to account for the specific conditions present within a community. As a result, a WSP from another jurisdiction will not be directly applicable to Nova Scotia water systems. An approach specific to Nova Scotian systems needed to be developed, adapting previous WSP templates.

Subsequently a different approach was taken to develop a WSP for Atlantic Canada. Instead of requiring a stakeholder from a water supply system to learn how to design a new WSP, an operator-informed WSP in the form of a web-application was developed to reduce the need for a stakeholder to learn how to choose proper risk matrices and metrics. This tool utilizes knowledge and expertise from water treatment plant operators or water quality monitors to answer directed questions about a water supply system. The tool generates results containing information about system improvements from operator knowledge. Previously research identified the concern a WSP can turn into a top-down approach if not properly designed (Perrier et.al., 2014), failing to account for individual system characteristics. The WSP tool in this study is rooted in the principles of water safety planning: hazard identification coupled with assignation of a risk level. Focus is placed on stakeholder collaboration, starting with operator knowledge and expertise instead of external or top-down WSP design.

The objective of this study was to develop an operator-informed water safety plan for use in Atlantic Canadian water supply systems using guidance from WHO manuals and case study documentation. The WSP developed in this chapter was reviewed by three small systems in Nova Scotia to refine and further develop the approach. The WSP method here is implemented in Chapter 5 and Chapter 6 of this thesis with both municipal small systems and First Nation water systems. Stakeholder experience was used to determine accuracy of the hazard identification process, to comment on the accuracy of the results generated from the operator-informed assessments and to provide general feedback on the WSP process overall. WSPs have been proposed as an additional method of water management to augment current regulatory practices for small communities in the Atlantic Canadian provinces and this study demonstrates a new process for developing WSPs that takes into account the needs of these systems

4.3 Background

4.3.1 WSPs in the Global Context

Water safety plans have been applied globally in 93 different countries (WHO &IWA, 2017), and the benefits and challenges associated with this risk assessment method are well documented. Benefits of water safety plans are numerous and include decreases in disease outbreaks, better overall understanding of water system hazards, improved communication and collaboration, better monitoring and record keeping, and better operational procedures. Challenges include the sustainability of the WSP approach, the need for external and internal auditing procedures, the need for strong management programs and procedures and the need for supporting programs that aid in the development and continuing effectiveness of WSPs.

Two studies from Iceland highlighted a decrease in the outbreaks of waterborne disease as a result of better microbial water quality after water safety plan implementation (Gunnarsdottir et.al., 2012, Gunnarsdottir et.al., 2015). These studies examined how water procedures have changed as a result of Iceland being an early adopter of WSPs (Iceland being the first in 1997). It was found there was an overall increase in the microbial water quality (Gunnarsdottir et.al., 2015). This case study in particular highlights the direct health benefits that have been observed as a result of introducing water safety plans to water supply systems.

While there are studies that have been performed by the World Health Organization, the International Water Association (IWA) and the United Nations' Childrens's Fund (UNICEF), an external auditing procedure to validate the implementation of a WSP still does not exist (WHO & IWA, 2017). Studies such as Kumpel et.al., 2018, have looked at specific regions of the world to determine the extent of WSP implementation and the challenges still faced by water supply systems. However, there is still currently no cohesive method for external auditing. There is also very little evidence in the literature that WSPs are audited internally to determine if a WSP is accurately identifying and addressing risk in a system (WHO & IWA, 2017). This auditing deficient speaks to concerns about WSP sustainability; while WSPs have been implemented in 93 countries (WHO & IWA, 2017), the sustainability of a WSP is measured by how well it functions over time and what improvements in water systems are observed.

Furthermore, supporting programs and strong management procedures are needed to improve WSPs and encourage increased adoption. Ferrero et.al., 2019 emphasized the importance of strong training programs for water safety plan stakeholders involved in implementation, citing the need for robust methods to monitor WSP implementation capacity development in water systems (Ferrero et.al., 2019). Kumpel et.al., 2018, demonstrated the need for strong financial programs to support water safety plan implementation in the Asia-Pacific region, speaking to the need for external audits and support that allows sustainable WSP adoption (Kumpel et.al., 2018). Strong management programs are needed to ensure that WSPs are properly used, not only during early implementation, but decades after implementation (WHO & IWA, 2017). As WSP implementation increases and becomes the accepted "best-practice" for managing water systems, the ability to ensure the longevity of this approach is an important consideration for water system stakeholders.

Buy-in from water supply systems is important to WSP adoption and implementation. Research from Summerill et.al. in 2010 reinforced the importance and key challenges of ensuring "buy-in" to WSPs. Every water system has a set of cultural norms that influence how water supply system stakeholders react to changes in management practices. Summerill et.al., 2010a highlighted how mindsets play a critical role in the successful implementation of WSPs, indicating that entrenched ideas about water quality monitoring regulations and practices generated conditions adverse to successful WSP adoption (Summerill et.al., 2010a, Summerill et. al., 2010b). There are cultural features that aid and inhibit WSP implementation. Features that enable WSP adoption include involved leaders, community focus, transparency and accountability (Summerill et.al., 2010a, Summerill et.al., 2010b). Features that impede WSP implementation include poor communication, inflexibility, lack of awareness and complacency (Summerill et.al., 2010a, Summerill et.al., 2010b). With these features in mind, WSP implementation must acknowledge and understand how stakeholder attitudes influence the success or failure of WSP adoption.

Finally, WSP adoption success depends on adequate programs supporting implementation in small water systems; systems that are defined by a lack of capacity that impedes a systems' ability to provide safe water to customers (WHO, 2012). While there is a manual dedicated to WSP implementation in small systems (WHO, 2012), studies of small system implementation have shown that there are still significant barriers to sustainable WSPs. Small systems experience concerns not seen in larger communities: remote geographic location, lack of access to resources, high personnel turnover, decentralized systems and lack of support for water operations (WHO, 2012, Kot et.al., 2011, Kot et.al., 2015). These small systems concerns are explored further in subsequent sections. However, case studies have shown that understanding the individual needs of each water system is imperative to successful adoption of the WSP approach. Community specificity is key, as small system needs are different (Greaves, 2011, Hansan et.al., 2011, Omar et.al., 2017, Strong and Lantagne, 2016, Summerill and Parker, 2013, Thompson and Majam, 2009, Perrier et.al., 2014, Kot et.al., 2015). This thesis focuses on WSPs in small systems taking into consideration the challenges associations with small and rural water supply systems.

4.3.2 A Review of Risk Matrix Methodologies Across Jurisdictions

While the WHO recommends using a risk matrix to assess risk in a water safety plan, not all case studies use the same risk matrix to evaluate risk. A review of the different templates available on the WSP Portal revealed that several different scoring scales for likelihood and consequence are available, as are several different risk matrices that result from scoring scales. In addition, the descriptions of each likelihood or consequence level and score present in a water safety is unique to each jurisdiction, making it difficult to compare risk matrices across case studies. Table 4.1 showcases the different descriptions of likelihood encountered in the review process and Table 4.2 summarizes the descriptions of consequence.

Table 4.1: Using descriptions of likelihood from eight different jurisdictions and case studies, it is clear that there are several different and conflicting definitions of likelihood in water safety plans. Scoring regimes are different across these studies and even though each case study has five different descriptions of likelihood, these descriptions vary considerably. No scores were available from the TECHNEAU report on 2009 but likelihood descriptions have been included (Hokstad et.al., 2009)

Jurisdiction	Likelihood Definition	Likelihood Score	Likelihood Description
WHO Manual	Almost Certain	5	Once a day
	Likely	4	Once a week
	Moderate	3	Once a month
	Unlikely	2	Once a year
	Rare	1	Once every 5 years
Iceland	Very high	5	More than once a week
	High	4	Once a week – once a year
	Average	3	Once a year - once every ten years
	Little	2	Once every ten years to once every hundred years
	Very little	1	Less than one every hundred years

Jurisdiction	Likelihood Definition	Likelihood Score	Likelihood Description
Ireland	Almost certain	5	Has occurred in the past, is an ongoing problem, and is very likely to happen in the future
	Likely	4	Has occurred in the past more than once, and is likely to happen again
	Foreseeable	3	Has happened in the past, is possible and under certain circumstances could happen again
	Unlikely	2	Has happened in the past, is possible and cannot be ruled out completely
	Most unlikely	1	Hast not happened in the past and is highly improbably that it will happen in the future
TECHNEAU (Hokstad et.al., 2009)	Almost certain		Once per day
	Likely		Once per week
	Moderately likely		Once per month
	Unlikely		Once per year
	Rare		Once every 5 years
Alberta	Not applicable	0	Not applicable
	Most unlikely	1	Very small chance in the next 4-5 years
	Unlikely	2	Possible, cannot be ruled out in the next 4-5 years
	Medium	4	Equally likely as not to happen in the next 4-5 years
	Probable	8	Expected to happen in the next 4-5 years
	Almost Certain	16	Will happen at least once in the next 4-5 years
Pacific Island Case Study	Rare	1	May occur only in exceptional cases (1 in a 1000 years)
	Unlikely	2	Could occur (once in 100 years)

Review of likelihood descriptions show that while most scales describe likelihood in terms of occurrence in a specific time frame (once per year, once per month, etc.), there are other descriptions of likelihood that focus more on how likely an event is in terms of qualitative measures. This causes ambiguity in how likelihood is evaluated. For example, an unlikely event in South Africa occurs once per year, which can be translated to a probability of occurrence if water quality sampling is known. However, if Alberta's scale is used, unlikely corresponds to an event that is possible in the next 4-5 years, a value harder to quantify as a probability. This shows a lack of consistency in likelihood descriptions contributing to the lack of comparability across jurisdictions. A lack of auditing and quality control for water safety plans has been noted by the WHO in a 2017 report (WHO & IWA, 2017). This review of likelihood descriptions show that without a consistent method for defining likelihood, it is difficult to compare WSPs globally.

In the Ireland WSP example, “unlikely” is described as “has happened in the past, is possible and cannot be ruled out completely”. This description of the likelihood of future hazardous events in the water system is based on events from the past. Bartram et.al., 2009 describes WSPs as proactive, not reactive, risk assessment tools, but Table 4.1 shows no descriptions that are predictive of future events. Likelihood is based on previous events with the exception of some descriptions presented in the Ireland WSP. While understanding previous trends is important to modeling and predicting future events, the descriptions above are steering water system stakeholders towards a system assessment report format instead of an improvement plan for the future. Considering the emphasis the WHO has placed on climate resilient WSPs and equitable WSPs to reflect changing global dynamics, (WHO, 2017, WHO, 2019) descriptions of likelihood in WSPs need revision to be more predictive and avoid turning a WSP into another report of past events.

Review of consequence descriptions shows the same comparability concern with greater scope. Table 4.2 reveals no consistent method for defining the consequence of a hazardous event across global jurisdictions. Definitions are based on health-based outcomes, financial outcomes, water quantity outcomes, water quality outcomes and customer impacts. Consequence is multifaceted and dependent on jurisdiction. None of these scales of impact is “incorrect”; these impacts are all concerns in a water system, and ideally all be included in a risk assessment. This demonstrates the need to broaden how consequence is quantified in a WSP. Including multiple definitions of consequence in an initial WSP with a small community is not feasible given the amount of time that would be required of an operator; however, once a WSP framework has been implemented, adding in different descriptions of consequence will allow a WSP to address the needs of all stakeholders in a water system. Given the desire to decrease equity gaps in WSPs (WHO, 2019), different descriptions of consequence that apply to different stakeholders provide an interesting way to understand different impacts in a water supply system.

Table 4.2: Descriptions of consequence definitions vary across jurisdictions.

Jurisdiction	Consequence Definition	Consequence Score	Consequence Description
WHO Manual	Catastrophic	5	Catastrophic public health impact
	Major	4	Major regulatory impact
	Moderate	3	Moderate aesthetic impact
	Minor	2	Minor compliance impact
	Insignificant	1	Insignificant or no impact
Iceland	Very high	5	Very high
	High	4	High
	Average	3	Average
	Little	2	Little
	Very little	1	Very little
Ireland	Catastrophic	5	Presence of microorganisms, parasites or substances that are an imminent danger to public health. Treatment compromised or regulatory failure. Disruption to consumers in the supply
	Major	4	Potential long-term health effects. Treatment compromised. Regulatory failure. Disruption to consumers in the supply.
	Moderate	3	Long term non-compliance, widespread aesthetic issues or not health related. Treatment compromised. Regulatory failure but no health risk
	Minor	2	Short term or localized, aesthetic or not health related. Treatment compromised. No regulatory failure.
	Insignificant	1	Wholesome water, no public health impact
TECHNEAU (Hokstad et.al., 2009)	Catastrophic	16	Mortality expected from consuming water
	Major	8	Morbidity expected from consuming water
	Moderate	4	Major aesthetic impact possibly resulting in use of alternate but unsafe water source
	Minor	2	Minor aesthetic impact possibly resulting in use of alternative but unsafe water source
	Insignificant	1	No detectable impact

Jurisdiction	Consequence Definition	Consequence Score	Consequence Description
Alberta	Not applicable	0	Not applicable to this water system
	Insignificant	1	Water meets appropriate standards or system interruption lasted less than 8 hours
	Minor	2	Short term or localized non-compliance (not health-related) or system interruption lasted 8-12 hours
	Moderate	4	Widespread or long term non-compliance (not health-related) or system interruption lasted 12-24 hours
	Severe	8	Potential illness or system interruption 24-48 hours
	Catastrophic	16	Actual illness, potential long term health effects or system interruption more than 48 hours
Pacific Island Case Study	Insignificant	1	Insignificant
	Minor	2	Minor impact for small population
	Moderate	3	Minor impact for large population
	Major	4	Major impact for small population
	Catastrophic	5	Major impact for large population
Microrisk Project	Catastrophic	5	Mortality expected from consuming water
	Major	4	Morbidity expected from consuming water
	Moderate	3	Major aesthetic impact possibly resulting in use of alternate but unsafe water source
	Minor	2	Minor aesthetic impact possibly resulting in use of alternative but unsafe water source
	Insignificant	1	No detectable impact
South Africa Case Study	Insignificant	1	No impact
	Minor	2	Small aesthetic impact
	Moderate	20	Large aesthetic impact
	Major	70	Population exposed to significant illness
	Catastrophic	100	Death expected from exposure

The scoring scales used for both likelihood and consequence definitions vary across jurisdictions. The most common scale is one through five, although there are risk scores calculated by multiplying likelihood and consequence and there is one jurisdiction that adds likelihood and consequence. The result is that even when the same scale is used, the numeric risk score that corresponds to “low” risk is different across jurisdictions. For example, from the WHO Manual, the risk score can range from 1 to 25, in Iceland can range from 1 to 10 and in Alberta can range from 0 to 256. While the lowest risk score will match across jurisdictions (automatically assigned to low risk), the scores in between may range across low, moderate, high and sometimes very high risk.

To further this investigation, a review of global risk matrices used in the water safety planning process was completed. This review demonstrated there are several different risk matrices available, most having small differences in structure that translate into large differences in the risk-level. For example, both the WHO WSP Manual and the Pacific Island Case Study use a 1-5 risk scoring scale. However, in the WHO Manual there are 10 entries in the risk matrix corresponding to low risk (scored as 1-6) (WHO, 2011) and in the Pacific Islands case study there are only 5 entries in the risk matrix scored as low risk (scored as 1-3) (AusAid and SOPCA, 2010). Additionally, the WHO Manual risk matrix shows 4 entries for very high risk and the Pacific Island case study shows eight. By assigning cut-off scores for low-risk and very high-risk shows it is possible to over- or underestimate risk in a water supply system when using difference risk matrices. If the WHO Manual regime was to be applied in the Pacific Islands case study, many of the risks that were considered very high would now be categorized by a lower risk level, potentially underestimating the true risk associated with a hazard. Similarly, if the Pacific Islands case study risk matrix were to be applied to a system using the WHO Manual risk matrix, risk-levels assigned to hazardous events may be an overestimation of actual risk.

While unique risk score scales alone are not problematic and are considered acceptable by the community-specificity principle, comparability across jurisdictions is a challenge. The number of risk levels in each jurisdiction are not the same, with some jurisdictions having three risk levels (low, medium and high, or a comparable set of levels) and some having four levels. This comparability problem presents a concern for external audits of WSPs, an aspect identified as lacking in the 2017 global report (WHO & IWA, 2017). Community specific hazard identification is important to the success of a WSP, but as Table 4.3 demonstrates, not all risk matrices are created equal. Standardizing the risk matrix approach would be beneficial to WSP development in new communities and jurisdictions.

Table 4.3: A comparison of the risk matrices used for water safety planning across global jurisdictions.

				# of entries in risk matrix			
Jurisdiction	Risk Score Scale	Risk Score Calculation	# of risk levels possible	Low	Moderate	High	Very High
Ireland	1-5	Multiplicative	4	10	7	4	4
Iceland	1-5	Additive	3	10	9	6	NA
Alberta, Canada	0-16 (2^n)	Multiplicative	3	7	9	10	NA
New Zealand		Multiplicative	4				
WHO WSP Manual	1-5	Multiplicative	4	10	5	6	4
Pacific Island Case Study	1-5	Multiplicative	4	5	4	8	8
South Africa Case Study	0.1 – 1 (Likelihood) 1-100 (Consequence)	Multiplicative	3	15	7	3	NA
Nepal Training Materials	1-3	Multiplicative	3	3	3	3	NA
Bhutan Rural Template	0-100 %	Scheme functionality calculation	4	0-25%	26-50%	51-75%	76-100%

4.4 Methods

4.4.1 Review of Hazard Identification Documentation

To develop an operator-informed system assessment for small Nova Scotian systems, a review of jurisdictions currently using WSPs was conducted. Several jurisdictions were considered based on the availability of documents detailing the WSP process and relevance to Atlantic Canada (similar source water types, preferred treatment processes, regulatory policies, etc.). The primary WSP reviewed was the Alberta Drinking Water Safety Plan, maintained by the Department of the Environment (AERSD, 2014); Nova Scotia is held to the same federal water quality guidelines but has small variances in provincially requirements. In Canada, federal guidelines are non-enforceable; provinces have the jurisdiction to enforce water quality regulations (Kot et. al., 2014, de Loe, 2017). Other jurisdictions reviewed included: Iceland, Australia, New Zealand, Ireland, case studies from the Pacific Islands and South Africa, and the WHO Small Systems manual. Case studies were also reviewed for comparison when questions were raised about specific environmental conditions and regulatory concerns that are unique to Nova Scotia. Focus was placed on New Zealand's hazard identification process; extensive detailed documentation is available and WSPs have been a requirement since 2004.

The purpose of reviewing the current WSPs used globally is twofold: (1) review of jurisdictional WSPs and policies highlights which methods work best in specific situations also applicable to Nova Scotia and (2) allows for a compilation of multiple hazard identification methods, risk matrices, and documents that can be used to construct a water safety plan. In Nova Scotia there are varied source water types: surface water, ground water and ground water under the influence of surface water. In Iceland, the majority of the systems use groundwater sources (Gunnarsdottir et.al, 2012); this provides good hazard identification documentation for groundwater wells but may overlook many surface water concerns (Samorka, 2016). To address specific conditions in Atlantic Canada, a review of jurisdictions was necessary to develop a WSP specific to these systems. Lists of possible hazardous events are often compiled in reference tables and provide baseline information for the hazard identification process during WSP development. Documentation from both Alberta and New Zealand was reviewed to determine how many hazardous events were applicable to Atlantic Canada. This list of hazardous events was then used to develop the WSP for testing in Nova Scotia water systems.

4.4.2 Developing a WSP System Assessment

How a water operator interacts with a WSP on a daily or weekly basis is an important consideration when developing a WSP to ensure the WSP does not become a yearly activity shelved until annual reports are due (WHO, 2011, Bartram et.al., 2009). As a result, the WSP developed in this research project takes the form of a web application where results are generated for a user based on questionnaire answers which prompts short-term and long-term follow-up actions also completed in the web application. The system assessments are designed as surveys and are divided into three major headings: source water, treatment operations by process and the distribution system. These headings are further divided to compile surveys specific to a community. For example, under treatment operations, there are individual surveys for chlorine disinfection, clarification, filtration, etc. This format allows a community to build a WSP containing modules specific to their water supply system instead of reviewing a template of all possible hazardous events for all these processes. Hazard identification for each of these processes is critical to formulating survey questions that pinpoint the risk level of hazardous events in the water supply system.

To evaluate the risk level associated with hazardous events, the survey format is designed using a fault tree to relate all possible applicable hazardous events for each process. A fault tree is a visual representation of how hazardous event contribute to an overall risk score for each process. This allows a user of the WSP to not only identify the semi-quantitative risk of a hazardous event using a risk matrix, but also understand relationships between hazards and calculate an overall risk score. For example, during chlorine disinfection, one hazard is the absence of standard operating procedures. The corresponding hazardous events would be lack of maintenance plans and chemical safety plans. The methodology used to construct a fault tree from hazardous events is presented in Figure 4.1 using chlorine disinfection as an example.

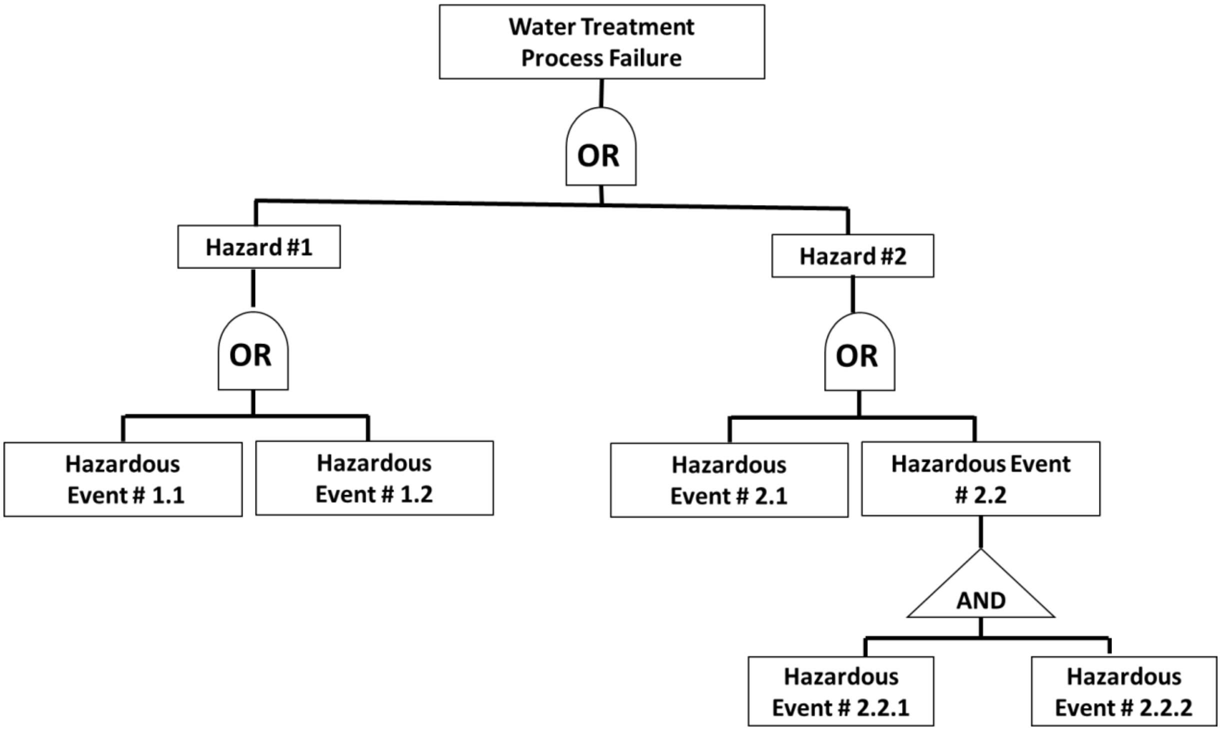


Figure 4.1: The methodology used to construct survey questions for the WSP involves identifying hazards and hazardous events that may impact a subsystem in the water supply system and translating these to a fault tree. The fault tree describes how hazards and hazardous events are related to each other within the subsystem. This figure provides a generalized representation of how hazards and hazardous events (as

defined by the WHO Manual, Bartram et.al., 2009) relate to cause the failure of a water treatment process. A specific example of a fault tree is present in Appendix A for chlorine disinfection.

Figure 4.1 is provided as a generalized representation of how hazardous events and hazards in a WSP can be related to one another to give structure and purpose to the questions being asked in each assessment survey. A fault tree was chosen because it allows a user to relate probabilities of occurrence for a series of hazardous events to determine overall risk for a system. As a result, as the WSP process evolves in a community, quantitative data from a supervisory control and data acquisition (SCADA) system or hand written records could be added to the WSP to improve risk calculations, using the fault tree developed for the semi-quantitative results. This approach is more rigorous than averaging risk scores to obtain an overall score and is rooted in risk assessment practices that have been previously reviewed for water systems (Hokstad et.al., 2009). For each questionnaire developed for this thesis, an individual fault tree was developed. A full fault tree for the chlorine disinfection questionnaire is presented in Appendix A to demonstrate how fault trees may be constructed for different treatment options in each individual water system.

4.4.3 Review of WSPs with Three Water Systems

Once a survey had been constructed using the hazardous events identified and the fault tree method, survey questions were reviewed with three small water supply systems in Nova Scotia. The purpose of the review was to evaluate wording and clarity of questions and to ensure that each question was pinpointing the correct corresponding hazardous event. The Alberta and New Zealand water safety plans were also reviewed for comparison during site visits. The water supply systems chosen were municipal systems with several common processes: a surface water source, membrane filtration, chlorine disinfection and a distribution system with at least two water quality sampling locations. Comments and recommendations from these systems were then used to revise the surveys to improve accuracy and to cover hazardous events that were not adequately addressed. Two operators at minimum were involved from each facility and managers were also asked to provide insights to the WSP development if he available for the site visits. Two visits were conducted to two of the facilities and one to the final facility due to time constraints.

Conversations with operators and utility managers also provided feedback about the utility of the WSP process as a whole. After survey revisions were completed, reports of risk levels associated with the hazardous events from each survey were generated for review. Reports contained detailed descriptions of the hazardous events, the assigned risk level (either high, moderate or low risk), a description of the current situation in the water system and suggested activities. Operators from the water systems were asked to provide feedback on the accuracy of the results generated, to suggest additional information needed in reports and other possible reporting mechanisms for communicating risk to stakeholders in the water system.

Finally, the Alberta and New Zealand WSPs were compared to the operator-informed WSP. A list of twenty-two hazardous events for chlorination was generated using documentation from both Alberta and New Zealand (AERSD, 2011) and from other relevant WHO documentation (Bartram et.al., 2009, WHO, 2012). Similar hazardous events across both Alberta and New Zealand were aligned with the hazardous events used in the operator-informed WSP to compare similar hazardous events. The same risk scoring scale is used in all three methods to eliminate risk matrix construction as a confounding variable when comparing the results. Water system stakeholders were asked to provide information for each of the three methods. The results were then compared to determine which method provides the most information to a water system.

4.5 Results

4.5.1 Review of Hazard Identification Documentation

A review of the hazardous events used in the Alberta drinking water safety plan showed that the Alberta WSP tool provided a logical starting point for development of a water safety plan in Atlantic Canada. In all four hazard sections in the Alberta WSP, 90% or more of the hazards were considered applicable in Atlantic Canada. All thirty-eight source water hazards were considered applicable to Atlantic Canada. The network and customer hazard sections were considered the least applicable at 90% each. Table 4.4 shows that the Alberta template provides a wealth of knowledge in the hazard identification step of water safety planning in Atlantic Canada. Additional hazards need to be added that are specific to Atlantic Canada, but the Alberta approach provided a strong place to start the hazard identification process.

Table 4.4: Based on review of the Alberta drinking water safety plan, the percentage of applicable hazards to Atlantic Canadian systems is presented. Ninety percent of more of the hazards from each hazard section are considered applicable in Atlantic Canada.

Hazard Section	Applicable Hazards	Total Hazards	Percentage of Applicable Hazards
Source	38	38	100%
Treatment	79	84	94%
Network	43	48	90%
Customer	18	20	90%

Review of the New Zealand water safety plan documentation showed that fewer hazards are considered applicable to Atlantic Canada. Only 36% of the source water hazards are considered applicable. In addition, there is no section of the New Zealand water safety plan dedicated to “customer” as seen in the Alberta WSP; this hazard section was instead replaced with “operations”. Overall, the New Zealand model identifies more hazardous events for source, treatment, and distribution than the Alberta model, contributing to the lower percentage of applicable hazards seen in the New Zealand review. Since the New Zealand WSP introduces the “operations” category, these applicable hazards should be included in a water safety plan for Atlantic Canada as the Alberta WSP does cover this category.

Table 4.5: A review of New Zealand water safety plan shows that less than 75% of the hazardous events are applicable to Atlantic Canada for each hazard section.

Hazard Section	Applicable Hazards	Total Hazards	Percentage of Applicable Hazards
Source	24	66	36%
Treatment	112	161	70%
Distribution	51	69	74%
Operations	14	19	74%

4.5.2 Developing a WSP System Assessment

Using the identified hazards from the Alberta and New Zealand, fault trees were developed for individual modules (source, treatment, distribution, etc.) in Nova Scotia water systems. The New Zealand approach of dividing treatment processes into individual components (such as sedimentation, chlorination, filtration, etc.) to identify hazards was utilized so that individual surveys could be developed for each module. This limited the size of each fault tree and the length of each survey constructed in the WSP, to avoid “survey fatigue” with the stakeholders involved in the review process. Focus was placed on ensuring that operational concerns were addressed in the surveys.

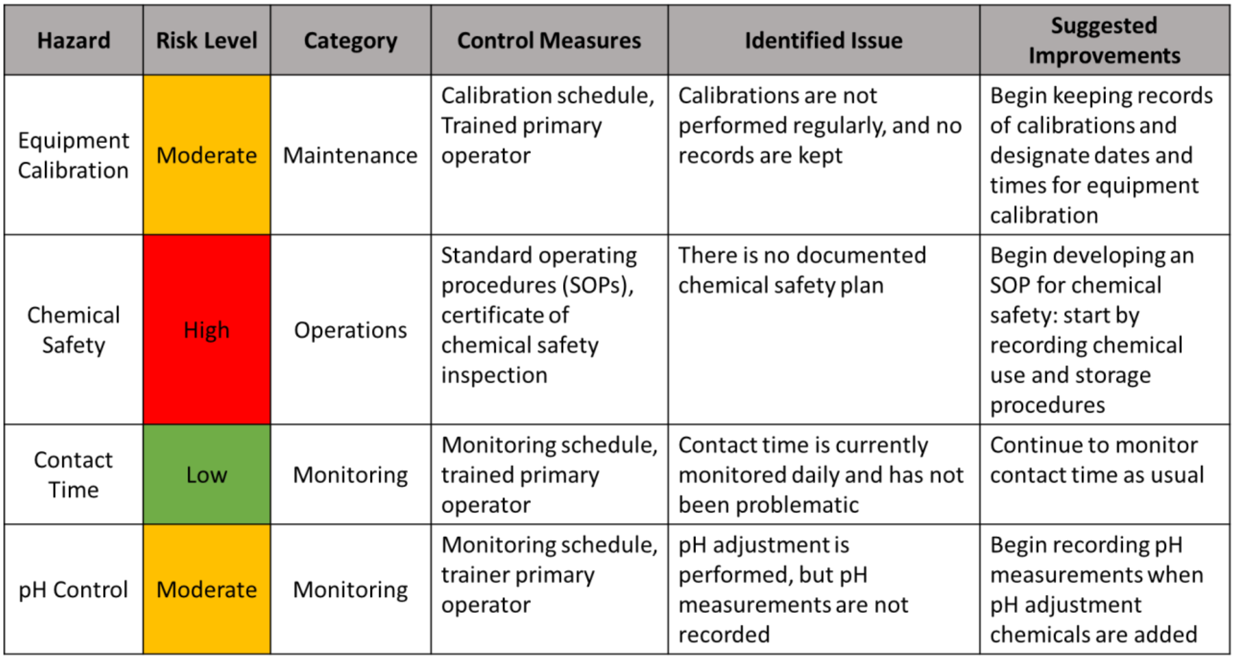
Questions in each survey were designed to gain information about each hazardous event in the fault tree in a module. The answers to each question were either yes/no answers, or frequency answers such as “frequently”, “occasionally”, “rarely” and “never”. Question answers did not present a risk score to stakeholders; instead, the score was internalized to the web application. This was done to limit bias in stakeholder responses; for example, a stakeholder assumed a hazard as low risk (a score of 1) but the answer selected corresponded to moderate risk (a score of 8). If the score was available to a stakeholder during the survey, the stakeholder may have chosen an answer with the “correct” risk level but the answer was not indicative of the actual situation in the water system. The survey was designed such that the risk scores and levels are not presented until after the survey was completed to attempt to limit bias in risk assessment.

4.5.3 Review of the WSP in Three Water Systems

During facility visits, the presence of multiple operators and a facility manager to answer questions was beneficial to the accuracy of the answers provided. Often, a question would provoke discussion as stakeholders involved in the meeting provided different perspectives of the same identified issue. For example, a question has the possible answer choices: “frequently”, “occasionally”, and “rarely”, defined in the survey in terms of a number of occurrences of an event in a given time frame. Often, the primary operator would have an immediate answer to a question, but a secondary operator or manager would identify a situation where the initial answer was not an accurate representation of the issue being identified.

In addition, when reviewing surveys, wording of the questions was critical to the accuracy of the risk results. A researcher was available to explain question intent to ensure questions were answered such that risk results were reflective of the targeted hazards. However, if the WSP tool was completed without an external aide, wording of the questions is critical to ensure that results are representative of the actual situation in the water supply system. For example, in a theoretical System A, the hazard related to chlorine disinfection contact time was easy to answer accurately. However, in a theoretical System B, there was confusion about contact time in terms of location: contact time can reference a clearwell or water storage tank or a mixing tank located inside the treatment facility.   Contact time generally refers to the amount of time chlorine is allowed to interact with water in a storage tank; however, given the variability in configuration of the chlorine disinfection system, contact time may be achieved by different methods based on system design.

An example of the risk results produced by this method is presented in Figure 4.2. Risk results include the hazard, the risk level assigned to the hazard, the category of the hazard, the potential control measures in place to control the hazard, the identified issue based on the operator-informed questions and suggested improvements based on identified issues. The risk results generated, particularly the identified issues and suggested improvements, are unique to each water system, thereby fulfilling the system-specific criteria of a water safety plan (WHO, 2012, Bartram et.al., 2009). Overall, the results generated from the operator-informed water safety plan provided the expected risk levels for the perceived risk in each system; that is, the risk level generated by the WSP matched the actual situation in the water system as understood by the treatment operator.



Hazard	Risk Level	Category	Control Measures	Identified Issue	Suggested Improvements
Equipment Calibration	Moderate	Maintenance	Calibration schedule, Trained primary operator	Calibrations are not performed regularly, and no records are kept	Begin keeping records of calibrations and designate dates and times for equipment calibration
Chemical Safety	High	Operations	Standard operating procedures (SOPs), certificate of chemical safety inspection	There is no documented chemical safety plan	Begin developing an SOP for chemical safety: start by recording chemical use and storage procedures
Contact Time	Low	Monitoring	Monitoring schedule, trained primary operator	Contact time is currently monitored daily and has not been problematic	Continue to monitor contact time as usual
pH Control	Moderate	Monitoring	Monitoring schedule, trainer primary operator	pH adjustment is performed, but pH measurements are not recorded	Begin recording pH measurements when pH adjustment chemicals are added

Figure 4.2: Example results from the operator-informed water safety plan web application. These results were presented to stakeholders at each water system to determine the validity of the results generated from

the operator-informed method and to understand how results could be better presented in future iterations of the application.

It is important to note that several of the suggested improvements in Figure 4.2 require increased capital spending and effort on the part of treatment facility staff to mitigate risks. While the benefits of WSPs have been documented previously in this thesis, Figure 4.2 indicates there is also a cost associated with implementing the prioritized changes advised by a WSP. Drachenburg, (2014) demonstrated in the case of the Alberta WSP implementation process, that adoption, at first, lagged due to the high costs of identified improvements and the increased time an operator was expected to spend completing the WSP. Loret et.al., (2016) performed a precursory investigation of the costs and benefits of the WSP and confirmed the importance of ensuring the suggested activities presented by a WSP are feasible for a water system. The methodology presented in this chapter does attempt to limit time spent identifying risk up front but has not yet addressed the associated costs with implementing the strategies recommended by the web application tool. Future work is needed to address this concern with WSPs in general.

The operator-informed WSP was then compared to the WSPs from Alberta and New Zealand. Table 4.6 shows a compiled list of twenty-two hazardous events, generated from review of both the Alberta and New Zealand WSP as well as relevant documentation from the WHO (WHO, 2012, Bartram et.al., 2009, AESRD, 2011). These twenty-two hazardous events are all included in the operator-informed WSP. Every potential hazardous event from Alberta and New Zealand is represented to ensure no bias interpreting the results. Table 4.6 is grouped by category of hazardous events (either maintenance, monitoring or operations) for clarity. Only results from System A are included in Table 4.6.

Table 4.6: Using a set of 22 hazardous events for chlorination processes, the Alberta and New Zealand WSPs do not account for several maintenance and operational concerns in a WSP that the operator informed WSP does. In addition, neither the Alberta nor New Zealand method account for the moderate-risk identified by the operator-informed WSP, showcasing the ability of the operator informed WSP to identify operational concerns previously unidentified.

Hazardous Event	Category	WSP Method – Chlorination Process		
		Alberta	New Zealand	Operator-informed
Equipment Calibration	Maintenance	Unknown	Low	Low
Equipment Failure	Maintenance	Unknown	Unknown	Low
Equipment Replacement	Maintenance	Unknown	Unknown	Moderate
Maintenance Plans	Maintenance	Unknown	Unknown	Low
Disinfection Failure Procedures	Operations	Low	Unknown	Low
Backup Systems (Subsequent Treatment Barriers)	Operations	Unknown	Unknown	Moderate
Chemical Safety	Operations	Unknown	Unknown	Low
Dosing Controls	Operations	Unknown	Low	Low
Chlorine Supply	Operations	Unknown	Low	Low
Incorrect Dosing	Operations	Unknown	Low	Low
Chemical Supplier	Operations	Unknown	Unknown	Low
Compliance with Regulations	Monitoring	Unknown	Unknown	Low
DBPs	Monitoring	Low	Unknown	Low
Feedwater Conditions	Monitoring	Low	Low	Low
Monitoring for High Chlorine	Monitoring	Low	Low	Low
High Chlorine at Booster Stations	Monitoring	Unknown	Low	Low
Monitoring for Low Chlorine	Monitoring	Low	Low	Low
Chlorine Concentration	Monitoring	Unknown	Low	Low
Chlorine Demand	Monitoring	Low	Low	Low
Contact Time	Monitoring	Low	Low	Low
pH Control	Monitoring	Low	Low	Low
Low Chlorine at Booster Stations	Monitoring	Unknown	Low	Low

Table 4.6 indicates that the operator-informed WSP provides the most data about maintenance and operational hazardous events in a water system. The Alberta and New Zealand water safety plans provide a wealth of information about monitoring hazards, with information only missing from four monitoring hazardous events from Alberta and two from New Zealand. However, the Alberta WSP does not account for any maintenance concerns in the chlorination process and only contained one hazardous event in the operations category. Similarly, the New Zealand WSP only identified one maintenance hazardous event and three operational hazardous events. Table 4.6 showcases the importance of including all categories of hazardous events in a WSP; the focus of a WSP is to prevent issues from occurring, yet Table 4.6 indicates that the majority of hazardous events from two previously constructed WSPs focus on predominantly on monitoring hazards.

In addition, the operator informed WSP identifies two moderate-level risk hazardous events not included in the Alberta and New Zealand WSPs. The two hazardous events are equipment replacement and backup treatment technologies, neither of which are monitoring concerns. The operator-informed WSP identifies these two hazardous events as priority concerns with a moderate risk level. The operator-informed WSP is therefore able to generate important information about operational and maintenance concerns that is not generated in previous template-based WSPs.

4.6 Discussion

4.6.1 Operator-informed WSPs better characterize operational risk

The operator-informed WSP structure developed in this study provided more information about operational and maintenance challenges in a water system than current WSP templates (see Appendix A for an example fault tree and Appendix B for an example questionnaire). Table 4.6 provided evidence previously generated WSP templates from both Alberta and New Zealand provide hazard identification primarily for monitoring hazardous events. According to the WHO, WSPs attempt to move water systems away from endpoint monitoring, placing focus on preventative actions instead of reactive measures (Bartram et.al., 2009, WHO, 2012, WHO, 2016). However, this study provided evidence that while monitoring hazardous events are being accurately identified in some jurisdictions, this is at the expense of larger operational concerns. Larger water systems, generally have the capacity to monitor several water quality parameters (such as chlorine residual, contact time, pH, etc.) that smaller or rural water systems do not (Kot et.al., 2011, Butterfield and Camper, 2004, Boag et.al, 2010). As a result, many of the identified monitoring hazardous events are skewed towards low risk levels since the infrastructure is available to ensure real-time monitoring. The presence of several low risk hazards based on advanced data collection technologies generates an underestimation of the potential risks in a water system, one that still focuses on monitoring as the sole preventative risk measure.

The increased focus on operations and maintenance concerns in WSPs is essential given previous research on drinking water advisory issuance in Canada. According to a 2018 report published by Environment and Climate Change Canada, 83% of all boil water advisories issued are due to equipment and process-related problems. Furthermore, only 4% of boil water advisories are due to the presence of *E. coli* (Environment and Climate Change Canada, 2018). This indicates a need for greater focus placed on mitigating operational concerns within a water system. Mitigation of these concerns starts with identification and prioritization, tasks that a WSP is uniquely designed for (Bartram et.al., 2009, WHO, 2012). Of the three WSPs presented in this study, only the operator-informed methodology has the capacity to pinpoint these concerns; the Alberta and New Zealand WSPs miss two important moderate risk hazardous events and focus predominantly on monitoring concerns.

WSP case studies in developing countries have reported infrastructure and operational improvements as a result of WSP implementation (WHO, 2018, Kumpel et.al., 2018, AusAID, 2016), however, in more advanced water systems there is a body of literature suggesting buy-in to WSPs is an important implementation factor (Summerill et.al., 2010a, Summerill et.al., 2010b, Amjad et.al, 2016, Baum and Bartram, 2017, Baum et.al., 2015). Intensive data collection procedures and advancements in data logging have compounded this factor (Summerill et.al., 2010a, Summerill, et. al., 2010b) This suggests that small, underdeveloped water systems are more likely to focus on operational concerns in WSP development, whereas larger, developed water systems are more likely to focus on monitoring concerns that can be addressed with current data collection practices.

This study therefore highlights potential bias in WSP design historically. The Alberta water safety plan template has largely remained the same since full implementation in 2014, as has the documentation provided by New Zealand (AESRD, 2011, New Zealand Ministry of Health, 2014). A WSP is intended to be a “living document” (Bartram et.al., 2009) needing revision and auditing to ensure that identified hazards are appropriate. However, this study reveals a lack of attentiveness to operational and maintenance concerns in WSP templates, issues that could have been identified by external audits of WSPs (WHO & IWA, 2017, Bartram et.al., 2009, WHO, 2018). The operator-informed WSP provides a solution to this concern; this WSP better captures operational concerns and design as a web-application allows for easy addition of new, relevant risk information. Development of this WSP reveals concerns with previous WSP templates well established in WSP literature, highlighting the need for stronger auditing of WSPs, both internally and externally as recommended by the WHO (WHO & IWA, 2017).

4.6.2 Operator-informed WSPs integrate water quality data

The operator-informed WSP design presented in this chapter (a fault tree to express hazardous event relationships, a questionnaire based on these hazardous events and a web application to deliver the questionnaire and results to water system stakeholders) also allows for the future integration of water quality data to better inform risk in a WSP. The generalized fault tree presented in Figure 4.1 was chosen as a method for constructing this WSP not only for its visual ability to show relationships between hazardous events (Rosen et.al., 2008a, Rosen et.al., 2008b, Risebro et.al., 2007, Hokstad et.al.,

2008) but also for the ability to calculate overall probability of failure. During WSP site visits, there was an expressed desire to integrate current water quality monitoring data into the WSP to eliminate redundancy and streamline hazard identification. The fault tree allows for this integration, utilizing water quality data to calculate probabilities of occurrence. Previous use of fault trees in water studies have focused on source water risks and theoretical models for the entire water systems (Rosen et.al., 2008a, Risebro, et.al., 2007). This study proposes the use of a fault tree both for better understanding of hazard relationships overall, but also to aid future, informed calculations of probability from water system data.

Expanding on the integration of data to better understand risk, this study also delved into how risk is scored in WSPs, building off the review of risk matrices presented in Table 4.3. Table 4.6 highlights the importance of proper hazard identification foremost, and the choice of risk scoring methods second. The risk matrix method is used for its simplicity and adaptability, particularly in small water systems (Bartram et.al., 2009, WHO, 2012). However, the risk matrix method has been critiqued for poor resolution and suboptimal resource allocation, which results in the same risk level assigned to qualitatively different risks (Cox Jr., 2008, McBean, 2019c). For example, a hazardous event may be highly likely but has minimal impact on a water system and is assigned a moderate risk level with a risk matrix. Another hazardous event may be unlikely, but the impact of the event is catastrophic and is assigned moderate level risk. There events are qualitatively different, but a poor designed risk matrix approach assigns the same risk level; this results in improper prioritization of mitigation procedure (McBean, 2019c).

However, the operator-informed WSP is designed such that hazards are assigned likelihood and consequence scores within the web application algorithms. This eliminates the need for the ambiguous inputs and outputs traditional seen in the risk matrix method (Cox Jr., 2008) giving water system stakeholders the ability to define hazardous events in the context of system specific measures. For example, chlorination contact time is used to determine appropriate disinfection. Instead of asking an operator how likely failure (low contact time) is and how impactful failure is (which can be expressed in monetary terms, health impact, failure to meet regulations, etc.), the WSP presented in this study asks questions related to how operators monitors and measure contact time and operate the chlorine disinfection unit overall:

(1) Do you measure contact time?
(2) How often do you measure contact time?

(3) How often is contact time too low to provide adequate disinfection?
(4) Is there an alarm in place if contact time falls below a predetermined threshold?
(5) Are all operators trained to properly calculate ideal contact time?

The answers to these questions determine frequency of occurrence of a hazard (likelihood), instead of scoring each question as an individual hazardous event or aggregating multiple questions into one hazardous event related to contact time. Consequence is assessed using follow up questions to determine how these events have impacted the system in the past and may affect the system in the future. The focus shifted from scoring events, to a focus on content and improved hazard identification.

4.6.3 Operator-informed WSPs prioritize operator knowledge and stakeholder communication

The main benefit of the operator-informed WSP is its ability to capture information about a water system from an operator's point of view, not from solely a regulatory perspective. A WSP is designed to include several stakeholders, both internal and external to the water system, often with a steering committee to provide guidance to community members throughout the process (Bartram et.al., 2009, WHO, 2012, WHO, 2016, WHO,2019). However, there is evidence in literature that WSPs can become top-down regulated approaches if care is not taken to preserve a collaborative approach (Perrier et.al., 2014, Amjad et.al., 2016, Ferrero et.al., 2019). Top-down regulated approaches often fail to consider the individual system characteristics present in water system design and operation. The design of the operator-informed WSP places focus on internal knowledge of a system first, augmented by information from regulatory agencies second. This design supports an "operations first" approach, as it is not solely designed to meet regulatory monitoring guidelines and design criteria although regulatory concerns are addressed within the WSP.

This WSP tool relied heavily on operator knowledge and expertise to provide an accurate picture of a water system. One of the concerns with this new method is avoiding "survey fatigue". Survey fatigue results when a participant in a study or information gathering process, fails to complete a full survey as a consequence of becoming fatigued by the large amount of data to be submitted (Wright, 2005). This method avoids survey fatigue by modularizing the WSP into water system processes (source monitoring, sedimentation, chlorine disinfection, etc.). A review of the Alberta WSP found operators considered the size of the template daunting (Drachenberg, 2014). Other studies of WSPs have demonstrated the need for progressive implementation over time as the volume of work needed to complete a full WSP is rigorous (Kot et.al., 2017, Perrier et.al., 2014, Ferrero et.al., 2019, Gunnarsdottir et.al., 2012, Loret et.al., 2016). There is often difficulty defining all hazards, which can inhibit the WSP process (Tsoukalas and

Tsitsifli, 2018, Loret et.al., 2016, Hasan et.al., 2011). While this method does not provide complete hazard identification for all situations, it does provide a modularized format to promote stepwise implementation of WSPs.

Communication of risk between stakeholders via a WSP requires further exploration. This study observed a clear need to provide accurate communication of risk amongst water system stakeholders. One of the key identified benefits of a WSP is its ability to open communication pathways between the many stakeholders in a water system (Byleveld et.al., 2008, Gunnarsdottir et.al., 2012, Hasan et.al., 2011, Loret et.al., 2016, WHO & IWA, 2017, Tsoukalas and Tsitsifli, 2018). However, communicating information about risk to stakeholders with different areas of expertise is difficult (Kolodzieg et.al., 2017, Kunreuther et.al., 2001, Covello and Johnson, 1987). How risk is communicated amongst stakeholders has not been explored in depth with respect to WSPs. Furthermore, outputs from a WSP are basic templates and documentation (Bartram et.al., 2009, WHO, 2012) which do not analyze how hazards interact and account for water system complexity. Continuing research that evaluates better methods for visualizing, communicating and understanding the risk outputs from a WSP is presented in Chapter Eight of this thesis.

4.7 Conclusions

Development of a WSP specifically for Atlantic Canadian water systems required review of current WSPs utilized in Alberta and New Zealand, the design of a survey-based system assessment technique and the review and validation of this method in three systems in Nova Scotia. Review of hazards identified by the Alberta and New Zealand WSPs provided a starting point for the hazardous event identification process, with the Alberta WSP being more directly applicable to the Atlantic Canadian context. Using identified hazards from both Alberta and New Zealand, a fault tree method was used to develop survey-based system assessments for an operator-informed WSP. Review of the operator-informed WSP in three water systems validated the utility of the method and also provided insight into the additions needed in future iterations. Using twenty-two identified hazards for chlorine disinfection, the operator-informed WSP was best able to identify operational and maintenance concerns in water systems. The operator-informed WSP method better characterizes operational risk, integrates water quality data and prioritizes operator knowledge and stakeholder communication. The objective of this study was met: an operator-informed WSP was constructed and validated for use in Atlantic Canadian water systems. This WSP is used in Chapter Five and Chapter Six of this thesis in both municipal and First Nation water systems to further understand factors influencing successful implementation of the operator-informed WSP.

5 Chapter Five - Practical guidance for the implementation and sustainability of water safety plans: evidence from municipal water systems

5.1 Abstract

Small water supply systems often face operational and capacity concerns not commonly experienced in larger water supply systems such as personnel turnover, limited financial capacity, lack of access to resources and geographic remoteness. New risk management systems are needed for these types of water supply systems as current methodologies are largely reactive, relying mainly on water quality testing to prove safety. This study examined the use of a water safety plan (WSP) method in nine small water supply systems in Atlantic Canada. The water safety plan was used to evaluate hazardous events in the water supply system through a series of questionnaires aimed at the primary operator of a water treatment facility. In addition, a review of the water safety plan methodology was conducted in each system to determine the barriers that exist to successful adoption and implementation in a municipal water system setting. Water safety plan implementation is hindered by a predominantly regulatory mindset in the majority of the municipal systems and a cultural shift in water systems is necessary for successful adoption. Additionally, this study demonstrated that risk score, instead of risk level is a better method for visualizing and communicating risk to stakeholders in a water system. Water safety planning methods would benefit from a closer examination of risk scoring methods, internal and external auditing procedures and guidance for WSP implementation where regulatory mindsets predominate in workplace cultures.

5.2 Introduction

This study utilized the principles of water safety planning to evaluate common hazardous events found within small municipal water supply systems. The water safety method for small systems consists of six tasks: (1) engagement stakeholders in the water supply system, (2) description of the water supply system, (3) identification of hazards and risks, (4) development of an improvement plan, (5) monitoring control measures and verifying WSP effectiveness and (6) documentation of the WSP process (WHO, 2012). This study focused primarily on tasks 1-3 to determine what is needed to ensure the WSP is successful from initiation. A WSP specific to Atlantic Canada was developed (Chapter Four) using these principles and hazardous events specific to this region. The WSP was used in this study to gather information about the following components of small water systems: (1) Information about source water risk using sanitary surveys, (2) Information about disinfection processes using a targeted chlorination survey, (3) information about the distribution system using a targeted distribution system survey, and (4) information about operator opinions of a WSP process through discussion of the risk results obtained by completing the WSP.

The objectives of this study are as follows:

1. Evaluate small system operator responses to the WSP process
2. Describe each small water system based on information gained from hazard identification
3. Use data visualizations to determine if risk score or risk level provides a better method for risk communication

Comparisons across systems help to refine the water safety plan designed in Chapter Four and focus was placed on uncovering common operational issues across water systems. The WSP method can require a cultural and mindset shift in the water industry (Summerill, et. al., 2010a, Summerill et. al., 2010b); this study attempted to show how common issues can be identified by a WSP and inform better water policy making. Conversations with water operators about the WSP process were conducted to understand how a water safety plan fits into the current water management landscape in Atlantic Canada. This study was designed to gain a better understanding of the practical limitations of implementing a WSP and to consult with water operations staff concerning the necessary changes needed for a successful adoption of WSPs in small, municipal, Atlantic Canadian water supply systems.

5.3 Background

Several studies of Canadian water systems (including municipal, registered or private) have demonstrated the disease burden associated with water systems and the key factors that impact the ability of a system to provide safe water to customers. Moffatt and Struck evaluated water-borne disease outbreaks associated with drinking water systems and found 15% of Canada is serviced by small drinking water systems and a relatively high portion of outbreaks occurred in these systems (Moffatt and Struck, 2011). A previous study, found that 288 outbreaks of disease were related to a drinking water source, and almost half were in semi-public systems (Schuster et. al., 2005). Furthermore, there is no consistent reporting format for reporting outbreaks, resulting in an underestimation of the disease burden, particularly in small systems (Schuster et. al., 2005). A 2017 study attempted to quantify the number of acute gastrointestinal illnesses that were associated with municipal drinking water sources and demonstrated that the annual burden is 20.5 million cases, with an estimated 334,966 cases per year associated with municipal tap water consumption from water systems serving more than 1000 people (Murphy et. al., 2017). Considering evidence that smaller water systems are more vulnerable to microbial contamination (Butterfield and Camper, 2004) and even a system with historically good water quality cannot be guaranteed to remain free of future contamination (Jalba, and Hrudey, 2006) there is a clear need to proactively manage small water systems.

The disease burden from water supply systems is only one element that contributes to concerns with small drinking water systems. Boag et. al., 2010 found many small systems are challenged by the cost of operating a treatment facility, the cost of taking samples required by regulations, accessibility to training and water operator retention (Boag et. al., 2010). Not all small systems, especially when remote, have the capacity or resources to meet water guidelines (Kot et. al., 2011, Boag et. al., 2010). Adequate operator training has been identified as a barrier in the multi-barrier approach (Moffatt and Struck, 2011), but evaluations of water system capacity have shown that operator turnover is high and training opportunities few (Kot et. al., 2011, Pons et. al., 2014).

The clear role of an operator as protector of public health, is often undermined by lack of capacity, and training programs are needed to bridge this gap (Pons et. al., 2014, Boag et. al., 2010, Kot et. al., 2011, Moffatt and Struck, 2011). Operators provide another barrier in the multi-barrier approach by analyzing data generated in a water system and making informed decisions and to ensure customers are receiving safe water. In addition, an operator is the first point of contact if an issue arises in a water treatment facility and is responsible for ensuring each component of treatment is functioning correctly. Lack of water system retention and inadequate training of operators is also compounded by remoteness of a community, lack of access to resources (both financially and operationally) and a regulatory system that can be prohibitive in small systems (Kot et. al., 2011, Pons et. al., 2014).

In addition, Pons et. al. found that approximately 50% of operators interviewed identified the cost of meeting regulations as prohibitive for small systems (Pons et. al., 2014). This is an indication of a larger problem that small systems face: water regulations and sampling requirements can impose a burden on small systems, particularly in a decentralized regulatory system such as in Canada. There are national non-enforceable guidelines for water in Canada (Kot et. al., 2011) which are used to create enforceable provincial guidelines and standards. While provincial standards cannot be less stringent than national guidelines, differences in provincial guidelines have evolved, making it difficult to compare water systems across provinces, leading to slower policy changes and adoption of different risk management methods at a federal level.

Current management policies account for the slow uptake of alternative risk management methods such as water safety plans. While a 2017 joint report by the WHO and International Water Association (IWA) identified Canada as a country with at least ten WSPs currently implemented, this is an inaccurate representation of WSP implementation in Canada as only the province of Alberta requires WSPS in water regulations for the province (AERSD, 2011). Water safety plans are not currently required in other provinces, although there have been recommendations to move to a more proactive water management strategy by government agencies (Health Canada, 2017). The WSP focuses on proactive management of key identified hazardous events in a water supply system from catchment to consumer (WHO, 2012, Bartram et. al., 2009). This differs significantly from current reactionary water guidelines in Canada.

The WHO has invested a significant amount of time developing and adapting the water safety plan methodology specifically for small systems. The manual for small systems details considerations for the challenges that are unique to these systems (WHO, 2012), including geographic remoteness, lack of financial capacity, high cost of sampling for water quality parameters, retention of trained staff, etc. (WHO, 2012). Water safety plans in small systems have been shown to increase personnel knowledge about risks in the water supply system, strengthen monitoring and maintenance programs, decrease costs associated with incidents, reduce water losses, reduce number of failures overall and provide better treated water quality (WHO, 2018). Several global case studies have validated these results (Byleveld et. al., 2008, Gunnarsdottir et. al., 2015, Gunnardottir, et. al., 2012, Greaves, 2011, Hubbards et. al., 2013, Kumpel et. al., 2018, Loret et. al., 2016, Rondi, et. al., 2016, Strong and Lantagne, 2016, Tibatemwa et. al., 2004, Viljoen, 2010, WHO, 2012). For example, long-term studies in Iceland have shown a decrease in the amount of waterborne illness outbreaks as a result of better microbial monitoring due to WSP implementation (Gunnarsdottir et. al., 2012, Gunnarsdottir et. al., 2015). In the Asia-Pacific region, WSP implementation has been associated with infrastructure improvements and increased financial support to the study sites (Kumpel et.al., 2018, WHO, 2018, Loret et.al., 2016). Considering the added benefits of WSPs to small water supply systems, this study seeks to evaluate applicability and feasibility of WSPs in Atlantic Canada.

The water safety plan method uses a risk matrix to evaluate the risk of each hazardous event based on likelihood and consequence factors. The recommended risk matrix from the WSP manual uses four different risk levels (low, moderate, high and very high), each defined by a risk score (Bartram et.al., 2009). Risk matrices were chosen for ease of use, especially in settings where little data is available

(Bartram et.al., 2009, WHO, 2012, WHO, 2016). However, critiques of a risk matrix show that risk matrices can have poor resolution, ambiguous inputs and outputs, and lead to errors in resource allocations (Cox Jr., 2008). As a result, the WSP used in this study was designed to be able to compare a risk level from a risk matrix to the risk score. This study is therefore designed to determine if greater granularity (risk score) is a better way of presenting WSP results to water system stakeholder than the traditional risk matrix approach (risk level).

5.4 Methods

5.4.1 Water System Visits

Visits were conducted to eight water systems in Nova Scotia to better understand WSPs implementation strategies in small water systems and to consult with stakeholders about the water safety planning process. The eight municipal systems are presented in Table 5.1. Visits typically lasted between one to three hours depending on staff availability and the duration of the conversations. Visits were scheduled not only with the primary operator of the water system, but also with secondary operators, environmental health officers, water quality samplers, managers and other water system personnel where applicable. The purpose of these visits was to introduce the WSP method, to complete a sanitary survey and two hazard identification modules. After completing the modules, the results and any feedback on the WSP process was discussed to better improve the WSP. A follow-up visit was conducted after the results from each component of the WSP were analyzed. The results of the WSP modules were presented to the water system stakeholders. Stakeholders were asked to share their thoughts on different potential data visualizations of the information and on the WSP process.

Table 5.1: Description of the eight municipal water systems included in this study

System	Source Type	Size of System
Municipal A	Surface Water	Small
Municipal B	Surface Water	Small
Municipal C	Ground Water	Small
Municipal D	Ground Water	Small
Municipal E	Surface Water	Small
Municipal F	Ground Water	Small
Municipal G	Surface Water	Large
Municipal H	Surface Water	Large

The water systems included in this study have several important characteristics to consider. Municipal systems A-F are managed by the same centralized water utility (located in a large city) and have substantial managerial oversight not typical in traditional rural or small systems. In addition, typical small systems literature (Kot et.al., 2001, WHO, 2012) indicate small water systems suffer from concerns such as high operator turnover and staffing constraints. In these eight water systems, operators had been working with the same municipality for five to fifteen years and are highly experienced and certified. This characteristic is important to recognize for any conclusions moving forward; these municipalities have capacity not typical of remote or rural systems.

Sanitary surveys are a simplified version of a WSP and contain a set of questions about the risk status of the source water (WHO, 2016). Sanitary surveys are designed as ten yes/no questions for either a surface or groundwater source and are focused on hazards that could present a health risk in a water system (WHO, 2016, WHO, 2012). Using guidance documents from the WHO, a set of questions was developed for small municipal systems in the Atlantic Canadian region. During the water system visits, a sanitary survey was completed at each facility to capture basic information about source water risk and to test the applicability of the sanitary surveys in these types of systems. Of the systems included in the study, three had groundwater sources and six had surface water systems (Table 5.1).

During the follow-up visit, a conversation about the feasibility of implementing a WSP was conducted. The purpose of these conversations was to determine (1) how a water system perceived the WSP and where WSPs fit in the current system, (2) how risk is perceived in each system, (3) how a WSP could integrate with water quality guidelines and regulations, and (4) what improvements need to be made for the WSP to be a useful tool in each system. Only two of the systems included in this study had more than 5000 customers and are considered large systems by Health Canada water quality guidelines (Health Canada, 2017). These larger systems were included to demonstrate population is not comprehensive definition of a small or rural water system. The WHO small systems manual defines a small system as one which does not have the capacity of a more advanced water system, or experiences issues with water quality and staffing not seen in advanced systems or otherwise deal with a lack of access to resources that allow the water system to function efficiently (WHO, 2012).

5.4.2 Analysis of WSP Results

Once visits were conducted, the results of the sanitary surveys and hazard identification modules were analyzed to determine if risk level or risk score was a better method for communicating risk to water system stakeholders. Several different visualizations were created, using both risk score and risk level and were presented to stakeholders for review. Stakeholders were asked to comment on which visualizations were easiest to understand and which provided the most valuable information. These conversations were used to determine if risk score or risk level is more valuable to a stakeholder and which visualizations best communicate risk amongst stakeholders. Table 5.2 shows the risk score versus risk level, using the Alberta scoring regime, linearized. Risk level can either be “low risk” (unlikely to occur and most likely not to significantly impact the system), “moderate risk” (probable or likely to occur or will impact the water system significantly if present) or “high risk” (highly likely to occur and/or will lead to large negative impacts for a water system if present). Risk score is the numeric value associated with risk level in this thesis chapter.

Table 5.2: Risk score is presented versus risk level in this table for reference interpreting the results of this study. Both the Alberta risk score is shown as well as the linearized risk score for clarity.

Risk Level	Alberta Risk Score	Linearized Risk Score
Low	1	1
Low	2	2
Low	4	3
Low	8	4
Moderate	16	5
Moderate	32	6
High	64	7
High	128	8
High	256	9

5.5 Results

5.5.1 Sanitary Surveys for Source Water Hazard Identification

Sanitary surveys revealed that while source water protection plans and watershed mapping are used in these water systems, there are several moderate risk systems due to the nature of the source water and the surrounding watershed. While none of the results from the sanitary surveys were considered new information to the water system staff, the overall score is useful from a regulatory or management viewpoint. Municipal Systems A-F are managed by the same water utility and managers and operators found the sanitary scores a useful comparison of systems. Having a concise summary of ten issues in the source water was useful to show not only what issues are present in an individual system, but also across systems.

Sanitary surveys consist of binary yes/no questions to determine if a behavior is risky or not. Figure 5.1 presents the results of the survey by assigning high risk and low risk to the answers of the questions to visually identify where concerns exist. The overall score is a summation of the high-risk hazards used to communicate the overall vulnerability of a water supply. Using the recommendations from the WHO guide on sanitary surveys, an overall score of 0-3 is low risk, a score of 4-7 is considered moderate risk and a score of 8-10 is high risk (WHO, 2016). For the seven systems where a sanitary survey was performed, five systems were considered low risk source vulnerability, and two moderate risk.

Figure 5.1: Sanitary survey results from seven of nine municipal water supply systems. Sanitary surveys are divided into ten questions and are created differently for ground and surface water sources due to the different characteristics of each source water type.

5.5.2 Risk Modules Results

Review of both the chlorination and distribution modules across 8 systems showed that the WSP pinpoints system specific hazards. Figure 5.2 demonstrates that the majority of the hazardous events for chlorination are consider low-risk in eight water systems (Municipal D is not included here; at the time of the visit to Municipal D, chlorination was not occurring on site and water was being trucked to the system from another system). However, areas of concern are easy to visually distinguish and compare across systems in Figure 5.2. A low risk situation, for example, entails daily monitoring of pH by an operator and is well controlled so that noticeable changes in pH do not immediately impact the effectiveness of chlorination processes. In this example situation, the likelihood of pH falling outside an acceptable range is low. In contrast, a high-risk scenario for pH control entails large fluctuations in pH on a weekly or more frequent basis that cannot be controlled adequately by an operator and greatly impact the chlorine disinfection system. In this situation, the likelihood of pH falling outside an acceptable range is high. If this situation occurs, it has a large impact on the water system that cannot be resolved immediately.

Municipal C has two clearly defined concerns that should be prioritized for improvements. Both the Dosing Controls and Chlorine Demand hazardous events were identified as high risk. Chlorine dose depends upon the conditions of the water being dosed and a high chlorine demand can result in a higher than needed dose to adequately maintain a disinfection residual. In this system, it is clear these two hazardous events are linked and dependent upon one another, highlighting key high-risk concerns. Figure 5.2 therefore provides critical information to the stakeholders in Municipal C that would not have been identified through water quality monitoring alone. Similarly, Municipal G has one issue to address that is moderate-level risk: Disinfection By-Products. The moderate-level risk does not signify it is moderately likely that disinfection by-products will form in the Municipal G chlorination system. Instead, this signifies that disinfection by-products are a concern but can be addressed by adequate control measures to manage risk. In the Municipal G system specifically, the source water is known to have a high organic load, containing compounds that are disinfection by-product precursors. There were historic issues with these compounds forming in this system, therefore, the probability of having disinfection by-products was moderately likely. The impact was also moderate as there are treatment barriers within the system that can be adjusted to compensate for these known concerns.

However, while Municipal C and Municipal G have clear issues for improvement, Municipal E and Municipal F have no clear improvements that could be made to the system to make the water system more secure. All of the hazardous events for the chlorination module from these two systems are low risk (Figure 5.2). Since a WSP is designed to highlight areas for improvement in a water system, the stakeholders from these systems had difficulty understanding how the water safety plan method could be useful for prioritizing risk mitigation. The problem is the lack or granularity in the results when presented as either low, moderate or high risk. This WSP tool utilizes the Alberta DWSP scoring regime (AESRD, 2011): a risk score of 1, 2, 4, or 8 corresponds to low risk (Table 5.2). If the results were presented with risk scores associated with each hazardous event, instead of as a risk level, it is possible to achieve greater granularity and better pinpoint specific issues. Even if a hazardous event is considered low risk, there are still improvements to be made if the risk score is not equal to one.

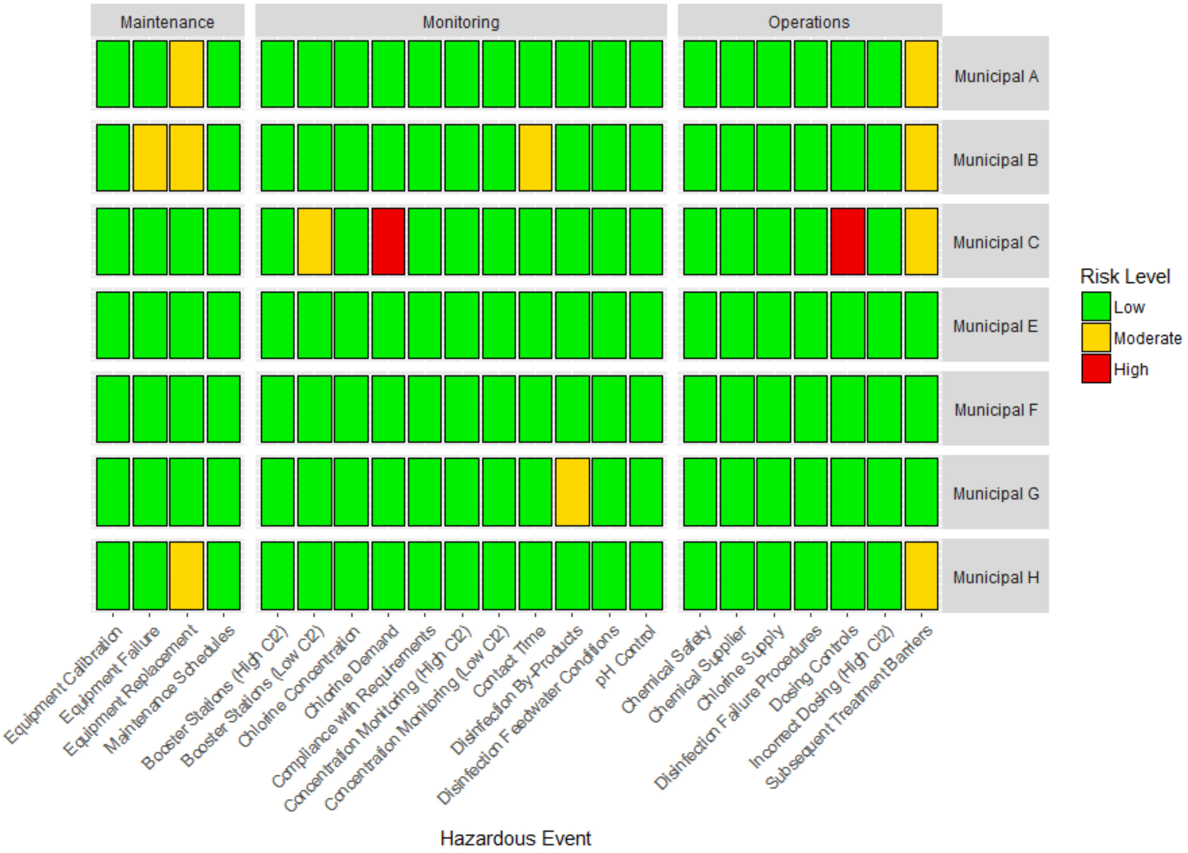


Figure 5.2: Results from the chlorination module in the WSP tool. Municipal D is not included in this figure as chlorination was not completed at the Municipal D facility at the time of the visit.

5.5.3 Risk Score vs. Risk Level

To show the difference between risk score and risk level, Figure 5.3 provides a similar analysis to Figure 5.2, but instead of translating a risk score to a risk level using the Alberta DWSP risk matrix, the scores have been translated to a score of 1-9 using the following formula:

Equation 5.1:

$$y = \frac{\log_{10} x}{\log_{10} 2} + 1 \; for \; x > 0$$

This formula was utilized by Post et. al., 2017 to linearize the results from a water safety plan to allow for easier presentation and communication of results (Post et. al., 2017). This formula takes the Alberta

WSP risk score as the x variable and outputs a linearized risk score as the y variable (shown in Table 5.2 as the translation from column 2 to 3). In Figure 5.3, particularly for Municipal E and Municipal F, a more granular look at each hazardous event is available.

Figure 5.3 provides a more in-depth evaluation of common hazards between municipal systems. For example, the Disinfection By-Products hazardous event now shows that most systems are on the high end of low risk, closer to moderate risk than shown in Figure 5.2. This is a reflection of the known presence of organic content in the source water for these systems. The WSP method used in this study asked questions about source water conditions to determine whether there were disinfection by-product pre-cursors in the source even if the water system had never had issues with these parameters. Figure 5.2 demonstrates that the conditions for disinfection by-product formation are present in all of the water systems evaluated and highlights the need for vigilance in these water systems. Figure 5.3 presents visualization of risk using risk score to better pinpoints areas of concern that are not critical, but that should not be ignored.

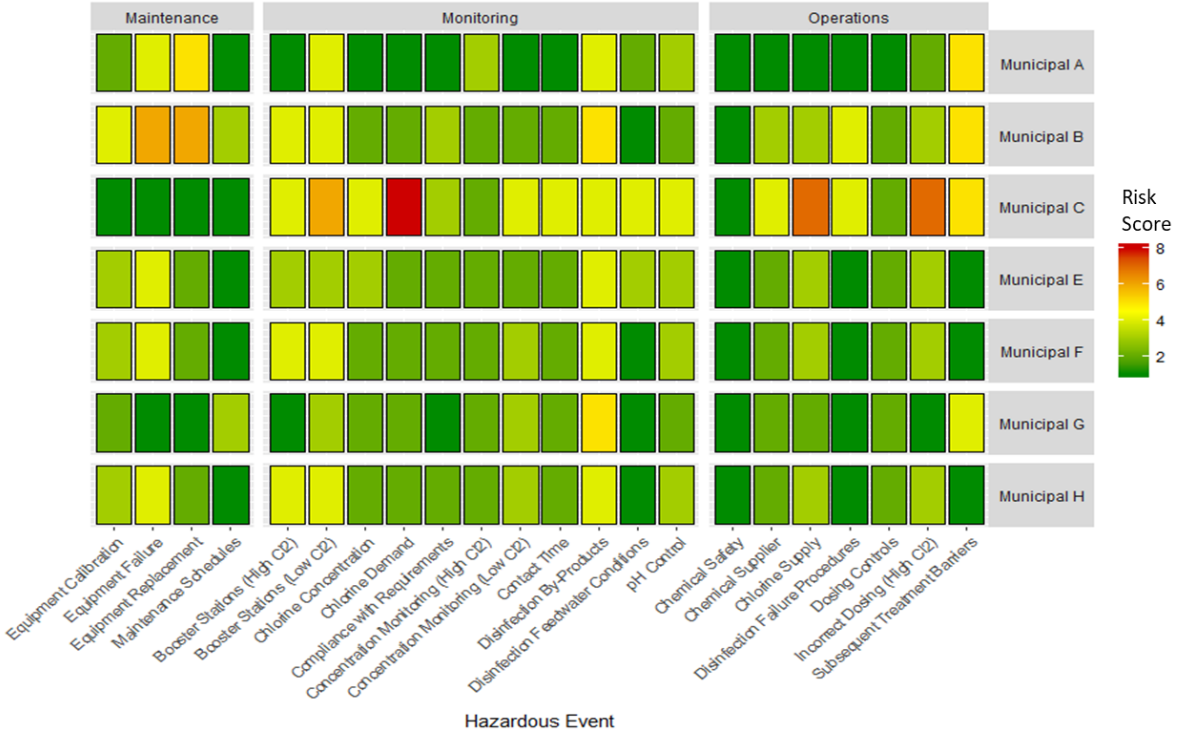


Figure 5.3: Hazardous events for chlorination shown by risk score instead of risk level. Risk Score has been translated from the Alberta scoring regime to a 1-9 regime using the formula previously presented in Equation 5.1 for simplicity.

5.5.4 WSP Implementation Barriers

For both the chlorine disinfection and distribution system modules completed in all water systems, there are very few hazardous events that were categorized as moderate or high-level risk. This is in part due to strong sampling programs, adequate staffing at each system, supervisory control and data acquisition systems (SCADA) as well as inline monitoring devices. Several of the assessment questions ask about frequency of water quality monitoring, with options such as “daily”, “weekly”, “monthly”, “annually”, etc. For the majority of the water systems included, the most frequent answer to these types of questions was “daily” or even “continuously”, as a result of inline monitoring equipment. While this constant monitoring is beneficial for adequate control of the system and provides a wealth of water quality data, continuously logged data does not guarantee that staff are reviewing this data at the same rate that it is being collected. Staff are most likely to interact with this type of data once a value falls outside of the optimized operational parameters and triggers an alarm, a reactionary action.

For example, the chlorine disinfection module asks questions about pH control, focusing on ensuring an operator is aware of the proper pH needed for adequate chlorine disinfection. Data about how often pH is being recorded or logged by an operator or SCADA system is also collected. If pH is monitored “continuously” there is the possibility that an operator will not look at the data as it is being recorded since some systems record data every ten seconds. Checking for pH every ten seconds physically is not feasible in a water treatment facility as an operator has other responsibilities. As a result, many operators rely on alarms pre-set into the SCADA or data logging system to notify an operator when the pH value is outside of an acceptable range. However, if an operator is now responding to an alarm, this is a reactionary approach and an operator is not actually monitoring pH “continuously” even though the data system is logging samples continuously. Since “continuously” corresponds to a low value for likelihood or consequence, the risk score calculated for “pH control” will be low or moderate risk at most which is not an accurate representation of how often an operator is checking pH in the chlorination system.

A summary of the four key themes recorded during conversations with water system stakeholders are presented in Table 5.3. Each theme is presented with supporting ideas and comments from water system stakeholders. The four key themes observed are as follows: (1) advanced and automated systems decrease risk, (2) entrenched regulatory culture impedes WSP implementation, (3) the WSP currently has unclear added benefits, and (4) the WSP method provides a diagnostic tool for identifying risk in a water system.

Table 5.3: Themes compiled from talking with water system stakeholders about WSP implementation

Theme	Supporting Ideas
Advanced and Automated Systems Decrease Risk	• Continuous monitoring means the system is safe • The WSP needs to be more sophisticated to match current systems and to be useful
Entrenched Regulatory Culture	• If not needed to meet regulations, an action is secondary • Still need to meet regulations at the end of the day • WSP needs to be required to get people to use it • Additional work for operators
Unclear Added Benefits	• What are the *tangible* costs and benefits to a WSP? • Not every stakeholder sees the same benefits
WSP as a "Diagnostic" Tool	• WSP good for visually pinpointing issues • Would be ideal for systems with limited capacity (but not necessarily in *my* system)

5.6 Discussion

5.6.1 Sanitary Surveys for Source Water Hazard Identification

The sanitary survey provides a useful tool to compare source water issues across water systems, whether within an individual utility or at a regional or provincial level. This not only helps water systems identify common concerns but informs policy making at a provincial or regulatory level or designing criteria for water systems with specific source water characteristics. For example, the groundwater sanitary survey demonstrated that all the water systems surveys have concerns with inorganic contaminants (metals), specifically iron and manganese. While the sanitary survey and the WSP methods are not defined by a specific regulation currently in the Atlantic region, this approach has the potential to inform and improve regulatory strategy and policy.

The sanitary survey tested in this study provides a valuable starting point in the WSP evolution for a water system (WHO, 2016, WHO, 2012). The systems included in this study were able to easily provide the information needed to complete the sanitary surveys, however, other small systems may not have the capacity to do so (WHO, 2016). Traditionally, focus has been placed on endpoint monitoring in a water system, not on source water monitoring, showcased by Canadian water quality guidelines (Health Canada, 2019). This study demonstrates a sanitary survey's capacity to identify risks in source water systems visually, providing information about the source in a compact manner (WHO, 2016). The primary utility of this tool is its ability to condense information about the source that would otherwise be kept in logbooks and engineering designs that have been reviewed recently (WHO, 2016). Knowledge about the source directly feeds into hazard identification for treatment processes and is considered an integral component of WSPs for small water systems.

5.6.2 Risk Score vs. Risk Level

Risk score presents results with greater granularity than risk level. By using risk score instead of risk level, the difference between a low risk hazardous event scored at 1, 2, 3, or 4 was clearly visible between Figure 5.2 (risk level) and Figure 5.3 (risk score). The eight water systems showed predominantly low-level risks for hazardous events, providing the appearance of safe water supply systems. Using only a risk level obscures the hazardous events that are on the edge of being moderate risk and could be impactful in a system in the coming years. A hazardous event scored as a 6 will be assigned moderate risk using the risk matrix but is one step away from 7 which is high risk. This demonstrates two of the key critiques of a risk matrix: poor resolution and suboptimal resource allocations (Cox Jr., 2008). Because there must be a risk score cut off for each level in a risk matrix, this often leads to poor resolution in a risk matrix. There are so few scoring combinations between the likelihood and consequence scores, and even if there are more than 20 scoring combinations, this will only translate to 3-4 risk levels (Cox Jr., 2008). A risk score of 6 would pinpoint a hazardous event that could become high risk if unaddressed. However if this score is represented as moderate risk, it is quite possible that a water system will not devote resources to mitigating this hazard since it is not yet considered high risk. This speaks to the concern of poor resource allocation: efforts are not placed where needed if hazardous events are only described by risk level from a risk matrix (Cox Jr., 2008).

The differences between Figure 5.2 and 5.3 demonstrate the need for research that explores how to best communicate and present risk from a water safety plan to all of the stakeholders within a water supply system. The WSP method relies on the risk matrix approach due to its ease of use and ubiquity across several industries (Bartram et. al., 2009, WHO, 2016). However, while a useful tool to evaluate risk, there is concern that risk results are being obscured or underestimated, as Figure 5.3 shows. Cox Jr. demonstrated the need for clear delineation between very low and very high-risk scores in order for a risk matrix to be useful (Cox Jr., 2008). Since each global jurisdiction or WSP case study uses a different modified risk matrix (as was explored in Chapter Four), it is difficult to audit each method to determine if the risk matrix construction was carefully considered and adequately allow a system to evaluate risk. Even the definitions of very low and very high risk are subjective and review of WSPs in a 2017 report showed that internal and external auditing is needed for successful WSP implementation globally (WHO

& IWA, 2017). This study shows the necessity of choosing risk scoring methods carefully and highlights the need to consider visualizations and communications of risk in a water safety plan. Risk score is able to differentiate between low-level risk hazardous events, providing a better picture of which hazardous events need to be addressed in a specific water supply system.

5.6.3 WSP Implementation Barriers

One of the largest barriers to WSP implementation in small municipal systems is staff mindset (Table 5.3), specifically the highly regulatory culture that is pervasive in decentralized regulatory regimes. The majority of water system staff involved in each visit recommended that the WSP needs to be a regulatory requirement for it to be successful and considered a legitimate approach to managing risk. Regardless of whether a WSP becomes a regulatory requirement, shifting the entrenched regulatory mindset in water systems poses a concern, requiring time and guidance for successful WSP implementation. Studies by Baum et. al., 2015 and Baum and Bartram, 2017, examined how a WSP could potentially be applied in the United States focusing on regulatory and enabling environments in water systems (Baum et. al., 2015, Baum and Bartram 2017). Both studies showed that the current regulatory structure in the United States (which is similar to Canada) can be a limiting factor to the success of a WSP. In addition, other studies have shown that WSP implementation success is grounded in an open-minded water system culture (Summerill et. al. 2010a, Summerill et al. 2010b, Ferrerro et. al., 2019, Summerill et. al. 2011). For the small municipal systems studied here, efforts will need to be made to change the regulatory mindset and encourage a water system culture that focuses on proactive risk management.

In addition to the regulatory mindset, a “not in my system” attitude was present in the majority of the water systems visited, with many systems stating an event would never happen in his or her system. When asked how the WSP benefits water systems in general, operations and water staff were most likely to describe benefits to other water systems. These “other” systems had less perceived capacity, fewer water system personnel, remote locations, and other characteristics that a stakeholder did not think characterized his or her water system. Most stakeholders understood how prioritization of system improvements was a benefit of the hazard identification process but were likely to describe this as a benefit for systems with lots of high-risk level hazardous events. When reviewing survey questions, many initial answers were “no” or “not applicable” to questions about whether an event could potentially occur. Discussion of the questions often revealed that the answer should be “yes”, “unknown” or “rarely” instead. Given that the water systems included in this study have higher than normal capacity to mitigate water quality concerns (established operators, strong ties to managers in utilities and capital available for improvement projects), this may account for the “not in my system” mindset observed in this study. This same conclusion would not be expected from water systems that have high operator turnover and inadequate record keeping procedures.

This “not in my system” attitude was common in the small municipal systems, demonstrating that attitudes towards risk and hazards are not always accurate, nor are they proactive in nature. The “not in my system” mindset shows that while staff can understand why an event could be hazardous, the risk level associated with the hazardous event could be an underestimation of actual risk. Previous studies demonstrated the need for receptive institutions and mindsets to encourage WSP adoption (Omar et.al., 2017, Summerill et.al., 2010a, Summerill et.al., 2010b). Currently, the predominantly regulatory mindset present in the studied systems is a barrier to WSP adoption. Changes in organizational culture are needed to encourage a proactive mindset (Summerill et.al., 2010a, Summerill et.al., 2010b) and agencies supporting WSP adoption need to be identified (Omar et.al., 2017).

The predominant attitude towards increased automation of water systems may account for the reason water system stakeholders fail to recognize the benefits a WSP adds to a facility. One of the identified themes presented in Table 5.3 concerned the desire for increased sophistication of the WSP developed for this thesis (Chapter Four) so that it either matched or surpassed the level of current automation. This desire for increased capacity of the WSP is not rooted in a desire for the WSP to be more system specific, but is instead based on the preconceived idea that web applications, surveys and data collection systems should be as easy to use as possible, and should autonomously with no or limited human interaction. However, less human interaction into the system limits the flexibility of the system (Groover, 2019). While automation increases ease of interaction with a system (Olsson, 2006), automation also requires large capital investment and a higher level of maintenance (Groover, 2019) which is difficult to achieve in small water systems as previously identified (Kot et.al., 2011). WSPs call for more interaction with a system, not less, and a heavy focus on automation is detrimental to developing a proactive mindset.

These predominant mindsets suggest that a WSP will need to be required, at the provincial level at minimum to achieve successful adoption and implementation. The preferred strategy is to require the WSP federally, however, Canada currently does not have legally enforceable water quality regulations nationally (Kot et.al., 2011, de Loe, 2017). As a result, previous water safety tools and policies, such as the drinking water advisory have suffered from a lack of consistent reporting formats and procedures

(Shuster et.al., 2005, Dunn et.al., 2017, Miller and Watson, 2011, Thompson et.al., 2017, Chapter Two of this thesis). Alberta already has a WSP in place as of 2014; as a result, federal requirements for water safety planning may not be the most suitable solution given preestablished strategies (Perrier et.al., 2014, Reid et.al., 2014). However, due to the predominant regulatory mindset observed in this study and in previous studies (Summerill et.al., 2010a, Summerill et.al., 2010b, Ferrero et.al., 2019, Amjad et.al., 2016) unless water governance structures in Canada undergo drastic change in the next five years, WSPs will have to be a requirement of water systems for adoption to take place.

5.7 Conclusions

The WSP used in this study was able to provide an accurate summary of risk for a suite of hazardous events in eight water systems. Each municipal water supply system identified individual hazardous events and comparisons across water systems showed the WSP can be used to identify commonalities leading to policy changes in water management. Water safety plan implementation in municipal water systems is a beneficial and proactive method for managing risk, but is limited by a predominant regulatory mindset, and a desire for automation of the water safety plan method. Consultation with water system stakeholders revealed an interest in adopting WSPs while also highlighting the need for changes in water system culture to promote proactive risk management. Furthermore, the water safety plan method itself needs increased auditing, both internally and externally to ensure that the risk scoring methods employed by different water supply systems are accurately representing the risk present in each system. Comparison of risk level versus risk score across eight municipal systems demonstrated risk level alone obscures key results from a water safety plan, leading to poor resource allocation in a water supply system when mitigating hazardous events. Risk score provides a better method for identifying risks which on the high end of each risk level. Future work is needed to understand how the use of risk score and alternate visualizations of risk can be used to best communicate risk between water system stakeholders.

6 Chapter Six – Exploration of water safety plan methodology in Canadian First Nation water supply systems

6.1 Abstract

Since 2001, the World Health Organization (WHO) has promoted the use of water safety plans as a risk management tool for assessing risk in water systems from the source water, through treatment processes, and ending with distribution to the customer. Water safety plans have not been previously explored as a strategy to manage risk in First Nations communities in Canada. First Nations in the Atlantic Canadian region (Nova Scotia, New Brunswick, Newfoundland and Labrador, and Prince Edward Island) have been chosen as a focus in this study to determine how water safety plans (WSPs) could be implemented in these water systems. A WSP developed for this thesis was utilized in six First Nations communities to gauge the appropriateness of the tool, to understand what policy changes are needed to implement WSPs, and to start a discourse about risk calculation and communication in First Nations water systems. Visits to six water systems were conducted in early 2018 to speak with water facility operators and water quality monitors about each water system and to review the WSP tool. Conversations during these visits provided useful feedback about the structure of the WSP tool and about how risk is presented and communicated to all stakeholders in the water system: chief and council within a community, community members themselves, and regulators in charge of reporting water quality results. Results showed more research and focus needed to be placed on how risk is communicated. A simplification of the WSP tool to align with water quality guidelines and regulations is necessary to encourage successful adoption of a water safety plan approach in these First Nations water systems.

6.2 Introduction

Current persistent issues with drinking water advisories and frequent adverse water quality results have necessitated the consideration of other water supply management tools for First Nations water systems (Neeghan Burnside Ltd., 2011, Health Canada 2014b, Indigenous Services, 2019, Murphy et. al., 2015, Eggerston, 2008, Black and MacBean, 2017). A water safety plan (WSP) is a form of proactive hazard identification that seeks to mitigate hazardous situations before occurrence as opposed to reactively measuring water quality parameters in treated water (WHO, 2012, Bartram et.al., 2009). In 2017, a Global Status Report on WSP Implementation reported 93 countries had completed implementation of WSPs to varying degrees, with 30% of those countries in the early development stage (WHO & IWA, 2017). In Canada, the province of Alberta currently uses WSPs to help meet federal water guidelines and previous research demonstrated how implementation has impacted Albertan drinking water systems (AESRD, 2011, Reid et.al., 2014, Perrier et. al., 2014, Kot et. al., 2017). Currently, Atlantic Canadian communities have not utilized a WSP approach to help manage water facilities except through initial scoping studies.

Previous research regarding water management in small systems has shown that smaller communities (less than 500 people) often experience issues that larger water utilities do not. These issue include limited financial capacity, lack of proper operator training and remote locations that limit the availability of more sophisticated methods of treatment (WHO, 2012, Murphy et. al., 2015, Kot et. al., 2011, Pons et. al. 2014). Paying for extra sampling to ensure that water quality parameters are meeting provincial or federal regulations is often beyond the capacity of small communities, leading to undiagnosed problems in communities that can persist for years (Kot et. al., 2011, Castleden et.al., 2017, Bradford et.al., 2017, Thompson et.al., 2017, Black and MacBean, 2017). In addition, First Nation water systems tend to have more frequent and longer lasting drinking water advisories as a result of a lack of information why the advisory occurred or lack of ability to remove the drinking water advisory (WHO, 2012, Neeghan Burnside Ltd., 2011, Indigenous Services Canada, 2018, Black and MacBean, 2017, Eggerston, 2008). Additionally, 79% of First Nation communities serve a population less than 1000 people; the majority of systems are designate “small” based on population (Neegan Burnside Ltd., 2011). In this situation, a WSP provides more proactive and manageable method for dealing with hazardous situations by augmenting current operational practices (WHO, 2012) in First Nation water systems.

To evaluate the benefits of adding a WSP in First Nation water systems, a review of system assessment reporting was completed to compare the status of water systems in 2013 to the status after completing a WSP in 2018. Several studies of WSP implementation (WHO & IWA, 2017, Gunnarsdottir et, al., 2012, Omar et. al., 2017, Baum and Bartram 2017, Tibatemwa et. al., 2004, Rondi et. al., 2015 and Kumpel et.al., 2018) have shown the status of a water system both before and after WSP implementation and discuss the factors that are conducive to successful adoption. System assessment reports have been used in case studies (Tibatemwa et. al., 2004) to help WSP stakeholders scope the extent of knowledge available about specific hazards before and after WSP implementation. Therefore, this study consulted previously generated reports about these water systems to determine how a WSP can better inform stakeholders (operators, monitors, managers, etc.) about the hazards in the water system. One of the main reported benefits of a WSP has been an increase in knowledge about the water system (WHO & IWA, 2017, WHO, 2012, Kumpel et. al., 2018, WHO, 2018, Gunnarsdottir et. al., 2012, Tibatemwa et. al., 2004) and this study aims to verify this result in the context of First Nations water systems.

The WSP method utilized in this study was developed using small municipal water systems in Atlantic Canada (Chapter Five). For the WSP method to be applied in First Nations water systems, it was essential that a review of the hazardous events chosen was conducted for appropriateness and applicability. Several studies have demonstrated that traditional, top-down approaches to water management do not consider Indigenous perspectives when designing and implementing new strategies or infrastructure improvements (Black and MacBean, 2017, Jimenez et, al., 2014, Bradford et.al., 2018, McCullough and Farahbaksh, 2012, Murphy et.al., 2015). In particular, the study by Black and MacBean in 2017 focused on how a WSP method can be adapted for Indigenous communities in a Water Sustainability and Security Strategy. Bottom-up participatory methods are paramount in Indigenous communities to allow for re-engagement and re-empowerment (Black and MacBean, 2017). Bradford et.al. 2017 also stressed the importance of strategies that promote “power with” policies instead over “power over” (Bradford, et.al., 2017). In the context of WSPs, the first step is to determine if a WSP approach is beneficial in First Nations water systems by understanding if the approach applicable to municipal systems needs revision or alteration to take into account the cultural significance of water, operator knowledge and expertise, and regulatory and cultural mindsets in community water systems (Jimenez et. al., 2014, McCullough and Farahbaksh, 2012, Bradford et.al., 2017, Castleden et.al., 2017).

The objective of this study is to determine the appropriateness of a WSP approach in First Nations water systems and the changes in policy and water regulation needed for a successful adoption of this method. WSPs are community-specific tools for risk assessment and are used to prioritize improvements (Bartram et.al., 2009, WHO, 2012); focus was placed on the appropriateness of identified hazards, which hazards are common amongst water supply systems and how risk is communicated to all involved in the water system. Furthermore, the objective of this study was to provide an evaluation of the added benefits of a WSP comparing results to previous system assessments, allowing for an examination of current and past water system knowledge. Together, these objectives provide a holistic and practical evaluation of WSP in First Nations water systems.

6.3 Methods

With these objectives defined, a study involving WSPs in six First Nations communities in partnership with the Atlantic Policy Congress of First Nations Chiefs (APC) was conducted. Community visits were organized to meet with both water operators (those in charge of operating the treatment facilities), water monitors (those in charge of taking water quality samples from the distribution system) and other water system stakeholders. Results were compiled and analyzed, and stakeholders were asked to provide feedback in a follow-up consultation on both communication of results as well as the efficacy of the WSP method.

6.3.1 Community Engagement

An engagement session was held in 2017 with water system stakeholders from six water systems including operators, monitors, water quality regulators from Health Canada and FHNIB-ISC and environmental health officers (EHOs) from the Atlantic Canada region. During the engagement session, the project goals were introduced, and the water safety planning process was explained in detail to participating systems. Hazard identification documentation was provided to operators and to encourage operators and monitors to think about potential hazards and risks in each water systems. Water regulators and EHOs were asked to provide feedback on this documentation and make recommendations for additional activities that should be completed during the initial water system visits. Community engagement sessions were held specifically to meet requirements from the First Nations Informations Governance Centre principles of Ownership, Control, Access and Possession (OCAP) and to ensure the project met sustainable community development best practices for indigenous populations (First Nations Informations Governance Centre, 2019, Black and MacBean, 2017, Kot et. al. 2017, Castleden et.al., 2017, Bradford et.al., 2017).

Visits to the six water systems were conducted in early 2018. The water systems that participated in this study were chosen based on several characteristics. Three factors were chosen when water systems were selected by the APC: source water type (surface water or groundwater), size of the water system based on population (small, medium or large) and whether the treatment facility as operated by a municipal operator under a municipal transfer agreement (MTA), or operated by the First Nation itself (non-MTA). Three water systems were selected in Nova Scotia, two in New Brunswick and one in Prince Edward Island. Water system names have not been included to preserve anonymity (First Nations Information Governance Centre, 2019) and several reports from this study have been reviewed by the participating water systems to ensure that the results of this project are being accurately communicated.

The purpose of the water system visits was two-fold: first, a tour of the facilities and water system were conducted to provide researchers with a better understanding of water system capacity. Second, during the water system visit, the water operator of the facility, the water monitor (sample collector) and any secondary operators and monitors were invited to answer relevant surveys in the WSP tool. Survey questions in the water safety plan were designed with a predetermined set of possible answers and review and discussion of the answer options was encouraged to provide feedback on both the survey questions and to arrive at the best possible answer to each question. WSP manuals provided by the WHO outline the importance of having a WSP team instead of one person solely in charge of the WSP (WHO, 2012, WHO, 2018) and thus multiple stakeholders (operators, water monitors, environmental health officers, chief and council, etc.) were invited to participate in this project.

Surveys relevant to each water system were compiled prior to the visit, based on previous internal reports provided by the APC. Chlorine disinfection and distribution system operations surveys were included for all water systems to facilitate comparisons. Based on each water system's treatment facility, additional surveys were added for specific treatment processes: UV disinfection at one facility, membrane filtration at two facilities and overall plant operations at one facility. The results presented in subsequent sections highlight the outcomes from chlorine disinfection and distribution operations surveys.

6.3.2 WSP Review

After water system visits were completed, conference calls were scheduled with the participating water systems to review the risk reports generated by the WSP tool and gather more feedback. Conference calls were 20-30 minutes in duration and results from the WSP tool were sent to the community prior to the call. Risk reports generated from the WSP tool consisted of the following information: the identified hazard being evaluated, the risk level assigned to the hazard, a description of specific issues identified by the surveys and suggested activities to be completed to decrease the risk level of a hazard.

Emphasis was placed on assessing the validity of the results from each completed survey: were risk levels identified for each hazard representative of the conditions in the water system or did the results over or underestimate risk? Furthermore, graphical representations of the results were sent to each water system to provide an alternative method to visualize and understand risk. Operators and monitors were asked to comment on which reporting method was easiest to understand, which would be best to communicate results to chief and council, or EHOs and water regulators, and which reporting methods did not adequately communicate the results.

6.3.3 Comparison to 2013 System Assessments

In 2013, a series of reports on both water and wastewater systems were commissioned by the APC and completed by a consulting firm (CBCL Ltd, 2013). The resulting system reports (CBCL Ltd, 2013) contained information about water quality, infrastructure age, deterioration rates, needed improvements through gap analysis and regulatory compliance status of each water system. These reports were reviewed in detail by researchers to determine how much information was known about potential hazards in 2013. This review provided a diagnostic of the system in 2013, before a WSP was explored in these 6 water systems. Where information was not available, the risk level of each hazard was designated as “unknown” to avoid underestimation or overestimation of risk. The results from the review are used to compare the knowledge available about the water system before WSP exploration studies (2013) and after WSP exploration studies (2018).

6.4 Results

After completing both the chlorine disinfection and distribution system operations surveys, the number of hazards corresponding to each risk level were separated into categories to summarize the overall results. Figure 6.1 shows the number of hazards per risk level for three major categories: operations, monitoring and maintenance. For the chlorine disinfection survey, all the hazardous events are considered water quality hazardous events; however, for the distribution system survey, two additional categories to separate water quality and water quantity issues were added. A hazardous event can either be monitoring, operational or maintenance related and can also be either water quality or water quantity related.

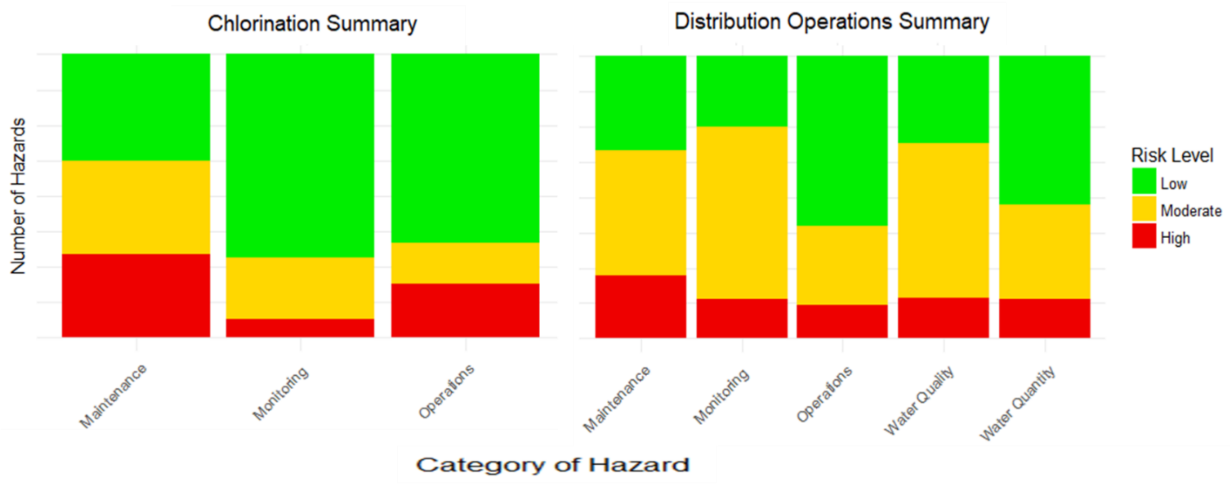


Figure 6.1: For all six communities, the number of hazardous events that correspond to each risk level (high, moderate and low) are presented by risk category to show the overall risk levels present in these communities. For both chlorine disinfection and distribution operations, there are three major categories: operations, maintenance and monitoring. For the distribution operations survey there are also categories for water quality and quantity hazards to better specify the issues experienced by these communities.

Figure 6.1 shows that for monitoring hazardous events, chlorine disinfection hazards are predominantly low risk whereas there are more moderate and high-level risk hazards in the distribution system. Health Canada guidelines for water quality and the operational of a chlorine disinfection system clearly state specific values that should be measured to determine the efficacy of a chlorine disinfection system (Health Canada, 2013, FNHIB, 2007). Operators comments during the survey process indicated that there are more resources available for the operation of the chlorine disinfection surveys and there is more knowledge about chlorine disinfection system function than in the distribution system. However, there are fewer guidelines on the maintenance and operation of the distribution system, with monitoring for many water quality parameters only required yearly (Health Canada, 2014). Endpoint monitoring in the distribution system is well defined by the Guidelines for Canadian Drinking Water Quality (Health Canada, 2014), however maintenance procedure are not. Several responses to survey questions in the distribution system survey were “unknown” which corresponds to a moderate risk level. Since regulatory samples are taken at the end of the distribution system and water operators predominantly interact with the distribution system as water is leaving the treatment facility, there is little knowledge about issues between these points. This result indicates more surveillance in the distribution system is needed to determine whether “unknown” hazardous events are harmful to the system.

Results were broken down by water system to determine specific issues in individual systems. For both the chlorine disinfection and distribution operations surveys, the portion of hazardous events corresponding to high, moderate and low risk levels are presented in Figure 6.2.

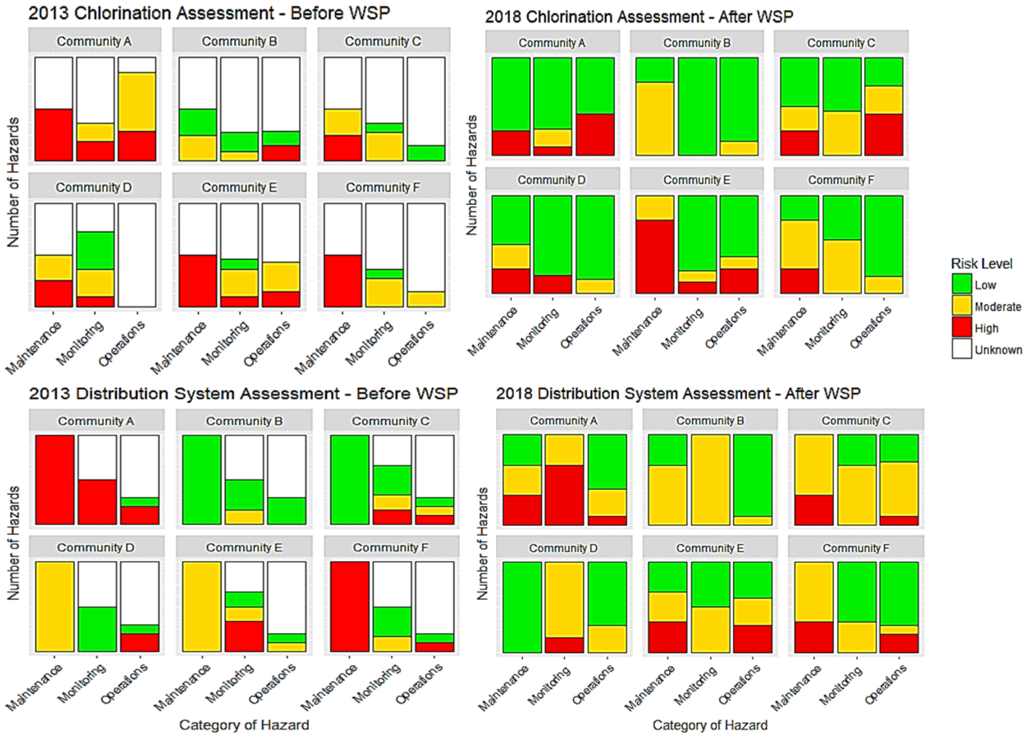


Figure 6.2: For chlorine disinfection and distribution system operations, the number of hazards per each risk level were counted and divided into three major categories: operations, maintenance and monitoring. The height of the bar sums to 1.0; the height of each color within the bar represents the portion of hazards within a category corresponding to each risk level.

Figure 6.2 indicates there are overarching issues to be addressed in Atlantic First Nations water systems and there are specific issues that are unique to each system. For example, Community A shows only moderate-level and high-level risks for monitoring in the distribution system whereas Community F shows only low-level and moderate-level risks in Figure 6.2 in 2018. In Community F, improvements in maintenance of the chlorine disinfection system is a higher priority than in Community B; Community F has higher risk levels than Community B. This visual representation of the results from the WSP tool was considered important to the majority of stakeholders involved in the community engagement process. This type of figure is designed to give a visualization of risk by category and serves to highlight broad differences between water systems. It should be noted that a high-level risk does not necessarily indicate failure of a system or process is imminent; it indicates that an issue that occurs frequently in the system or has the potential have severe impacts if left unaddressed.

Figure 6.2 also demonstrates in 2013 there is a lack of knowledge about specific hazardous events, particularly for the operations category in the distribution system. In contrast, there was “complete” knowledge about maintenance risk in the distribution system in 2013. However, compared to the 2018 WSP, the 2013 system assessment report over- or under-estimates the risk level of these maintenance hazards. This issue occurs in both chlorination and distribution system modules in all categories. The 2018 WSP relies on operational knowledge from the stakeholders that interact with the water system daily, whereas, the 2013 system assessment reports were conducted by external consultants, which accounts for the observed differences in risk. The difference between 2013 and 2018 is rooted in different perspectives of the water system, perspectives that come from a regulatory standpoint and an operator perspective. The WSP method can be completed by either stakeholder but risk levels assigned are different, as shown in Figure 6.2. Neither perspective is “correct” and both stakeholders provide valuable insight to the water system; however, the WSP gathers operational data and specific data from an operator perspective that a system assessment does not. The WSP tool focuses on generating knowledge about a water system from the stakeholders that interact with the water system on a regular basis.

To explore similarities and differences between water systems, Figure 6.3 shows a summary of risk level by the hazardous event, categorized by maintenance, monitoring and operations for all six systems. In this figure, interpreting the graph horizontally shows which hazardous events correspond to each risk level for an individual water system. Evaluating the graph vertically shows commonalities between water systems in both 2013 and 2018. There are hazardous events in the chlorination module not considered in the 2013 assessments or were only documented in one or two water systems. Chlorine demand in 2013 has an unknown risk level for all water systems. Information about pH control and dosing controls was only known in Community E in 2013 and only Community D was specifically examining water as it was entering the chlorination system as a preventative measure to reduce disinfection by-products.

Figure 6.3: For the chlorine disinfection survey, the results from each hazardous event are shown separated by category and community to facilitate comparisons. Reading the figure vertically highlights issues common between communities while reading the figure horizontally highlights community specific issues.

For chlorine disinfection processes, all six water systems have predominantly moderate and high-level risks maintenance related hazardous events in 2018. Maintenance of the chlorine disinfection system is therefore an issue that needs to be addressed at a regional or federal level as it is common these six systems. In contrast, Community D is the only water system that shows high level risks for disinfection by-products (DBPs). This concern should be addressed at an individual system level since it is unique to this system. This type of visualization provides information not by only by individual water system, which meets the “community-specific” design criteria of a WSP (WHO, 2012), but can also pinpoint commonalities. Commonalities allow regional, provincial or federal agencies to develop better policies to mitigate issues across First Nations water systems. For example, equipment failure, calibration and replacement are predominantly moderate and high-level risk for all systems. Agencies can use this information to develop a stronger guidance tool for maintenance of a chlorination system and operator templates for reporting equipment issues to address identified issues in a timely manner.

Figure 6.4 provides a similar analysis of hazardous events for the distribution system survey. As opposed to the chlorine disinfection survey, the distribution systems in these systems reveal several common issues. Monitoring hazardous events are predominantly moderate or high-risk level for all six communities in 2018. As indicated by operators and monitors when surveys were conducted, there is often a lack of knowledge about issues occurring within pipes in the distribution system as samples are taken as they leave the treatment facility and at the end of the distribution system at a household tap. For example, little is known about the presence of biofilm build-up in distribution pipes; this hazard is potentially harmful to customers if biofilm shears off pipes and reaches a household tap. This is a question that cannot be easily answered or is not correctly worded to properly identify risk. However this indicates more testing and monitoring is needed to identify issues occurring in distribution systems.

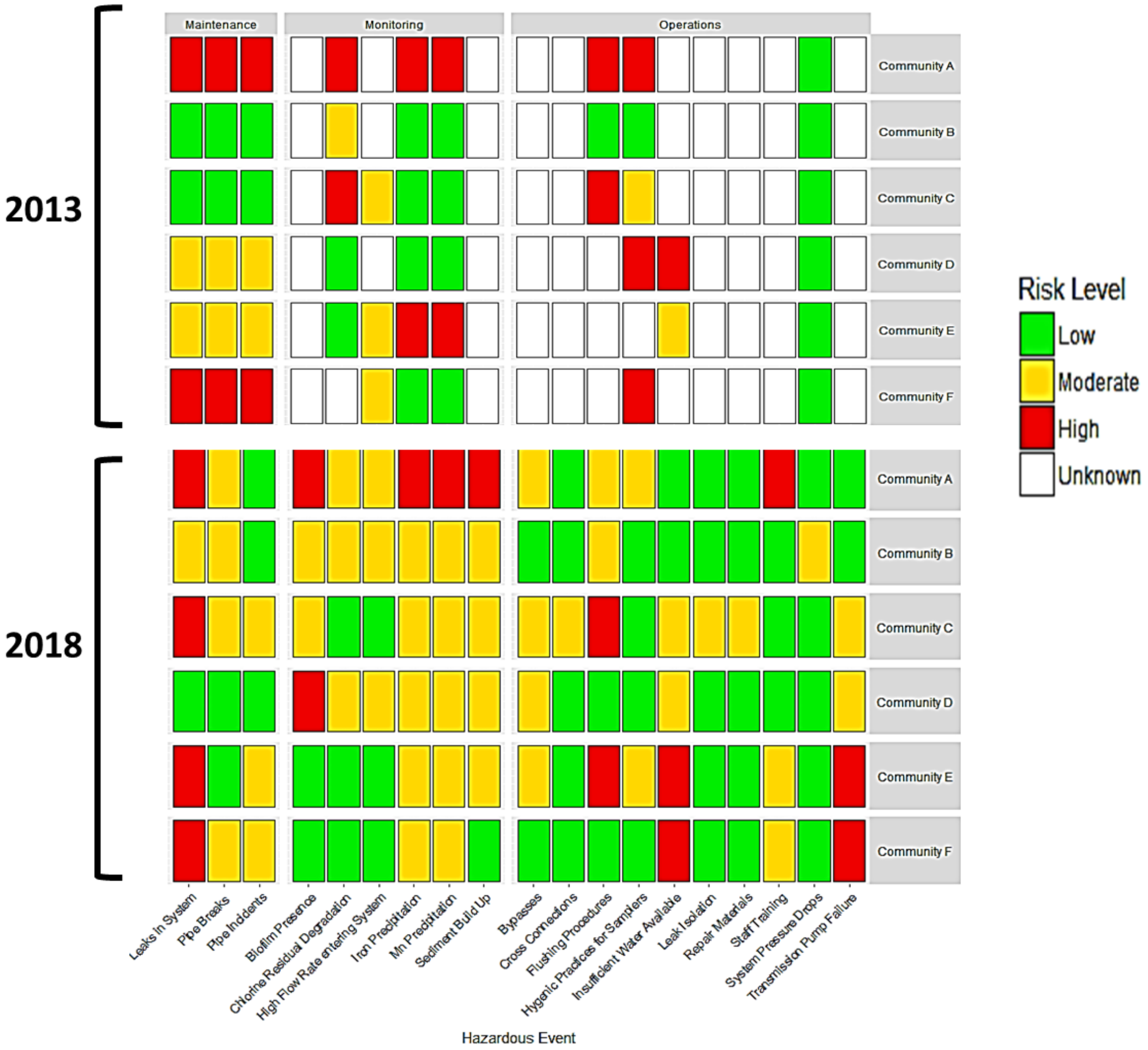


Figure 6.4: For the distribution system operations survey, the results from each hazardous event are shown separated by category and water system to facilitate comparisons. Reading the figure vertically highlights issues common between systems while reading the figure horizontally highlights water system specific issues.

In 2013, there were eight distribution system hazardous events with an unknown risk level for all water systems: biofilm presence, sediment accumulation, bypass procedures, cross connection management, leak isolation procedures, staff training and/or certification and transmission pump failures (from the treatment facility to the distribution system). Operational hazards constitute 75% of these unknown hazardous events, in comparison to 25% from the monitoring category. This is a clear example of how a WSP identifies concerns within a water system monitoring regulations and system assessments cannot. Furthermore, the water safety plan focuses on operational concerns, which are not easy to evaluate through monitoring and water system records in a system assessment. The WSP tool can therefore be used to improve the system assessment by focusing on specific issues of importance not only related to water quality monitoring. Furthermore, Figure 6.4 indicates maintenance of the distribution system is also a concern in most systems except Community D in 2018. Additionally, there are system specific operational issues identified by Figure 6.4. For example, only Community A indicated there were concerns about staff training and only Community C and E expressed concerns about flushing procedures. These results give further credibility to the need for better policies and procedures to manage these issues.

While there are identifiable hazards for all water systems, in 2013 not all water systems had information about every hazard. Furthermore, the information about hazards was not accurate (compared to 2018) and system assessment reports underestimated or overestimated risk. Table 6.1 shows the percentage of hazards that were "known" in 2013 for both the chlorination and distribution system WSP assessments. There are 22 potential hazards for chlorination and 19 for the distribution system. As an example, the Community A 2013 system assessment report only accounts for 12 of 22 hazards (55%), most related to meeting regulatory guidelines set by Health Canada (Health Canada, 2018), an observation in all six water system assessments.

Table 6.1: The percent of hazards "known" in 2013 was 40% for chlorination and 48% for the distribution system on average. While the system assessments performed in 2013 contained a wealth of information about water quality monitoring, the assessments did not provide information for more than half of the hazards included in the water safety plan.

Community	% of known hazards in 2013	
	Chlorination	Distribution System
A	55	53
B	32	47
C	32	53
D	45	47
E	45	47
F	32	42

Across the six systems, only 40% of hazards were considered "known" in 2013 on average. Community A had the highest percentage of "known" hazards at 55%, while Communities B, C and F have the lowest percentage (32%), corresponding to 7 of 22 "known" hazards. In Community A, there are no "known" hazards that fall into the low-risk category, indicating that more hazards in this water system are "known" because there are more identified water quality issues or operational challenges. For the distribution system WSP assessments, only 48% of hazards are considered "known" on average.

6.4.1 WSP Review and Feedback

In general, operators viewed the WSP tool as an added benefit for their water supply system operational and the monitoring procedures. For the WSP to be more effective in these six First Nations communities, the following suggestions were summarized to help tailor the WSP process to water system conditions and to revise the current survey format.

First, operators expressed a desire for a risk score output from each module and for the water system overall. Currently, results are presented as a break-down of each possible hazardous event that could occur within a module (treatment process, distribution system, etc.). However, operators indicated that an overall risk score would improve his or her ability to communicate these results to chief and council or to community members who do not deal directly with the water system regularly. The idea of a gauge indicating the level of risk would be a welcome addition to the WSP results. In the future, this would also facilitate reporting to provincial, regional or federal authorities to fulfill yearly risk management requirements.

Results at the end of the water safety plan module are presented as a table containing general suggested activities a water system can perform to help improve water safety and security. Operators suggested a section with recommendations to lower the risk level would be a welcome addition to the WSP output. Recommendations need to specifically detail how to achieve a low-risk level in a module of the water system for a hazardous event identified as moderate or high risk. Operators expressed a desire to also include comments in the detailed risk report to provide to context for chief and council for a better understanding why hazardous events are ranked as high or moderate level risk. This would provide better quality results presented as a detailed table summary and qualifying rational for each assigned risk level, especially when communicating WSP results to external stakeholders.

Operators indicated having hazards broken down into maintenance, monitoring or operational events was a useful way to view the results from the WSP. This allows an operator to quickly identify which sections of his or her water system need immediate attention, and which are situations do not need immediate intervention. For example, in Community E, maintenance issues in the chlorine disinfection systems are higher priority than monitoring or operations activities. Additional categories besides the three chosen for this study can also be addressed if necessary.

When completing the WSP modules, the project team actively tried to include both the water monitor and operator present at water system visits. However, it was noted that the water monitor cannot answer many of the operational questions posed in the treatment surveys and can best answer questions regarding sampling in the distribution system. Specifically, in the case of the MTA community, it was noted a monitor does not have as much interaction with the water operator on a daily or weekly basis, whereas in some water systems, the operator and the water monitor are the same person. This led to the suggestion of a new module specifically for water monitors, to better reflect his or her specific knowledge of the distribution system. Instead of asking about manganese and iron presence in the distribution system, the water monitor would be asked to check taps for red or black staining during regular sampling, to determine if there are any indicators of manganese and iron presence. This distinction is critical to engage all stakeholders in the WSP process.

Finally, one community voiced concerns about liability concerning the stakeholder actively completing the WSP modules. Many WSP module questions ask about staff *training*, but do not address staff *certification*. In some communities, there is a primary operator and a secondary operator, both of which have years of experience operating and maintaining the system but are not certified by provincial guidelines or other relevant protocols. In this case, the operators were concerned about who in the water system would bear the responsibility and liability for completing the WSP and communicating the results. This question needs to be addressed in future WSP studies if water safety planning is to become an integral tool for managing water systems in First Nations.

6.5 Discussion

6.5.1 WSPs increase communication between water system stakeholders

One of the key benefits of the WSP in First Nations water systems is the ability of the WSP to communicate information about risk in the water system to multitude of stakeholders interacting with the system. Communication improvements from WSPs have been seen previously in case studies globally (WHO & IWA, 2017, Byleveld et.al., 2008, Hasan et.al., 2011, Kot et.al., 2015, Gunnarsdottir et.al., 2012, Loret et.al., 2016, Tsoukalas and Tsitsifli, 2018). Water system stakeholders include treatment facility operators, water quality samplers (monitors), chief and council, environmental health officers, Health Canada, Indigenous Services Canada, First Nations Health and Inuit Branch and other related agencies such as the Atlantic Policy Congress. Often these stakeholders are working to improve community water systems but are not working in tandem or have different improvement policies, leading to a noticeable disconnect in the priorities from a water system (McCullough and Farahbaksh, 2012, Castleden et.al., 2017, Bradford et.al., 2017, Dunn et.al., 2017). The WSP is designed to help prioritize high-risk hazardous events, and operators and monitors viewed the WSP as an opportunity to communicate concerns to other stakeholders. The WSP method used in this study relied on operator expertise and risk results generated were able to highlight operational concerns in the water system. Operators and monitors found the method valuable to communicate risk because it provides evidence to chief and council. For example, infrastructure improvements or other risk mitigation activities that operators already promote are not funded due to competing projects in a community. Communication amongst stakeholders, particularly governance agencies, has been identified as a critical component of successful WSP implementation (Hasan et.al., 2011, Loret et.al., 2016, Amjad et.al., 2016, Perrier et.al., 2014), particularly important when adapting new methodologies to Indigenous communities (Castleden et.al., 2017, Bradford et.al., 2017).

Using the WSP as a communication tool was particularly valuable for the MTA water system where the operator and monitor are different people and the water facility is operated by a municipality, not the First Nation band. The operator and the monitor actively communicate water quality results, but the monitor is not involved in the treatment or distribution of water, only sampling for water quality parameters at the endpoint of the system. The WSP method provides another way to encourage communication between operators and monitors about the hazardous events present across the entire water system. Until this study, the monitor in this community had not considered the other components of the water supply system outside of designated sampling locations. The WSP helped to provide a more holistic view of the system and opened new conversations about sampling location appropriateness.

The WSP provides not only a tool to communicate amongst stakeholders but to communicate risk visually and accurately. Several of the comments made by operators pertained to how risk is presented after the hazard identification process. Conversations with EHOs and government agencies echoed this sentiment, emphasizing a metric available to compare results across systems. Initially, results were presented to stakeholders as a detailed table, specifying hazardous events, likelihood, consequence, risk scores, identified issues and suggested risk mitigation activities. However, operators suggested using different visualizations to better communicate risks to other stakeholders in the water system (specifically chief and council). An overall risk score for the system, gauges color-coded by risk level, bar charts, pie charts and interactive graphics were all suggested and have been incorporated into the WSP method for future studies. The necessity of WSP result visualization was initially acknowledged in Chapter Five of this thesis; other studies have also remarked on the necessity of providing comprehensible representations of risk to stakeholders (Kunreuther et.al., 2001, Kolodzieg et.al., 2017).

The desire for increased utility and interaction with the WSP method study highlights to a larger theme observed in these six systems. While concerns about how the WSP method fits into current water quality guidelines did arise, the predominant comments about the WSP method were focused on improving the results generated from the tool. Better results allow operators and monitors to leverage risk mitigation and infrastructure improvements in the water system. Instead of focusing on meeting water quality guidelines with the WSP, comments from operators and monitors emphasized the need to evaluate how the results from a WSP are analyzed and presented to stakeholders effectively. Manuals and research on WSP development has largely focused on proper hazard identification, benefits of water safety planning and enabling environments for successful WSP implementation (Byleveld et.al., 2008, Gunnarsdottir et.al., 2015, Kot et.al., 2015, Omar et.al., 2017, Perrier et.al., 2014). This study demonstrates that more effort needs to be placed on accurate communication of risks to all stakeholders and graphical visualizations instead of tables and reports are one method available.

6.5.2 WSPs in a First Nation context

A study of the Alberta drinking water safety plan implementation highlighted the importance of ensuring a WSP does not become a “top-down” or bureaucratic tool water systems are mandated to complete (Perrier et.la., 2014). In First Nation water systems, this idea is particularly important. A study in 2017 considered how governance and water policy particularly impact First Nations water systems (Bradford et.al., 2017). Bradford’s study demonstrated the importance of using methodologies that promote “power with” dynamics between water systems and external stakeholders, instead of the traditional “power over” dynamic (Bradford et.al., 2017). This sentiment is echoed by Castleden et.al., 2017, and explains how traditional mindsets surrounding water safety lead to the development of singular technical solutions for problems that are multi-faceted (Castleden et.al., 2017). In the context of this study, a WSP is a non-technical solution designed to look at a water system holistically (Bartram et.al., 2009, WHO, 2012) and aligns more closely with Indigenous perceptions of water systems (Castleden et.al., 2017). Black and McBean previously proposed the modification of the WSP approach to a First Nations Sustainability and Security Strategy (Black and McBean, 2017). This study provides a series of initial observations surrounding WSP implementation in First Nation water systems, and there is a defined need to expand future studies to account for Indigenous viewpoints and appropriate implementation strategies (Castleden et.al., 2017).

The water governance regime in Canada currently does not account for Indigenous perspectives. Several WSP studies point to the importance of strong supporting institutions and stakeholders, such as federal governments, to support successful WSP implementation (Kot et.al., 2017, Gunnarsdottir et.al., 2012, Amjad et.al., 2016, Baum and Bartram, 2017). However, in Canada the water policy landscape is fragmented and hierarchical, a system which historically, has not suited most Indigenous water systems (De Loe, 2017, Bradford et.al., 2017). In addition, due to remoteness and small system size, Indigenous systems have lacked a voice and had little opportunity to participate in water policy discussions at a national level (Bradford et.al., 2017, Norman and Bakker, 2017). Considering the wealth of concrete evidence that water related issues disproportionately impact First Nations, governance models need revision to better support First Nation communities (Castleden et.al., 2017). In the context of WSPs, this translates to a need for more supporting institutions at a nation-level or regional level for First Nation water systems. If WSPs were required federally, the WSP approach risks becoming another top-down, bureaucratic tool, instead of a useful new management framework for the provision of safe water (Perrier et.al., 2014, Castleden et.al., 2017, Bradford et.al., 2017).

Concerns with water governance policies relate to how improvements are prioritized in First Nation communities. In 2017, there were twenty federal agencies operating under eleven legislative frameworks, each having separate but competing or overlapping mandates (Bradford et.al., 2017). This has historically led to duplications of efforts to improve water systems (Bradford et.al., 2017). Ultimately, there is competition for federal funding within communities, leading to suboptimal resource allocation for water systems. To compound this issue, chief and council are responsible for operation and maintenance costs (Bradford et.al., 2017). Given this evidence, the WSP has an advantage over current water governance regimes. A key output of the WSP is a complete evaluation of risks in a water system, prioritized by using the risk matrix to assign risk levels (Bartram et.al., 2009, WHO, 2012). The WSP effectively provides a prioritized set of improvements, focused on operations and maintenance (as shown in Chapter Four) for chief and council, informed by the water system stakeholders (operators, monitors, etc.) from the water system, not an external agency. The outputs of a WSP are system specific (WHO, 2012) which helps an individual water system to identify clear, pressing issues. This limits competition for funding within a community: a concise evaluation of the water system is available, supported by an internationally recognized methodology for water management.

Historically, technical solutions have been favored for multi-faceted problems encountered when providing safe water to consumers. Research shows this has resulted in heavy reliance on Western methods to solve problems in Indigenous water systems (Castleden et.al., 2017). For example, traditional Indigenous knowledge supports the use of slow sand filters and UV disinfection, as these treatment processes mimic natural processes (Mohseni et.al., 2017). However, the proven effectiveness and ubiquity of chlorine disinfection has led to the installation of chlorine disinfection units in First Nation water systems, a solution that does not account for cultural appropriateness (Mohseni et.al., 2017). These studies highlight the need to move towards management and policy solutions for First Nation water systems, as opposed to strictly technical solutions. Emphasis needs to be placed on water systems management and operation in order to holistically address the concerns identified by this study.

With current emphasis placed on removing long-term boil water advisories in First Nation communities across Canada (Health Canada, 2018), the water safety plan provides a strategy that is management-based and proactive. Studies of drinking water advisories, particularly in First Nations have identified operational concerns as the leading cause of precautionary DWA issuance (Thompson et.al., 2017, Post et.al., 2018, Black and McBean, 2018). The water safety plan examined in this study provides a tool focused on prioritization of risk mitigation procedures including operational hazardous events, instead of focusing only on water quality monitoring programs (WHO, 2012, Chapter Four). Recent literature related to Indigenous water system concerns advocates for changes in water policy governance and water system management in these water systems; current approaches are not considered culturally appropriate (Castleden et.al., 2017, Bradford et.al., 2017, Dunn et.al., 2017). As shown in Chapter Two, the drinking water advisory lacks the sophistication to communicate information about risk in a water system and the water safety plan is a method acknowledged globally for its capacity to provide safe water to systems (WHO & IWA, 2017). To remove long-term drinking water advisories in First Nation communities, new approaches such as the water safety plan should become a focus in future water management practices.

6.6 Conclusions

The purpose of this study was to review the appropriateness of the WSP approach in First Nations water systems in comparison to current system assessment methodologies. The results demonstrated revisions are needed to the current WSP structure to more accurately gather information about risk from these water systems. In order for a water safety plan to be considered a useful tool in a First Nations context, the WSP needs to produce meaningful results that are communicated effectively to the different stakeholders in the water system. The ability to accurately and easily communicate information about risk to chief and council, environmental health officers and other government agencies was considered the most important improvement needed to sustain WSPs long-term. Previous system assessment reports for these water systems did not account for water system operator knowledge; the WSP provides a more cohesive and thorough analysis of risk. Additionally, several of the risks identified in system assessment reports under- or over-estimate the risk level of each hazardous event in a water system, in part because water system operator expertise was not a focal point of these assessments. The WSP tool increased the water system knowledge and revealed similar issues across water systems regionally. The WSP method provides a stronger risk management tool for First Nations water systems than current regulatory guidelines and protocols and continued research is needed to optimize adoption and successful implementation.

7 Chapter Seven – Comparing quantitative probability of occurrence to the risk matrix approach: a case study of water quality data

7.1 Abstract

Implementation of water safety planning methods globally has focused primarily on developing an evidence base to demonstrate the benefits of this methodology for risk management in water systems. However, little work has been completed to understand the appropriateness of the risk matrix method used to capture levels of risk for identified hazardous events. This study examines two possible quantitative risk calculations (probability density functions and event trees) compared to the risk matrix method to understand if the risk matrix method provides an accurate estimation of risk in a water system. Two data sets were collected from nine water supply systems, both SCADA data (continuous inline monitoring) and grab samples collected in water distribution systems (discrete events) for chlorine residual data. Using both data sets and quantitative risk calculations, the risk matrix does not accurately evaluate risk compared to risk calculated using water quality data from a water system. Thirty-four (77%) of the forty-four possible scenarios investigated were inaccurate, with the water safety plan method providing an underestimation or overestimation of the actual risk observed using water quality data. The highest accuracy was obtained using SCADA data and the event tree method, indicating larger data sets, with simpler methods provide the best estimation of risk compared to the risk matrix. The lack of accuracy obtained reveals the need for a reevaluation of the risk matrix within a water safety plan (WSP), particularly for systems that have data available to perform advanced risk analysis. The risk matrix method has been used historically for systems with little data; however, for water systems with advanced water quality monitoring, adding quantitative risk calculations to a water safety plan provides a stronger incentive to adopt the WSP method. Quantitative risk analysis utilizes current data collection methods, adds sophistication and is able to handle the broad range of probabilities that are observed in different water systems.

7.2 Introduction

Since 2004, the water safety plan (WSP) approach to managing and assessing risk in water supply systems has been promoted by the World Health Organization (WHO) (Bartram et. al., 2009, WHO, 2012, WHO, 2016). The WSP Manual developed to guide the implementation and creation of WSPs promotes the use of a risk matrix approach to evaluate the risk level associated with an identified hazard in a water system (Bartram et. al., 2009). A risk matrix is a tool used to qualitatively understand risk, using a scoring regime to determine whether a risk is “low”, “moderate”, or “high” risk. A risk matrix calculates risk by multiplying a “likelihood” score by a “consequence” or “severity” score to obtain a risk score. The risk score is then used to specify which score are considered low, moderate or high risk (Bartram et.al., 2009, WHO, 2012).

While a risk matrix has been shown to work well in situations where data is scarce or unavailable (Cox Jr., 2008, Bartram et.al., 2009, WHO, 2012), there are drawbacks to risk calculation. A risk matrix approach is subjective to the person utilizing the matrix: descriptions of likelihood and consequence levels vary not only between different industries, but within different jurisdictions (WHO, 2012, Bartram et. al., 2009, Hokstad et. al., 2009, AusAID and SOPAC, 2010, Thompson and Majam, 2009, The Environmental Protection Agency [EPA]: Office of Environmental Enforcement, 2011). As an example, “unlikely” can be defined as once in a year (Bartram et.al., 2009, Hokstad et. al., 2009, Thompson and Majam, 2009) but is also defined as occurring with a frequency of less than one incident monthly in other jurisdictions where an incident refers to a data point falling outside the optimal operational parameters (AusAID and SOPAC, 2010, The Environmental Protection Agency [EPA]: Office of Environmental Enforcement, 2011, AESRD, 2011).

Currently, the WHO promotes 3 different forms of risk assessment for water supply systems: a sanitary inspection, a risk matrix approach and a quantitative microbial risk assessment (QMRA) (WHO, 2016). The data inputs for these methods increase in complexity from sanitary surveys to QMRAs. As previously discussed, the risk matrix approach is considered semi-quantitative by the WHO (WHO, 2012) and considered qualitative for the purpose of this study. The QMRA approach was therefore a logical starting point to determine which types of quantitative data are used in currently available risk assessment tools. A review of the WHO guidance documentation of QMRA methods (WHO, 2016) revealed that while a quantitative model is used to determine the risk of infection by or presence of micro-organisms in a water system, there is little emphasis placed on other water quality parameters collected in a system (such as chlorine residual, temperature, pH and turbidity). These parameters are easier to collect than microbial parameters due to the wealth of field equipment available, proven laboratory methods and the ease with which a large sample size can be taken (WHO, 2016). Microbial data needed for a QMRA is very specific and a large volume is needed to complete a full scale QMRA (Howard et.al., 2006, Smeets et.al., 2010, WHO, 2016). In the small systems included in this study, this approach is impractical.

Quantitative calculations using water quality parameters such as chlorine provide a potential bridge between the risk matrix method and a QMRA approach. In the context of WSPs, the ability to accurately compare a traditionally used qualitative risk matrix to a quantitative risk calculation is important to the evolution of WSP practices as water systems using the WSP approach gather and analyze more data. Quantitative calculations are often unattainable or unreliable in a system with data sets that are sparse, with sampling programs based on regulatory guidelines (WHO, 2012, WHO, 2016); therefore, a qualitative risk matrix allows all systems to characterize risk. Qualitative risk also describes more types of hazardous situations related to maintenance and operations that quantitative calculations cannot capture (WHO, 2012, Bartram et.al., 2009). It is therefore important to recognize that quantitative calculations are not meant as a replacement of the risk matrix approach, but an addendum. In high-income countries, or advanced water supply systems, monitoring systems that generate a high volume of data are already in place and stronger incentives to adopt a WSP are needed (Summerill et.al. 2010, Amjad et.al., 2016, Baum et.al., 2015, Baum and Bartram, 2017). The purpose of the comparisons and calculation methods presented in this study are to provide stakeholders in these systems with a meaningful metric for risk based on currently collected data.

A review of several possible risk analysis techniques was completed in 2009 by TECHNEAU, detailing possible applications of risk analysis using water quality data, from simple to complex (Hokstad et. al., 2009). However, little evidence or literature exists suggesting these methods have been tested in countries where WSPs are established or where case studies are being completed. Medema and Smeets, 2009, demonstrated that there are different applications for quantitative water quality data in a WSP, but largely focused on microbial data and the QMRA approach. In their study, turbidity, temperature and chlorine data were used to augment microbial data, but the probability of being outside an optimal operating range was not calculated, nor were statistical tests used to quantify risk (Medema and Smeets, 2009).

The objective of this study is to explore how traditional calculations (such as probability density functions, event trees, etc.) of quantitative probability of failure can be compared to the results of the risk matrix method. Risk matrices are recommended for systems that do not have a large volume of water quality data; however, the water systems used in this study do have sufficient data to justify quantitative calculations of probability. This study will compare quantitative probabilities calculated by using probability density functions and event trees to a probability obtained using definitions of probability in the risk matrix method. The goal is to understand whether the risk matrix method is over or underestimating the likelihood of a hazardous event compared to water quality. Based on this analysis, recommendations will be made for the use of probability calculations in water safety plans and in water systems that have similar data availability.

7.3 Methods

7.3.1 Determining Risk Matrix Probabilities for Comparison

To translate the risk matrix scores to probabilities, the descriptions of likelihood and consequence scores were evaluated. The majority of WSPs are designed such that the likelihood is the probability of occurrence. Each likelihood level is described as 1 event in a month, or 1 event in a year, etc. Using these descriptions, it was possible to obtain a probability for each likelihood description. Consequence was not considered; this study is focused on understanding the comparability of probabilities. There are several ways to quantify consequence or impact but choosing a specific method here for comparability is beyond the scope of this study. Likelihood descriptions from eight jurisdictions and case studies (Bartram et. al., 2009, Hokstad et. al., 2009, The Environmental Protection Agency [EPA]: Office of Environmental Enforcement, 2011, Gunnarsdottir et.al. 2012, AESRD, 2011, AusAID and SOPAC, 2010, Hokstad et.al., 2009, Thompson and Majam, 2009) were considered and compared to choose a range of probabilities for each likelihood level. Likelihood scores were then extracted and translated to probabilities from available WSP results from nine water systems (from Chapter 5 and 6 of this thesis). These probabilities are presented in Table 7.1.

Table 7.1: Using descriptions of likelihood from WSP case studies, the probabilities presented in the calculated probability column were chosen for use in this study. One occurrence here represents one day where an adverse water quality result was reported. This enabled comparisons between the risk matrix method and the probability calculations explored in this study. Based on likelihood descriptions, and calculated probabilities, each possible risk score from a risk matrix was assigned a probability for comparison to the quantitative probabilities of occurrence used in this study.

Qualitative Risk Description	Qualitative Probability	Calculated Probability	Risk Matrix Score
Never	1 occurrence per 100 years	2.7 E-5	1
Extremely Rare	1 occurrence per 50 years	5.4 E-5	2
Very Rare	1 occurrence per 10 years	2.7 E-4	3
Rare	1 occurrence per 5 years	5.4 E-4	4
Unlikely	1 occurrence per year	2.7 E-3	5
Equally likely as unlikely	1 occurrence per six month	5.4 E-3	6
Likely	1 occurrence per month	0.0323	7
Moderately Likely	1 occurrence per week	0.143	8
Almost Certain	1 occurrence per day	1.0	9

7.3.2 Quantitative Probability Calculations

Probability density functions (PDFs) and a simple event tree calculations were selected as two important risk calculations to consider for comparison to the risk matrix. The PDF calculation was chosen for its ability to work with different types of data sets and is a proven method for finding probabilities of occurrence based on different cut-off criteria (McBean, 2019d). Since water quality data available was always a positive number, non-negative distributions were fit to the data. Four distributions were considered: lognormal, exponential, Weibull and gamma. After initial review of the data, the exponential option was removed as visually (using probability-probability plots and empirical cumulative distribution functions) it was not a good fit for the data and would not provide accurate calculations of probability. Data was initially reviewed using a probability-probability plot to determine visually which distribution best fit the data. Several “goodness of fit” tests were considered and the Akaike information criterion (AIC) was selected as it compares the relative fit of a distribution to the other selected possibilities. The Anderson-Darling test and the Chi-Squared test were also used to conduct best fit tests and the results were similar to the AIC test.

The event tree calculation was developed using ideas from TECHNEAU (Hokstad et. al., 2009) which combined fault trees and event trees to describe the overall risk in a system. Event trees were constructed for chlorine residual and used critical control points to determine if a data set contained key features. For example, according to the Guidelines for Canadian Drinking Water Quality (GCDWQ) (Health Canada, 2017), chlorine residual must have a minimum value of 0.2 mg/L to provide adequate disinfection. Data sets were partitioned to determine not only if samples failed to meet this minimum, but if enough samples were consistently taken. This allowed comparisons of hazardous events in relation to both regulatory compliance and to sampling frequency. The event tree is a visual method of separating types of samples and finding the probability of each critical control point by dividing by the total (sample probability) (Hokstad et.al., 2009). The chlorine residual event tree is shown in Figure 7.1. In this situation “low chlorine” is considered the hazardous event, providing an indicator of inadequate disinfection. The 0.4 mg/L threshold was chosen as a “near miss” situation to determine how many samples were close to being below the 0.2 mg/L threshold but were not yet considered low chlorine. Probabilities are calculated at each node (for example, “Sample Taken”, “Adequate Chlorine”) by dividing the total number of samples meeting the criteria by the total number of samples.

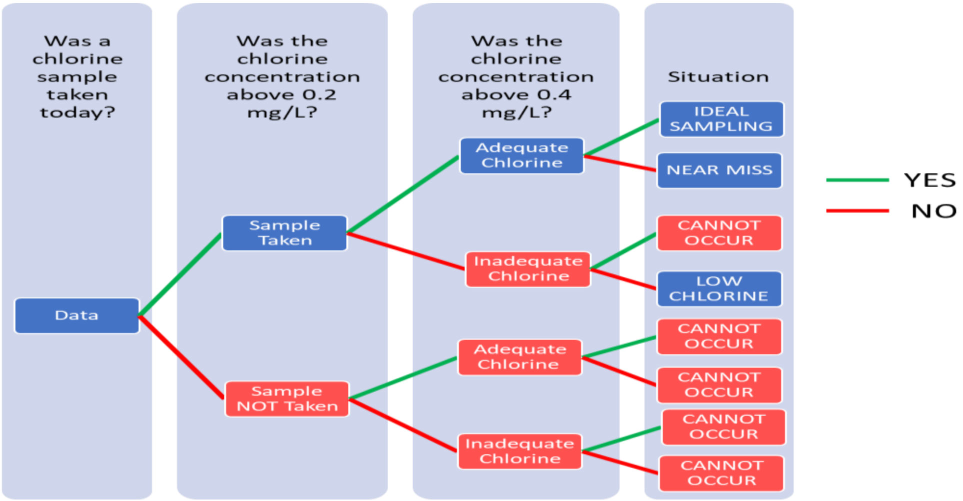


Figure 7.1: The event tree for chlorine residual examines three factors: if a sample was taken on a given day, whether the sample was above 0.2 mg/L and if the sample was above 0.4 mg/L. The 0.2 mg/L threshold represents low chlorine as defined by national regulations. The 0.4 mg/L threshold was chosen as a “near miss” situation to determine how many samples were close to being below the 0.2 mg/L threshold but were not yet considered low chlorine. There are three final situations where samples can feasible fall in the event

tree: ideal sampling, near miss and low chlorine. The probability of low chlorine was used to compare to the risk matrix method.

7.3.3 Data Collection and Analysis

With risk methods chosen, two different types of data were requested from the water systems involved in this study: supervisory control and data acquisition (SCADA) data (representing a large sample size with consistent sampling frequency for a given parameter) and grab sampling data (samples collected periodically although not always consistently and in a smaller volume). The water system characteristics are shown in Table 7.2. Municipal systems from Chapter Five were used to calculate risk matrix probabilities used for comparison in this study. First Nation systems from Chapter Six were also included, however, only Community A and Community C provided sufficient data to facilitate calculations. The risk score for each hazardous event was translated to a probability of occurrence using Table 7.1 The data was then processed using the event tree calculation for both grab samples and SCADA to determine if there was a difference in the effectiveness of this method based on data type. PDFs were fitted to both data types and a best fit test was applied. The results were then compared to the probabilities obtained using Table 7.1. Emphasis was placed on chlorine residual data using both the probability density function and event tree methods. Chlorine residual was chosen as a chlorination hazardous events are relatively well understood, and chlorine residual data is required by water quality guidelines (Health Canada, 2017).

Not every water system had complete data sets available to make accurate estimations of qualitative versus quantitative risk. In the case where an asterisk is located after the estimation in the following tables, this result was estimated using assumptions of probability of risk based on Table 7.1. If water safety plan risk matrix results were not available (as seen in Municipal G, Table 6.6), risk was assumed to be moderate risk and a probability of 0.03225% was used as the risk matrix qualitative probability. In the case of SCADA data missing from a water system, the probability of quantitative failure was assumed to be one in one thousand events or 0.1 % for both the probability density function and event tree methods. If grab samples were missing, 0.1% probability of failure was assumed for the probability density function and 1.0% was assumed for the event tree method. Since the probability density function more often identifies the probability of failure as a relatively small percentage, these numbers were chosen to avoid underestimating risk in cases where data was unavailable.

Table 7.2: The water systems included in this study included seven municipal systems and two First Nation systems. All of the systems serve less than 5000 customers with the exception of Municipal G, which is classified as a "large" system. Five of the systems have ground water wells as the source water, while the remaining four draw water from surface water sources.

System	Source Type	Community Type	Size of System
Municipal A	Surface Water	Municipal	Small
Municipal B	Surface Water	Municipal	Small
Municipal C	Ground Water	Municipal	Small
Municipal D	Ground Water	Municipal	Small
Municipal E	Surface Water	Municipal	Small
Municipal F	Ground Water	Municipal	Small
Municipal G	Surface Water	Municipal	Large
Community A	Ground Water	Indigenous	Small
Community C	Ground Water	Indigenous	Small

7.4 Results

7.4.1 Probability Density Functions

Data from the nine different water systems had sample sizes ranging from 107 samples in one year to over eight million samples taken in one year from SCADA data (continuous sampling, larger data sets). In Community A and C, there was no automated data collection system and written daily logbook data was substituted for SCADA data. For the probability density function method, the Akaike information criteria (AIC) revealed the relative best fit for seven of the nine systems was the gamma distribution. The second-best fit distribution was also considered for the larger data sets and the lognormal distribution provides the second-best fit in five of the nine communities. The only system that did not have the gamma distribution as the best or second-best fit was Municipal System D, which had the largest data set at over eight million data points. Similar results were observed for grab sample data using probability density functions: gamma provides the most accurate estimation most of the time. PDF results for SCADA data are presented in Table 7.3; results from grab samples are provided in Appendix F.

Table 7.3: For nine different communities, the best fit and second-best fit probability density function are presented for chlorine residual water quality data.

Treatment Facility	Number of Samples	Best Fit Distribution	2nd Best Fit Distribution
Municipal A	30807	Gamma	Weibull
Municipal B	30822	Gamma	Weibull
Municipal C	30825	Gamma	Lognormal
Municipal D	8264367	Lognormal	Weibull
Municipal E	3980646	Gamma	Lognormal
Municipal F	5423040	Gamma	Lognormal
Municipal G	44582	Gamma	Lognormal
Community A	376	Weibull	Gamma
Community C	107	Gamma	Lognormal

Using the best fit distribution for each individual water system, the probability of failure was calculated by specifying a probability that a chlorine residual sample was less than 0.2 mg/L (in accordance with the Health Canada guidelines for chlorine disinfection). For the majority of systems, the calculated probability of failure was relatively small (less than 10^{-5} %). Table 7.4 shows the probabilities obtained using the best fit probability density function, with the SCADA data set. Due to the presence of several low risk hazardous events, the majority of systems had a qualitative probability (from the risk matrix conversion using Table 7.1) in the range of 0.0548-0.00273%. Table 7.4 shows qualitative probability (from the WSP risk matrix method) in comparison to quantitative probability (from the PDF) as percentages. The final column in Table 7.4 indicates whether the qualitative estimation is an overestimation, underestimation or accurate estimation based on the quantitative probability calculated using the PDF method. Overestimation represents a situation where the risk matrix probability is larger than the calculated probability, underestimation occurs in a situation where the risk matrix probability is smaller than the calculated probability and accurate estimation occurs when the calculated probabilities fall in the range specified by the risk matrix. For the purpose of this study, the water quality data is considered accurate compared to the risk matrix. Results for the grab samples are presented in Appendix F.

Table 7.4: Using the probability density function method and continuous water quality data (from SCADA systems), the qualitative probability achieved from a WSP is compared to the quantitative probability of occurrence (chlorine residual less than 0.2 mg/L). The qualitative estimation shows how the WSP method compares (underestimation, overestimation or accurate estimation) to the actual water quality data.

Treatment Facility	Qualitative Level	Qualitative % (WSP)	Quantitative % (Data)	Qualitative Estimation ?
Municipal A	Low	0.0548 – 2.7 E -3 %	1.167 E – 5 %	Over
Municipal B	Low	0.0548 – 2.7 E -3 %	2.618 E -16 %	Over
Municipal C	Low	0.0548 – 2.7 E -3 %	4.35 E-25 %	Over
Municipal D	Low	0.0548 – 2.7 E -3 %	1.18 E – 11 %	Over
Municipal E	Low	0.0548 – 2.7 E -3 %	6.23 E- 34 %	Over
Municipal F	Low	0.0548 – 2.7 E -3 %	2.11 E- 92 %	Over
Municipal G*	Moderate*	3.23 – 0.275%	0.01 %*	Over
Community A	Low	0.0548 – 2.7 E -3 %	4.8001 %	Under
	Moderate	3.23 – 0.275 %	4.8001 %	Accurate
Community C	Low	0.0548 – 2.7 E -3 %	3.452 E -5 %	Over
	Low	0.0548 – 2.7 E -3 %	3.452 E -5 %	Over

Table 7.4 establishes the risk matrix method most often overestimates the probability of occurrence of low chlorine (< 0.2 mg/L); the probability calculated with a risk matrix is greater than the PDF method in 9 of 11 situations (82 %). Community A and Community C both have two possible hazardous events for chlorine, one for the chlorine residual in the distribution system and one for the chlorine residual in storage in a treatment facility. Community A is the only system where the risk matrix underestimates or accurately predicts the quantitative probability of occurrence. These results indicate that the probability of occurrence of low chlorine residual is small in practice when compared to a risk matrix evaluation (which is based on operator expertise but limited by the design of the risk matrix) where SCADA data is analyzed.

For grab samples, a similar trend exists for probability density function calculations although less overestimation occurs. Overestimation occurs in six of eleven cases, underestimation occurs in four cases and there is one case where there was an accurate estimation of risk. The case where the PDF method with grab samples matched the risk matrix probability was the case where the risk level was identified as moderate in Community A. Without additional water systems to evaluate, it is difficult to determine if this is unique to Community A or if hazards identified as moderate or high-level risk may be more accurately represented in water quality data.

7.4.2 Event Tree Method

Using event trees with the two data sets showed different results compared to the PDF calculation. Event tree probabilities were calculated by simply dividing the number of samples matching the given criteria were divided by the total number of samples. First, where grab samples were evaluated with the event tree method, there was more underestimation and accurate estimation than observed when using the PDF calculation; in fact, the risk matrix method does not overestimate the probability of occurrence with grab samples in the event tree. Table 7.5 shows that for seven of eleven cases (64%), the risk matrix (qualitative estimation) was an underestimation of the risk observed using the event tree to calculate probability and was accurate in the remaining four cases. This is markedly different than the PDF method, which generally overestimated the actual risk in a system as calculated from water quality data. Results for the event tree method with SCADA data are presented in Appendix F.

Table 7.5: Using the event tree method and discrete water quality data (from grab sampling), the qualitative probability achieved from a WSP is compared to the quantitative probability of occurrence (chlorine residual less than 0.2 mg/L). The qualitative estimation shows how the WSP method compares (underestimation, overestimation or accurate estimation) to the actual water quality data.

Treatment Facility	Qualitative Level	Qualitative % (WSP)	Quantitative % (Data)	Qualitative Estimation ?
Municipal A	Low	0.0548 – 2.7 E -3 %	1.1%	Under
Municipal B	Low	0.0548 – 2.7 E -3 %	3.8 %	Under
Municipal C	Low	0.0548 – 2.7 E -3 %	6.5%	Under
Municipal D	Low	0.0548 – 2.7 E -3 %	0.86 %	Accurate
Municipal E	Low	0.0548 – 2.7 E -3 %	1.15 %	Under
Municipal F	Low	0.0548 – 2.7 E -3 %	0.284 %	Accurate
Municipal G*	Moderate*	3.23 – 0.275 %	1.0 %*	Accurate
Community A	Low	0.0548 – 2.7 E -3 %	5.8%	Under
	Moderate	3.23 – 0.275 %	5.8 %	Accurate
Community C	Low	0.0548 – 2.7 E -3 %	4.9 %	Under
	Low	0.0548 – 2.7 E -3 %	4.9 %	Under

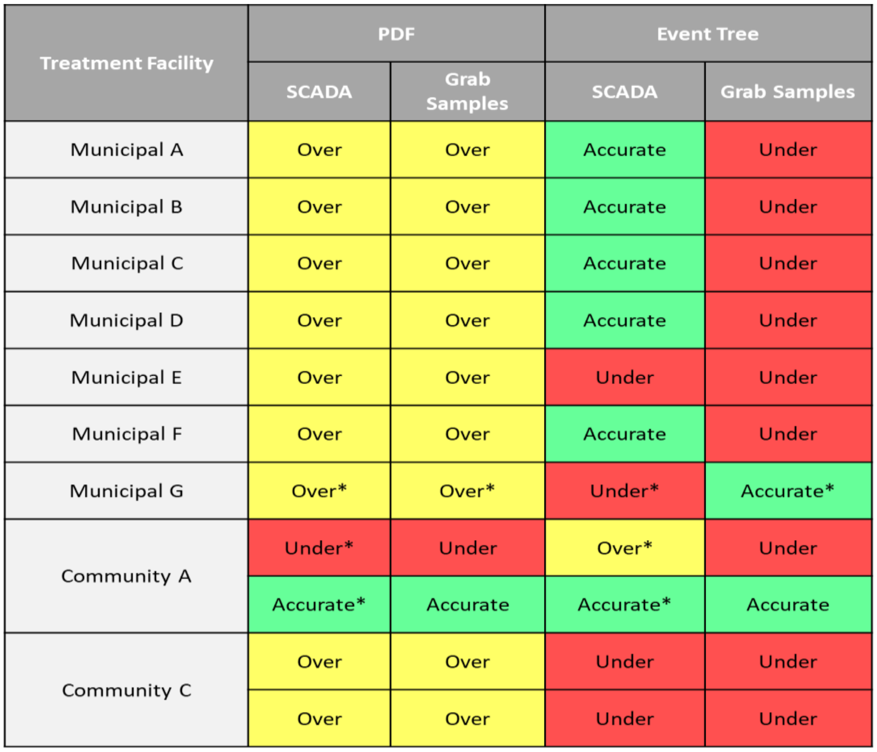
For the event tree method, more data available provided a more accurate estimation of the probability of occurrence. Six of the possible cases proved an accurate estimation of risk compared to the water quality data, only one case was an overestimation and the remaining cases were underestimations of risk. These results indicates that the risk matrix is most similar to the event tree method with a large data set.

7.4.3 Comparing Methodologies

Overall, Table 7.6 reveals that the event tree method using SCADA data most closely aligns with the risk matrix method. The event tree method with grab samples predominantly overestimates risk compared to the risk matrix as does the PDF method with grab samples. The risk matrix is an overestimation of risk in 9 of 11 cases compared to the PDF method using SCADA data. Table 7.6 therefore highlights the ideal risk calculation methodology in water systems similar to the systems studied is the event tree methodology used in concert with large data sets.

When comparing qualitatively obtained probabilities to those found from water quality data, there are few cases - ten cases out of 44 possible combinations (23%) of data size and probability of occurrence calculation - where the probabilities are of the same order of magnitude. The risk matrix method showed the most accuracy with the results from the event tree method with SCADA data, indicating that large data sets in a simpler probability calculation is a better way to estimate probability of occurrence. However, only seven water systems were involved in this analysis and more water system data sets are needed to confirm this conclusion.

Table 7.6: Using both the probability density function method and the event tree method, this table shows how the WSP method compares to each method. Two different data sets were used: continuous water quality data (SCADA systems) and discrete water quality data (grab samples). For example: for Municipal A, the WSP overestimates the probability of occurrence of low chlorine residual compared to the probability density function calculation completed with SCADA data. The asterisk represents a situation where an estimation was applied as described in the methods section due to an incomplete data set for a water system.



Treatment Facility	PDF		Event Tree	
	SCADA	Grab Samples	SCADA	Grab Samples
Municipal A	Over	Over	Accurate	Under
Municipal B	Over	Over	Accurate	Under
Municipal C	Over	Over	Accurate	Under
Municipal D	Over	Over	Accurate	Under
Municipal E	Over	Over	Under	Under
Municipal F	Over	Over	Accurate	Under
Municipal G	Over*	Over*	Under*	Accurate*
Community A	Under*	Under	Over*	Under
	Accurate*	Accurate	Accurate*	Accurate
Community C	Over	Over	Under	Under
	Over	Over	Under	Under

To better visualize these results, Figure 7.2 presents a probability-probability plot that compares the risk matrix qualitative probability to quantitative risk as calculated by either of the two methods described. The y=x line represents accuracy: a point on or relatively close to this line indicates that quantitative and qualitative probabilities are approximately the same. A point above this line represents an overestimation of risk since the qualitative risk (risk matrix) is greater than the quantitative risk (water quality data). A point below this line represents an underestimation of risk since the qualitative risk is less than the quantitative risk. The color of the point represents how far away from the y=x line a point is.

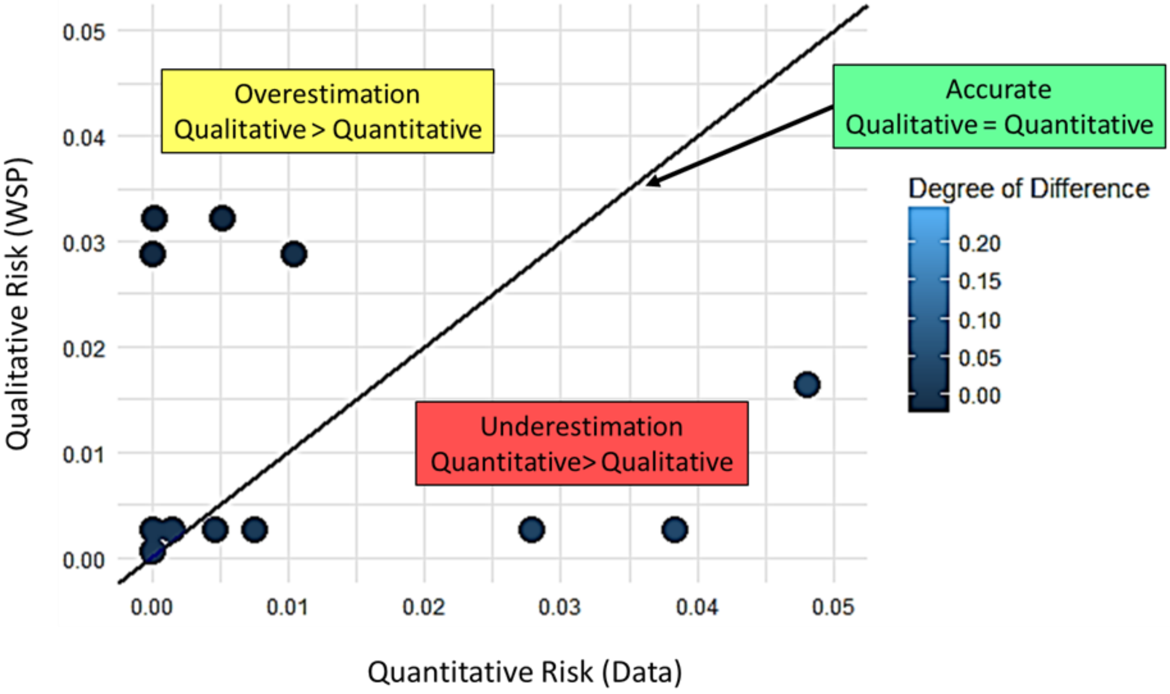


Figure 7.2: Using both risk calculation methods and both data sets available, this figure shows how accurate a WSP is at estimating probability of occurrence of a hazardous event. The y=x line represents when qualitative probabilities is equal to quantitative probabilities. Any point above the line represents an overestimation of probability by the qualitative prediction and any point below the line represents an underestimation of qualitative probability.

According to Figure 7.2, there are only four of cases where the risk obtained from the qualitative calculation is an accurate estimation of the quantitative risk in a system as calculated by using water quality data. There are 4 cases of overestimation and 4 cases of underestimation presented on this plot. This result demonstrates the risk matrix method is inaccurate and highly susceptible to stakeholder knowledge of a water system. There is no clear indication whether the risk matrix tends to overestimate or underestimate the risk obtained from a PDF or event tree as accuracy occurs at the same frequency as over or underestimation. Thus, the risk matrix method is highly variable, depending upon stakeholder interpretation of likelihood and consequence definitions. One stakeholder may interpret "unlikely" as an event that occurs once in a year, while another may interpret "unlikely" as once in ten years, leading to different resulting risk scores with the risk matrix method. The lack of consistency observed here suggests that changes need to be made to the risk matrix method. Additionally, quantitative calculations need to be considered as an addition to water safety planning to address this concern.

7.5 Discussion

7.5.1 Probability Calculation Comparisons

A key result from this comparison study revealed how often tends a risk matrix to underestimate risk in a water system compared to a probability density function. Most studies of small systems state more data collection is needed to make more accurate predictions of risk (Butterfield and Camper, 2004, Kot et.al., 2011, Schuster et.al., 2005). However, using SCADA data in a traditional method of determining probability of occurrence showed that this is not the case. The SCADA samples used in this study were taken every hour, which was chosen to decrease the serial dependency in the data set but still provide a sufficiently large data set to analyze. However, it is possible that there is still a large degree of serial dependency in the data set that could be impacting the fitted distribution mean, standard deviation and shape or scale (for gamma and Weibull distributions) (McBean, 2019e). The probabilities obtained with the probability density function method were less than 1% with the exception of Community A, signifying the risk matrix method was an overestimation in all but 2 scenarios for SCADA data.

In addition, use of a large data set (SCADA data) and the event tree method results in the highest risk matrix accuracy. This result is consistent with examination of risk assessment strategies for water system as performed by TECHNEAU in 2008 (Hokstad et.al., 2009). Simpler methods were found to be more appropriate for most water systems, particularly for small water systems without automated data collection (Hokstad et.al., 2009). However, the municipal systems in this study are all considered small systems by Nova Scotia regulations (Nova Scotia Environment, 2019), serving less than 5000 people. These municipal systems had sufficient data to complete quantitative risk assessment calculations. However, in the WSP manuals for small systems, the risk matrix method is used specifically due to concerns with adequate data collection (WHO, 2012). The WHO small systems manual defines a small system as a system that experience issues as a result of limited access to resources to resolve these issues (WHO, 2012). Therefore, this study confirms population is not the best definition of a small system, as the small municipal systems in this study do have strong data collection procedures but are experiencing issues larger municipal systems do not.

The results presented for the water systems in this study provide a limited representation of how quantitative data can augment a WSP. Focus was placed on chlorine related hazards, and only 2 of the possible 22 hazards from the water safety plan template (Chapter Four) were used for comparison to quantitative data. Having data to support this comparison for other related hazards such as high turbidity, maintenance records and a log of chlorine analyzer calibrations would improve future studies. In addition, most of the water systems involved in the study (6 of 7) had low risk assigned to the hazardous events considered in this study, with only one community (Community A) having a moderate risk hazardous event. This predominance of low risk hazardous events needs to be considered in the interpretation of the results. Low level hazards are often more difficult to quantify and convey to stakeholders (Kolodzieg et.al., 2017, Kunreuthner et.al., 2010) in a water system, which may account for the lack of accuracy observed. However, without additional water systems with moderate and high risk hazards, it is difficult to conclude whether quantitative calculations are more accurate for moderate or high-level risks.

The results from this study can only make accurate conclusions about low-level risk in these nine water supply systems. Using the WSP method to obtain a risk level for chlorine monitoring in these systems resulted in low-level risk being assigned to all but one of the hazardous events considered. As a result, it is currently unknown whether the probability density function method and event tree method would provide the same results if these hazardous events had been identified as moderate-level or high-level risk, and thereby have a higher probability of occurrence based on Table 7.2. Future work that evaluates risk matrix performance in comparison to quantitative risk analysis needs to assess a broader spectrum of water supply systems with chlorine residual data available, but that may have higher risk associated with chlorine residual monitoring. This study is able to confirm that low-risk hazardous events have smaller probabilities but cannot verify if the conclusions made about each method and data set are valid for higher risk situations.

7.5.2 Impacts for Water Safety Planning

Previous studies of WSP implementation have shown that buy-in to this management method can be challenging, particularly where water system culture is focused on regulation (Summerill et.al., 2010a). The addition of water quality data to the risk assessment component of water safety planning provides a new incentive for water system to adopt this methodology. As observed previously in Chapter Five, there is a desire in municipal water systems to utilize monitoring data already collected in the water system. Additionally, benefits of WSPs were not always clear to water system stakeholders and the qualitative nature of the water safety plan method made it difficult for stakeholders to understand how this method could fit into the current water management culture (Summerill et.al. 2010a, Amjad et.al., 2016). The quantitative risk calculations utilized in this study provide a new avenue for integrating water quality data to a water safety plan that aligns more closely with municipal stakeholder mindset. This includes not only meeting regulations and continuing to sample for water quality parameters, but by highlighting how a water safety plan can be beneficial. The data-driven culture found in the water systems studied in Chapter Five is not unique; several other advanced water systems place focus on data collection to help meet requirements for regulatory compliance at a provincial level. Using quantitative risk analysis fits nicely into this culture and is more acceptable to many stakeholders as evidence of water safety.

Quantitative methods are currently utilized in the quantitative microbial risk assessment (QMRA) approach (WHO, 2016), however, the focus is placed on pathogenic organisms and microbial contaminants. This study demonstrates utilizing water quality parameters already collected in water systems, such as chlorine residual, provide additional information about quantitative risk not previously captured in WSP methods. The method presented in this study provides a bridge between the current risk matrix approach and the QMRA. The WHO promotes three levels of risk assessment, sanitary surveys, risk matrices and the QMRA (WHO, 2016). Studies of the QMRA process in small systems provide mixed results. Howard et.al., 2006 found that a QMRA can be used in situation with limited data but point estimations at sampling locations in a distribution system do not necessarily capture the full range of disease exposure (Howard et.al., 2006). Another study advocated for the use of water quality data where possible to strengthen the QMRA approach, as a single indicator is unlikely to be appropriate across all water systems (Saxena et.al., 2015). These examples indicate that there is benefit to adding quantitative probability calculations presented in this study, and use of indicator parameters such as chlorine residual will aide water system evaluations of microbial contamination. For water systems without capacity to collect the needed data for a QMRA, but enough monitoring data to necessitate a more sophisticated method than a risk matrix, the PDF and event tree discussed provide a logical first step.

In addition to integrating this approach into the continuum of risk assessments recommended by the WHO, this method is adaptable to specific water system needs, a requirement of the WSP methodology (Bartram et.al., 2009, WHO, 2012, WHO, 2016). For example, 0.2 mg/L of chlorine residual was chosen in the event tree method as this is the regulatory value specified by Health Canada (Health Canada, 2017). A near miss was defined as less than 0.4 mg/L of chlorine residual. However, these values are specific to the water systems being considered in this study and can be adapted to individual water systems as needed. Furthermore, the probability density function method has the same flexibility; the probability of occurrence or failure was calculated using the 0.2 mg/L value. If a water system desired a higher threshold to serve as an advance warning of possible inadequate disinfection, this is available with both examined methods. Compared to the risk matrix method this is an advantage; the risk matrix method does not allow for multiple, easy calculations of risk based on several different scenarios (Cox Jr., 2008, McBean, 2019c). However, with the addition of quantitative risk assessment calculations, it is possible to model several concerns simultaneously to best adjust control measures and risk mitigation procedures in a water system.

7.5.3 Data Availability

One concern with practically implementing the risk analysis strategies presented in this chapter is whether sufficient data is available to accurately and reliably complete calculations and have these analyses provide meaningful data to water systems. Many small systems do not have the capacity or finances to continuously monitor water quality data (Kot et.al., 2011, Dunn et. al., 2014) and will be unable to generate a similar amount of data as seen in the water systems in this thesis. While most water systems would be taking grab samples to meet provincial regulations to continue to operate (Health Canada, 2014a), it is unlikely that all other rural or remote systems would be collecting the volume of SCADA data seen in the water systems in this study.

The data used in this chapter consisted of at least 100 data points over the course of one year. The key characteristic of the data that is important to the risk analysis calculations is the presence of data that spanned all seasons to best account for changes in water quality. Water quality is dependent on temperature, pH and other seasonal conditions (Granger et.al., 2014, Health Canada, 2014a); therefore, any risk analysis performed with water quality data should include data points that span the full operational year. The number of data points needed to complete the probability density function and event tree probability calculations is less clear. However, it is recommended moving forward, that the quality and quantity of data used in water quality risk analyses needs to be evaluated to determine if the data is representative of the actual conditions observed in the water system.

While continuously logged data is preferred due to the volume of data that can be generated, maintenance and operational data can also be included in the risk analysis component of a water safety plan. For example, equipment calibration is ideally performed daily in a water system. A daily checklist completed by a water operator would indicate, in a binary fashion, whether this calibration had been performed. This type of data is also potentially useful in a water safety plan as it provides quantification of operational concerns and could be modeled with a binomial distribution. This example shows that while intensive data collection may not be present currently in a rural system, there are still other methods that can be used to collect data to inform risk analysis in a WSP. A rural water system can start from maintenance and operational data if the system lacks the capacity to implement a SCADA system and then scale data collection up once the resources and capital are available to implement continuous water quality data logging.

The data required to complete the risk analyses proposed in this chapter would need to be obtained from an operator of a water system. To ensure that the needed data is collected, it is recommended that data collection procedures for water quality parameters should be included as a component of the WSP implementation process. Given the defined hazardous events identified in a water system, the stakeholders in a water system can define which water quality parameters or operational checks are needed to numerically evaluate probability. Including data collection as part of the WSP process would provide one potential solution to the concern that not enough data will be available to perform risk calculations. Operators would be aware at the start which parameters are needed and can start with a handful of these parameters if capacity is low. Water systems can prioritize which data points need to be collected to better inform hazard identification and risk mitigation and focus on these parameters. This methodology would place the responsibility of increased data collection on a water system operator and future studies are needed to determine if this strategy would be effective or places an additional burden on a water system operator.

7.5.4 Interpretation of Low Probabilities

One of the primary concerns with the low probabilities generated by the PDF and event tree methods the interpretation of these values by water system stakeholders. Most lay people (who have no or limited experience with risk assessment) cannot accurately process or properly understand small probabilities less than 1% (Tyszka and Sawicki, 2011, Idzikowska et.al., 2017). Furthermore, depending on the amount of information available about probabilities and risks, people have different perceptions of how risky a low probability, but high impact event actually is (Michailova et.al., 2017, Idzikowska et.al., 2017, Tyszka and Sawicki, 2011, Tyszka and Zielonka, 2017). Small probabilities represented as numeric values are difficult for people to understand and how risk is communicated greatly impacts a stakeholder's understanding of a risky situation (Michailova et.al., 2017, Kolodzieg et.al., 2017, Visschers et.al., 2009). In the context of this study, the probabilities generated by the PDF method are less than 1 E-10 % in five of eleven scenarios for SCADA data sets and less that 1.0% in nine of eleven scenarios. This translates to event with "extremely rare" or "never" likelihood from a risk matrix. However, events that have never occurred in water systems can occur in future situations (Jalba and Hrudey, 2006) and the low probabilities observed in this study provide information that will lead to the misconstrued assumption of safe water quality. According to Tyszka and Zielonka, this result is termed "unrealistic optimism", the underestimating of the likelihood of negative events and the overestimating of the likelihood of positive events (Tyszka and Zielonka, 2017).

The WSP approach promotes interaction with multiple stakeholders in a water system to best describe risk (Bartram et.al., 2009, WHO, 2012). However, research has shown that decisions made from experience and descriptions of hazardous situations tend to underestimate risk (Tyszka and Zielonka, 2017). A study of the Alberta drinking water safety plan in 2014 showed stakeholders tend to rate risks as low or moderate risk because high risk indicated a stakeholder was not completing his or her job (Drachenberg, 2014). Given that 15 of 44 scenarios examined in this study were underestimations of risk in a water system and ten scenarios were accurate, stakeholder knowledge alone does not provide consistent or accurate understanding of hazardous event likelihood in water systems. Other studies of probability perception have indicated that people care more about the impact of a risky situation than the probability of a situation (Michailova et.al., 2017). This observation alludes to inherent bias in how risk assessment is performed in a WSP; information about risk from water stakeholders needs to be properly balanced with calculations of probability to mitigate underestimation of likelihoods.

Communication of the low probabilities observed in this study is therefore critical. Several studies have been conducted to best understand how to present information about low probability, high impact events to stakeholders. Kunreuther et.al., 2001 concluded that the best method for overcoming communication concerns is by providing comparisons (Kunreuther et.al., 2001). One possibility is a Paling Perspective Scale, a visual representation of probabilities in relation to probabilities of well-known events or scenarios (Visschers et.al., 2009). The underlying conclusion is that a reference point or contextual information is needed in for low probabilities to be comprehensible (Kunreuther et.al., 2001, Visschers et.al., 2009).

In general, graphical representations of probabilities are easier to understand (Chua et.al., 2006 as cited by Kolodziej et.al., 2017). Pictographs function well in situations where low literacy or numeracy exists but are difficult to use with low probabilities (Visschers et.al., 2009). In the context of the water quality data evaluated in this study, further explorations of risk communication are required. Visschers et.al., 2009 found that verbal probabilities are often better to communicate probabilities to people but lack the technical accuracy to capture the entire suite of hazards. Verbal probabilities are currently used in the WSP risk matrix method but are defined qualitatively instead of scaled numerically. To better improve both likelihood descriptions in risk matrices, probabilities obtained by using water quality data need to inform more accurate descriptions of probability. In water systems with advanced data collection, calculations of probabilities can be used to define likelihood levels as a range of values. The verbal probabilities such as “likely” can then be used to better communicate results to all stakeholders in a water system.

7.6 Conclusions

While the risk matrix is ideal for situations where there is little water quality data available, there are water systems that do not recognize the benefits of a WSP due to stringent data collection policies and a culture of water quality monitoring. Integrating quantitative risk analysis techniques into the WSPs developed for these water systems provides another incentive for WSP adoption that did not exist previously, one that aligns with water system cultural mindsets. Comparing the risk matrix method utilized in water safety planning to quantitative calculations of probability of occurrence revealed that the risk matrix approach is only accurate 23% of the time (10 of 44 possible scenarios). When the probability density function was used, the risk matrix method tended to overestimate risk in a water system, while risk matrices tended to underestimate risk compared to the event tree calculation. The highest accuracy was seen where data sets were larger, and the quantitative risk calculation was simpler. Expansion of this study to include other operational parameters such as pH and turbidity would provide additional evidence to support the conclusions presented here for chlorine residual. Quantitative calculations are not appropriate in all water systems, particularly where data availability does not support calculations of probability of occurrence. However, where data is available, the addition of quantitative calculations provides a more accurate picture of risk than the risk matrix method.

8 Chapter Eight – Understanding relationships between hazardous events in a water system using data analysis techniques

8.1 Abstract

The majority of studies examining water safety plans (WSPs) have focused on the preliminary steps to encourage the adoption of this risk assessment technique in water systems. However, there is little evidence in the water safety plan literature examining how results generated from a water safety plan are presented, communicated and interpreted across stakeholders in the water system. This study proposed analysis of WSP risk assessment results to uncover relationships between hazardous events to help stakeholders make management decisions. Most water safety plans generate improvement plans and lists of risk levels; this study demonstrated the utility of taking WSP results further by analyzing results between hazardous events using clustering analysis and principal component analysis. In addition, the differences between hazardous event relationships in municipal systems and First Nation systems were examined to better understand the drivers behind water system operations and monitoring plans. Clustering analysis was able to show expected relationships between hazardous events and was able to validate the operator-informed method for WSPs previously developed. Principal coordinate analysis revealed the most important hazardous events that drive both chlorine disinfection and distribution system operations in the fourteen water systems examined. Both analyses showed there is greater variability in the First Nation systems risk results than the municipal system results which translated to different key drivers of water system risk. Visualizations provided in this study represent a first look at how risk can be expressed and communicated at a technical level to decision-makers in a water system. This study reveals the utility of taking WSP risk result analysis further than improvement plans and reports, to better inform all stakeholders about water system performance.

8.2 Introduction

The majority of water safety plan (WSP) research in the past ten years has focused on providing evidence of WSP effectiveness in water systems globally (WHO & IWA, 2017, Gunnarsdottir et.al., 2012, Baum et.al., 2015, Baum and Bartram, 2017, Omar et.al., 2016, String and Lantagne, 2016). Initial steps in the water safety planning process involve the identification of hazardous events and the assignation of risk level to hazardous events (Bartram et.al., 2009, WHO, 2012, WHO, 2016). After risk assessment, an improvement plan is generated and agreed upon by stakeholders in a water system involved in the water safety planning process (Bartram et.al., 2009, WHO, 2012). Examples of improvement plans are available in WHO WSP manuals and from several global case studies (WHO, 2012, WHO, 2018).

Despite extensive documentation of hazardous events and risk levels, very little research has been conducted to understand how water safety plan outcomes and risk analysis results can be utilized to better inform a water supply system. While WSPs increase communication amongst stakeholders and provide a valuable tool for documenting issues in a water system (WHO & IWA, 2017, Kot et.al., 2015, Amjad et.al., 2016, Loret et.al., 2016, Byleveld et.al., 2008), once WSPs have been completed, further analysis of the hazardous events is not conducted. Several studies have noted the importance of buy-in in the water safety plan process and the importance of providing clear benefits to stakeholders in systems starting WSP development (Summerill et.al., 2010a, Summerill et.al., 2010b, Summerill et.al, 2011, Ferrero et.al., 2019, Amjad et.al., 2016, Omar et.al, 2017, Tibatemwa at.al., 2004). In water systems where data collection is required by regulations or where policy change is slow due to water governance structures, the benefits of WSPs are not clear to water system stakeholders. In addition, as WSP development progresses, there is a need to ensure that the WSP is an evolving document and not an annual report (WHO, 2012, Bartram et.al., 2009). In water systems considering WSP development, the addition of more rigorous hazardous event relational analysis provides a potential avenue to secure buy-in from heavily regulated water systems.

Water safety planning is a system-specific methodology focused on hazard identification for an individual water system to ensure relevant hazards are identified and addressed (WHO, 2012, Bartram et.al., 2009). However, several studies have noted changes in water quality policy as a result of WSP implementation and the importance of integrating WSPs into policy making for successful and sustainable implementation (Amjad et.al., 2016, Baum et.al., 2015, Baum and Bartram, 2017, WHO & IWA, 2017, Gunnarsdottir et.al., 2012, Hasan at.al., 2011). As a result, while water safety plans focus on individual community needs, implementation and adoption at a national scale must be supported by relevant external stakeholders (Hasan et.al., 2011, Gunnarsdottir et.al., 2012, Loret et.al., 2016). Previous research has not explored analysis of hazardous events across several water systems can facilitate the adoption of WSPs at a regional or national level. Chapter Five of this thesis presented one method of visualizing risk results across water systems, enabling comparisons, but also stimulating conversations about policy changes and guideline revisions that are needed at a regional scale. More in depth analysis of hazardous events across water systems has the capacity to identify regional water system concerns that are not visible at an individual system level.

Needed policy changes are different dependent on the type of water system. Chapter Five and Six of this thesis studied the changes that need to be made to the developed water safety plan for successful water safety plan adoption. In municipal systems, this included clearer benefits to a water system, increased integration of current data collection procedures and a change in water system mentality to a more proactive management approach. These concerns have been raised by previous studies of water safety plans (Summerill et.al, 2010a, Summerill, et.al., 2010b, Summerill, et.al., 2011, Amjad et.al., 2016, Ferrero et.al., 2019). In the case of First Nation systems, Chapter Six showed the power of WSPs as communication tools and the desire to have more interaction with the results generated the tool to facilitate collaboration. An identified benefit of the WSP is the power to communicate results across several stakeholders (Loret et.al., 2016, Kot et.al., 2015); the expressed desire to further stakeholder communication provides an outlet to explore tools and analysis methods that best inform policy making by understanding how hazardous events are interrelated

The objective of this chapter is therefore threefold. First, using data from Chapter Five and Six, this study seeks to understand how hazardous events are related within a WSP module (as developed in Chapter Four). Second, using principal component analysis and clustering analysis, visualizations of hazardous events relationships and how risk can be presented in a WSP are explored. Finally, using all fourteen systems studied in this thesis, this chapter evaluates at how relationships between hazardous events are different between municipal water supply systems and First Nation water supply systems for the purpose of informing policy-making that supports WSPs. This will provide a foundational understanding of how the WSP can be expanded to include more in-depth analyses of risk results.

8.3 Methods

8.3.1 Cluster Analysis

Data from fourteen water systems was aggregated from the WSP tool used in Chapter Five and Six of this thesis. Using the risk scores for each hazardous event from six First Nation communities and eight municipal water systems, a matrix was constructed for use in cluster analysis. Risk scores were linearized using the following formula:

Equation 8.1: $$y = \frac{\log_{10} x}{\log_{10} 2} + 1 \; for \; x > 0$$

This formula was utilized by Post et. al., 2017 to linearize the results from the Alberta drinking water safety plan to allow for easier presentation and communication of results (Post et. al., 2017). This matrix was then converted to distance matrix using the R statistical programming language (version 3.4.0) and normalized. The distance matrix was constructed by taking the Euclidean distance between pairs of objects in the dataset. Euclidean distance (calculated using the standard Pythagorean theorem) was used in this study as the number of dimensions was considered low enough that error would not be introduced; no other distance metrics (manhattan, binary, maximum, canberra or minkowski, available as arguments in the dist() function in R) were considered appropriate for this particular data set. The distance matrix is a matrix of the pairwise distances between all fourteen water systems and all hazardous events where the diagonal distances are zero.

From this distance matrix, the data was then clustered using hierarchical clustering using an unweighted pair group method with arithmetic means (UPGMA)(Hartigan, 1975). This method assumes that all distances contribute equally to each average computed. Since no weights have been given to the hazardous events in the WSP system assessments, the unweighted average was chosen over the weighted average (Hartigan, 1975). The clustered data was then plotted as a dendrogram to visualize the relationships between hazardous events, color-coded by hazardous event category. An individual data set is here defined as the risk scores for all fourteen systems in one given questionnaire; there are two questionnaires included in this analysis, the chlorine disinfection and distribution system questionnaires. The cophenetic correlation coefficient (CCC) was calculated for each data set to determine if the dendrograms produced are considered an accurate representation of the original data sets (Sneath and Sokal, 1973). The CCC is found by taking the ordinary pariwise Euclidean distances, subtracting the average distance between these pairwise distances and multiplying it by the difference between the model distances minus the model average distance. This figure summed for all pairs and divided by the square root of the product of the differences squared, summed over all pairs (Sneath and Sokal, 1973). If the correlation between the original distance matrix and the cophenentic distance matrix is high, then the dendrogram is considered an accurate summary of the data (Sneath and Sokal, 1973, Teknomo, 2009).

8.3.2 Principal Component Analysis (PCA)

For each system assessment (chlorination and distribution system operations), principle component analysis (PCA) was performed to identify and visualize similarities and differences between hazardous events in fourteen water systems (22 hazardous events for chlorination and 19 for distribution system operations, shown in Table 8.1). PCA was chosen as it focuses on similarities in groups of data by finding the main axis in a matrix. The water systems chosen had different source water types (groundwater or surface water), different populations served (large: >5000 people, small: <5000 people) and were either municipal water systems or First Nations community water systems. PCA calculates a set of eigenvalues from a Euclidean distance matrix and ranks these values from greatest to least (Mardia et.al., 1979). This calculation captures the maximum variance in a data set, the first principal component capturing the most variance.

Table 8.1: For each survey module, there are a set of hazardous events identified. The hazardous events for (a) chlorine disinfection and (b) the distribution system are numbered for reference.

(a) Chlorine Disinfection

Number	Hazardous Event
1	Equipment Calibration
2	Equipment Failure
3	Equipment Replacement
4	Maintenance Plans
5	Compliance with Regulations
6	Disinfection Failure Procedures
7	Backup Systems (Subsequent Treatment Barriers)
8	Chemical Safety
9	DBPs
10	Feedwater Conditions
11	Monitoring for High Chlorine
12	Incorrect Dosing
13	High Chlorine at Booster Stations
14	Monitoring for Low Chlorine
15	Dosing Controls
16	Chlorine Supply
17	Chlorine Concentration
18	Chlorine Demand
19	Contact Time
20	Chemical Supplier
21	pH Control
22	Low Chlorine at Booster Stations

(b) Distribution System

Number	Hazardous Event
1	Insufficient Water Available
2	Leaks in System
3	Transmission Pump Failure
4	Pipe Breaks
5	Pipe Incidents
6	System Pressure Drops
7	Cross Connections
8	High Flow Entering Distribution System
9	Sediment Build Up
10	Biofilm Presence
11	Iron Precipitation
12	Manganese Precipitation
13	Chlorine Residual Degradation
14	Flushing Procedures
15	Staff Training
16	Hygienic Sampling Procedures
17	Leak Isolation Procedures
18	Repair Materials
19	Bypasses

After PCA was performed, screeplots of the variances explained by the principal components were constructed to determine if the analysis provided valuable analysis (Mardia et.al., 1979). The PCA was visualized using a biplot to show clusters of hazardous events (Gabriel, 1971). In the context of this analysis, the variables were the individual water systems and the units evaluated were the hazardous events. The Euclidean distance was used and the variables were not important to the end analysis of the hazardous events; this principal component analysis is also considered principal coordinate analysis for clarity as differences between groups of hazardous events are highlighted in the results sections(Mardia et.al., 1979).

8.3.3 Other Analysis Techniques

Using the same data set, several other graphical visualizations were constructed to examine alternative methods for presenting hazardous events in water systems. These visualizations each provide different information to stakeholders in a water system and each visualization was evaluated to determine which graphs would be most useful for communicating risk. Visualizations included boxplots to determine ranges of risk scores across communities, dot plots where the size of the dot represents the number of communities, and tile plots showing distance between hazardous events. Each visualization was evaluated to determine utility to several water system stakeholders: operators, sampling staff, managers, regulators, provincial authorities, federal authorities and chief and council in the case of First Nation water systems.

8.3.4 Case Study Sites

Fourteen water supply systems were included in this study, spanning eight municipal water supply systems (as seen previously in Chapter Five) and six First Nations water systems (as seen previously in Chapter Six). These systems are shown in Table 8.2. Two of the systems (System G and System N) had populations served greater than 5000 people and were considered large water systems for the purpose of this study. Seven of the systems included raw water from a ground water source, and the remaining seven raw from a surface water source. These system characteristics are used to differentiate between systems when performing principle component and clustering analyses to better understand how source water and community type impact hazardous events relationships within a water system.

Table 8.2: Fourteen water systems were included in the WSP hazardous events analysis, including both clustering and PCA methods. Each system has been labeled alphabetically to ensure water system anonymity. Source types can either be surface or ground water, size of the system can be large or small and community type can be municipal or indigenous. These three factors are used for comparisons in the PCA and clustering methods.

System	Source Type	Community Type	Size of System
System A	Surface Water	Municipal	Small
System B	Surface Water	Municipal	Small
System C	Ground Water	Municipal	Small
System D	Ground Water	Municipal	Small
System E	Surface Water	Municipal	Small
System F	Ground Water	Municipal	Small
System G	Surface Water	Municipal	Large
System H	Ground Water	Indigenous	Small
System I	Ground Water	Indigenous	Small
System J	Ground Water	Indigenous	Small
System K	Surface Water	Indigenous	Small
System L	Surface Water	Indigenous	Small
System M	Ground Water	Indigenous	Small
System N	Surface Water	Municipal	Large

8.4 Results

8.4.1 Clustering Analysis

The clustering algorithm described previously was applied both to the chlorination survey (22 potential hazardous events) and the distribution system survey (19 potential hazardous events). The results from the clustering algorithms were then plotted as dendrograms to show the relationships between hazardous events. The hazardous events are color-coded by category (maintenance, monitoring and operations) to better understand the relationships between hazardous events. The dendrogram for the chlorination survey is shown in Figure 8.1.

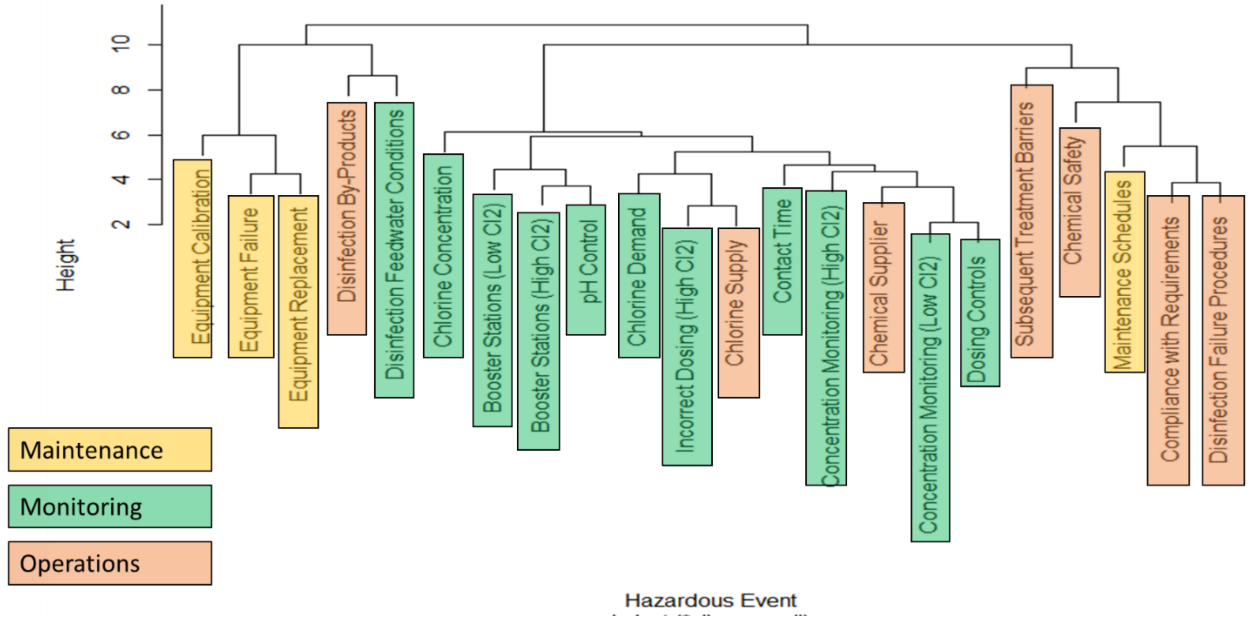


Figure 8.1: The dendrogram of the 22 hazardous events include in the chlorine disinfection (chlorination) survey shows that specific hazardous events are clustered together in a logical fashion. Height here specifies the length of the vertical line connecting each horizontal branch of the dendrogram.

The dendrogram for the chlorination systems shows that across all fourteen water systems included in the analysis (Municipal D does not have on site chlorination), specific hazardous events group together in an intuitive way. For example, on the left of the dendrogram, three maintenance hazardous events (equipment calibration, failure and replacement) are closely related to each other. From a water operator's perspective, this is an intuitive grouping of hazardous events since equipment care and maintenance is linked to proper calibration and timely replacements of components to avoid failure. In addition, the hazardous events related to disinfection by-product formation (disinfection by-products and disinfection feedwater conditions) are closely related on the dendrogram. These logical groupings of hazardous events demonstrate that across these water systems, this WSP method is showing important relationships between hazardous events regardless of the risk level or score that is assigned to a hazardous event. For example, in Community D, both disinfection by-product hazards are considered high level risk (with risk scores of 9 and 8). However, in Municipal C, disinfection by-products were moderate level risk (a risk score of 5), but disinfection feedwater conditions were low level risk (a risk score of 1). Despite possible difference in risk levels for these two hazardous events, across all the systems in the analysis, the clustering method and dendrogram visualization were able to show a close relationship between the disinfection by-product hazardous events that is expected.

Figure 8.1 also shows other important clusters of hazardous events. The five hazardous events furthest to the right on the dendrogram are all events related to standard operating procedures, both for compliance with water quality regulations and procedures in place in the event of a failure of the disinfection system. The majority (4 of 5) of these hazardous events are operational concerns and only one is a maintenance issue. In addition, with the exception of disinfection feedwater conditions, all of the monitoring events are grouped together, indicating that the majority of water systems are monitoring these water quality parameters with similar frequencies or monitoring the parameters at the same time when samples are taken. These types of figures only present an estimate of which hazardous events are closely linked in these water systems only, but nonetheless provide an important visualization of relationships between hazardous events.

Similar to the chlorination module, Figure 8.2 depicts the dendrogram for the distribution system risk assessment. As with the dendrogram in Figure 8.1, there are defined clusters of hazardous events by category of hazard. Particularly for monitoring hazards, specific water quality parameters are closely related in the majority of the 14 water systems. There are close pairings between chlorine residual and flow rate, iron and manganese presence, and biofilm presence and sediment build-up. From a sampling procedure perspective these pairings are logical: chlorine dose is often flow-based in a treatment facility, iron and manganese are required quarterly by water quality guidelines and sediment and biofilm are often only measured when a pipe break occurs or not at all depending on water system policies. These parings of hazardous events are justified by knowledge from the water industry: standard operating procedures, operator experience and design criteria for water treatment facilities. This indicates, for these 14 water systems, that the operator-informed WSP is capable of extracting accurate and logical information about risk based on an operator's experience and expertise.

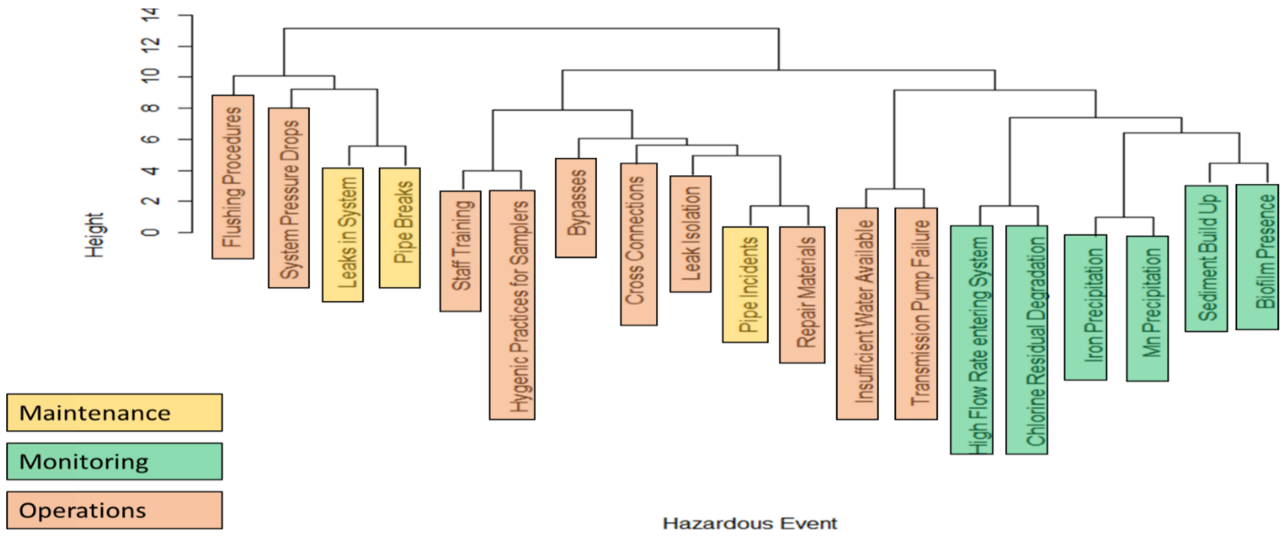


Figure 8.2: The dendrogram for the distribution system hazardous events (19 in total) show a more drastic clustering of the category of hazardous events (either maintenance, monitoring or operation) than the chlorine disinfection survey. Hazardous events are very clearly grouped by category with few exceptions in comparison to the chlorine disinfection survey.

Figure 8.2 also shows close pairings between the following hazardous events in the distribution system: leaks in the system and pipe breaks, staff trainings and hygienic practices for samplers, pipe incidents and repairs materials and insufficient water available and transmission pump failures. In each of these pairings, high risk or an issue with one of the hazardous events could feasibly lead to a concern or high-risk situation with the paired hazardous event. For example, proper staff training has been shown to decrease waterborne disease outbreaks as staff are more aware of the risk of contamination of a water supply and are better trained to ensure adequate disinfection (Butterfield and Camper, 2004, Moffatt and Struck, 2011, Pons et.al., 2014). Having hygienic sampling procedures in place also helps to limit contamination of samples as they are taken. Both hazardous events fall under the operations category and are primarily concerned with ensuring contamination of samples is not a result of inadequate training. Clustering analysis indicates these hazardous events are closely related in these 14 water systems and the rationale behind each pairing of hazardous events provides evidence the relationships are logical.

To determine if the dendrograms presented in Figure 8.1 and 8.2 are considered an appropriate summary of the data, the cophenetic correlation coefficient was calculated. For the chlorine disinfection assessment, the correlation coefficient was 0.8024, comparing the distances from the original data set to the cophenetic distances. For the disinfection system assessment, the correlation coefficient was 0.8794. In the case of both assessments, the correlation coefficient is relatively close to 1.0, indicating that for both cases, the dendrogram is an appropriate summary of the data (Teknomo, 2009).

The operator-informed water safety plan used to gather information about risk in these fourteen systems (presented in Chapter Four, data gathered in Chapter Five and Six), was designed to present questions in randomized order, using a fault tree backbone. The results from this study indicate the operator-informed method is accurately identifying related hazardous events in the chlorination and distribution operations modules. In Figure 8.1 and 8.2, hazardous events that are expected to be related, are in close proximity on these dendrograms. For example, disinfection by-products and disinfection feedwater conditions are two hazardous events that are closely linked: changes in source water quality entering chlorination processes can impact disinfection by-product formation. While each system had a different risk level for each of these two hazardous events, across all fourteen systems, the clustering analysis showed that these events are linked.

8.4.2 Principal Component Analysis (PCA)

Principal component analysis results for both chlorination and distribution system hazardous events are depicted in Figure 8.3. The analysis performed in Figure 8.3 indicates which hazardous events were most closely related. Hazardous events are colored by category for clarity and used to determine if hazardous events cluster by category.

In the chlorination assessment, there are no distinct clusters of hazardous events by category. There are four hazardous events that are positively associated with principal component one and negatively associated with principal component two: disinfection by-products, equipment failure, equipment replacement and disinfection feedwater conditions. Of these hazardous events, the association between equipment failure and equipment replacement and the association between disinfection by-products and feedwater conditions are intuitive given water industry knowledge. There are five hazardous events positively associated with principal component one and positively associated with principal component two: maintenance schedules, chemical safety plan, subsequent treatment barriers, compliance with requirements, and disinfection failure procedures. All these hazardous events are related to procedural measures water systems or to meeting regulatory guidelines.

In the case of the distribution system, there are clear relationships between hazardous events based on category. All monitoring hazardous events are negatively associated with principal component two. The majority of operational hazardous events are positively associated with principal component two and slightly negative associated with principal component one. Principal component one is positively associated with pipe breaks, leaks in the system and system pressure drops, all events that can be linked in actual distribution systems. Furthermore, water quantity issues (insufficient water available and transmission pump failure) group with water quality issues (monitoring category hazardous events); all these hazardous events can be monitored with currently implemented technologies in a water system. Finally, the remaining operational events are negatively associated with principal component one but positively associated with principal component two; this group of hazardous events primarily focuses on pipe inspection procedures and other procedures such as sampling programs and staff training.

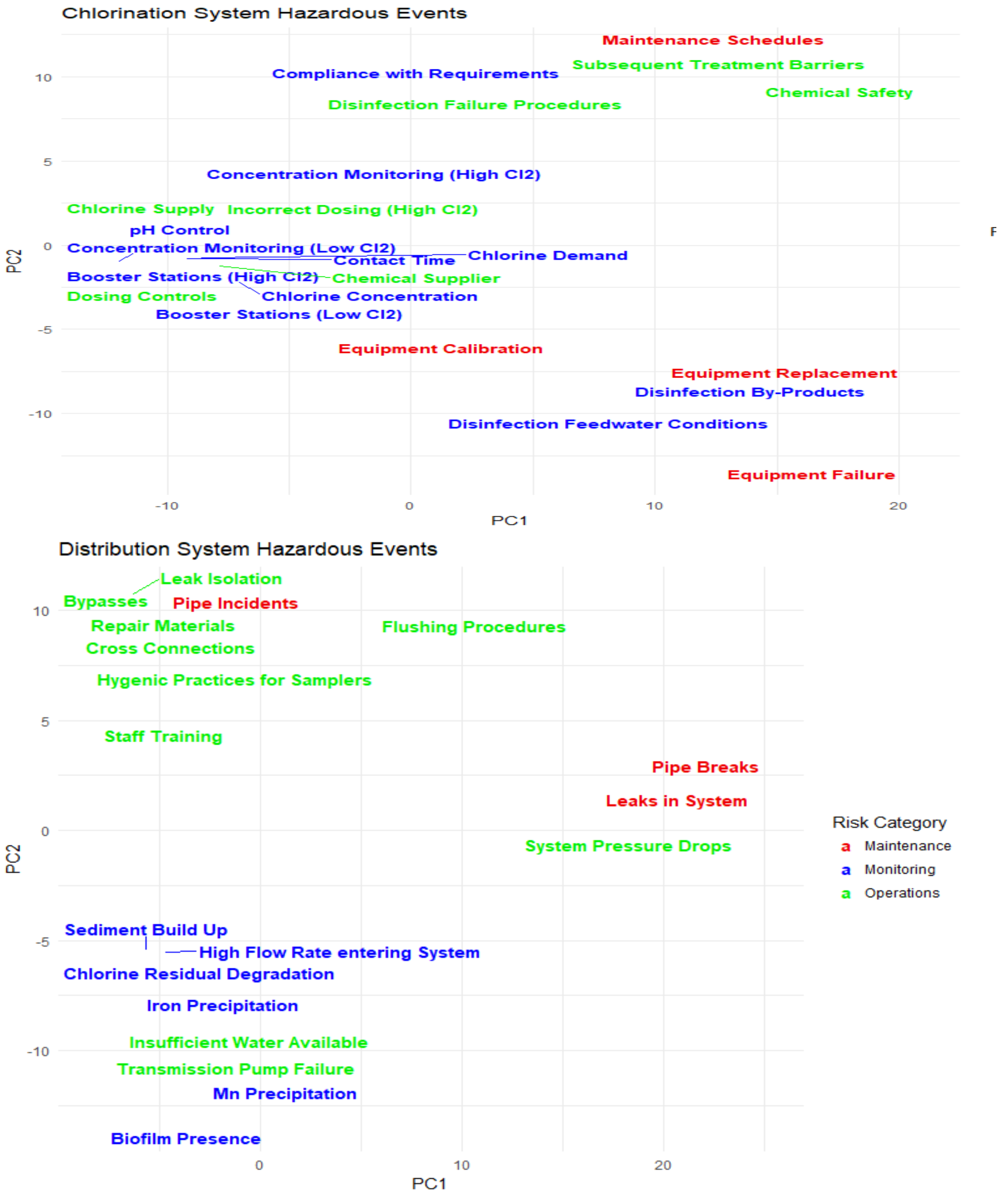


Figure 8.3: Principal component analysis depicting the principal components of the data set by community contribution. This figure shows how hazardous events are related to one another (by showing clusters formed

between hazards, closer distances indicating a closer relationship) for the two community water systems that contribute most to the analysis.

In the case of the chlorination system assessment, 51.8% of the cumulative variance is explained by the first principal component, 73.4% is explained by the first two principal components and 82.1% by the first three principal components. For the distribution system assessment, the first principal component explains 39.4% of the cumulative variance, 67.9% of the cumulative variance is explained by the first and second principal components and 78.1% is explained by the first three principal components. The variance is show in the scree plots in Figure 8.4. Both scree plots visually indicate that the PCA is a relatively good analysis for this data set, with the cumulative variance being explained primarily by the first two principal components.

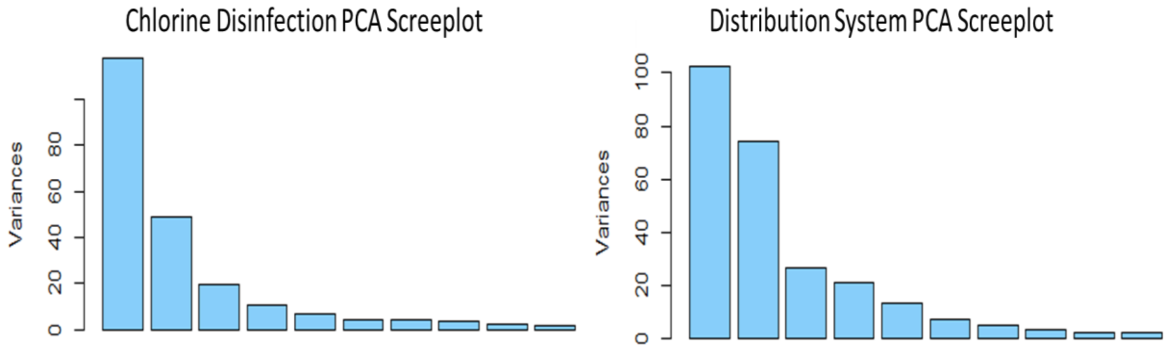


Figure 8.4: Scree plots for both chlorination and distribution system assessments. The scree plots demonstrate that the PCA method provides a relatively accurate summary of the data as the majority of the variance is explained by the first two principal components, which are the two systems contributing the most to the variance in the data set for each questionnaire.

8.4.3 Deepening our Understanding through Additional Data Analytics

Figure 8.5 presents a boxplot of the range of risk scores present for each hazardous event across the fourteen water systems evaluated. The 22 hazardous events for chlorine are presented across the x-axis and the linearized risk score is presented on the y-axis, with shading of the background representing the risk level assigned to each risk score. Across the fourteen systems, the risk score median is predominantly low risk, with no median risk scores in the high-risk level category. For hazardous events such as Chemical Supplier, the range of risk scores is within one risk level (low risk only in this case), indicating that across these fourteen systems, chemical supply for chlorination is not considered an issue or priority in these water systems. However, for hazardous events such as Chemical Safety, there is larger variation in water system operations with the risk score spanning the full spectrum of risk scores available.

Hazardous events with the widest range of risk scores highlight situations where individual interventions are needed to solve concerns. In contrast, a smaller range of risk scores indicates hazardous events that are similar across water systems and can be best addressed by policy changes or regulations at a regional level. The boxplot visualization is most useful to stakeholders at a regional level, or to a manager in charge of several different water systems. The boxplot provides a water system stakeholder with the range of risk scores present in water systems for each hazardous event; as a result, a stakeholder can discern hazardous events with a similar risk level across water systems, and the events that are variable between water systems. Managers or regional authorities can use this visualization as a general overview of all the systems managed. At an individual water system level, this visualization does not provide as much utility as it focuses on risk scores across water systems.

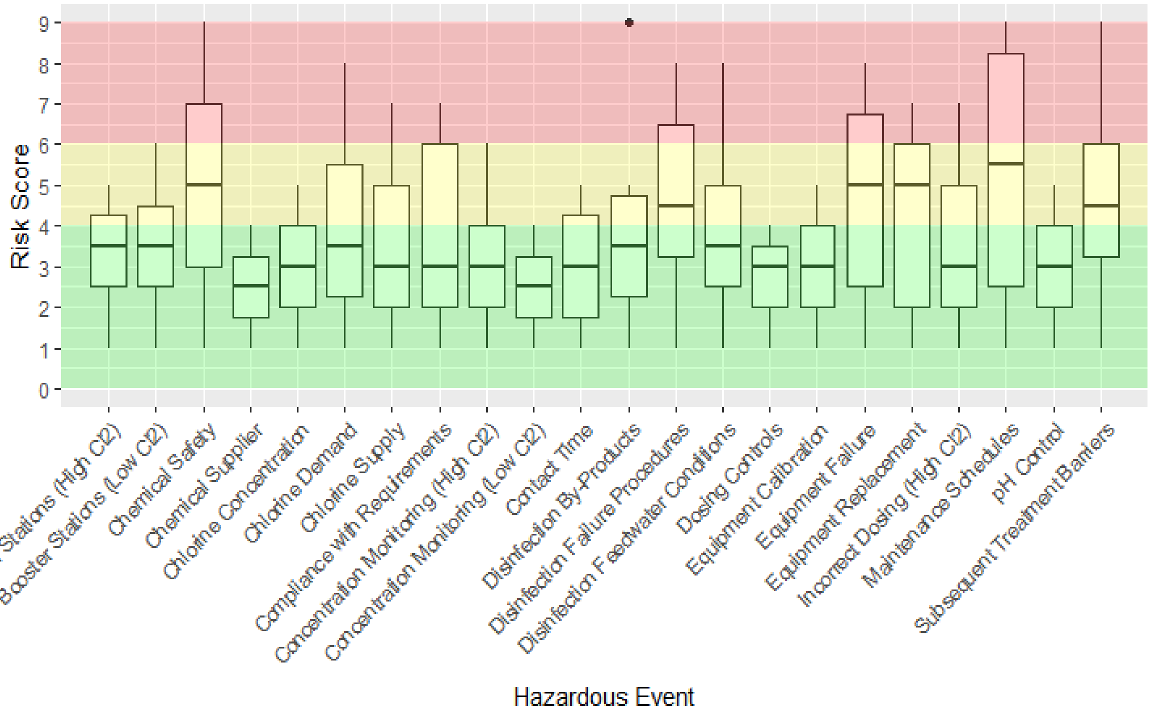


Figure 8.5: Using a boxplot, the range of risk scores for each hazardous event is shown. Risk scores are linearized background shading indicates the risk level associated with each risk score (red for high risk, yellow for moderate risk and green for low risk).

Similar to Figure 8.5, Figure 8.6 shows how many water systems have the same risk score for a given hazardous event. In this plot, the size of the point represents the number of water systems with the same risk score for an event, focusing on chlorination (the distribution system results are presented in Appendix G). From a stakeholder perspective, the larger points highlight hazardous events that need immediate attention across several water systems and require interventions from managers or regional authorities to mitigate risk. For example, Disinfection By-products is one hazardous event with a risk score of 5 for six or more water systems. Similar to the boxplot, this plot is beneficial to policy makers and regulators overseeing multiple water systems as it highlights areas of concern across several different water systems.

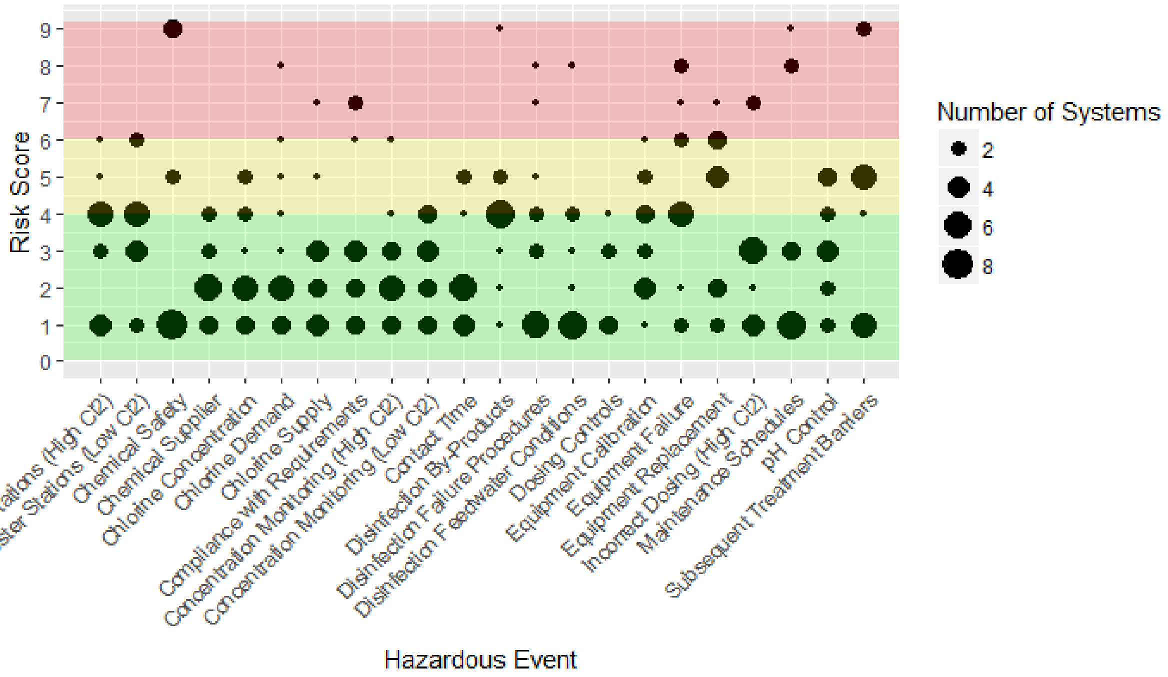
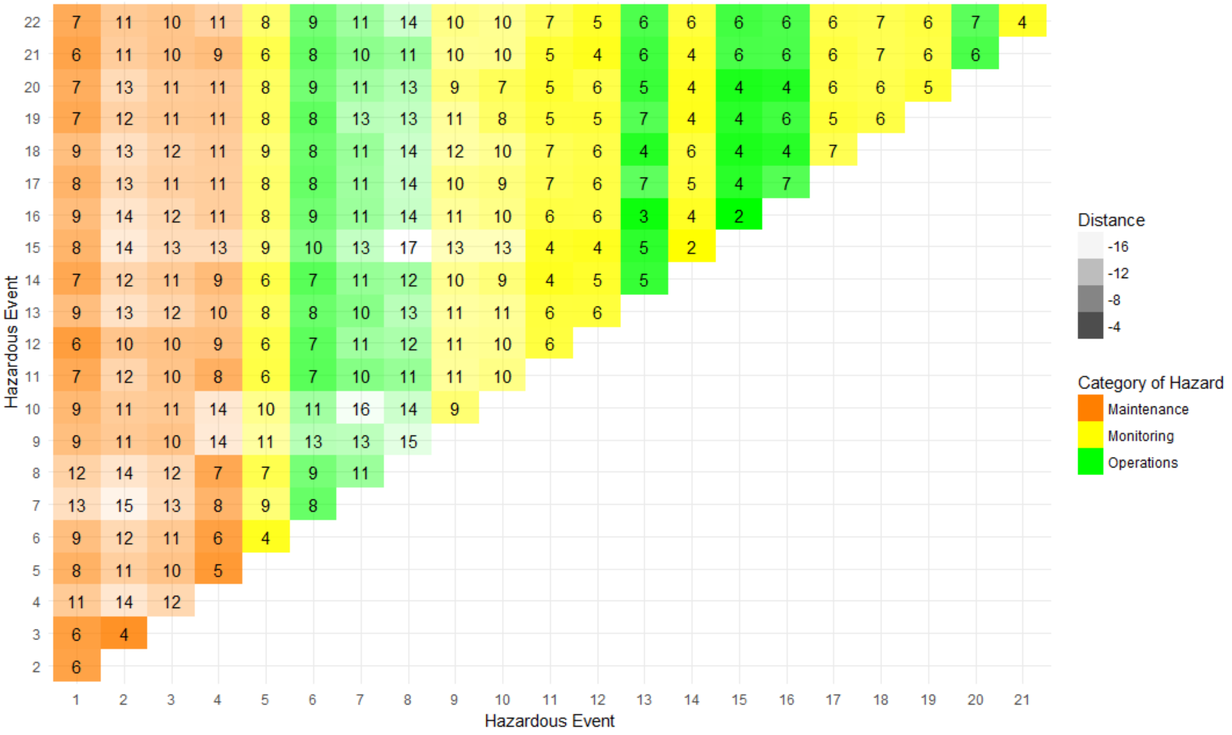


Figure 8.6: Using the chlorination hazardous events, this plot shows the number of water systems with the same risk score for each individual hazardous event. The size of the point represents the number of water systems with the indicated risk score. Larger points represent issues that are common across water systems and may be best addressed by changes in policy at a regional or provincial level.

The last visualization explored uses a tile plot to show relationships between hazardous events. The tile plot in Figure 8.7 shows the distance between hazardous events, coloring each hazardous event by category on the x-axis. The transparency of the tile represents the Euclidean distance between each event (calculated using the Pythagorean theorem); a more transparent tile represents a greater distance and two events that are not closely related. Figure 8.7 represents the distance between the 22 hazardous events for the chlorine disinfection process. The closest related events across all the water systems are hazardous events 14, 15 and 16, corresponding to Monitoring of Low Chlorine, Dosing Controls and Chemical Supply. The events most unrelated to each other are events 8 and 15 and events 7 and 10. Events 8 and 15 are Chemical Safety and Dosing Controls. Events 7 and 10 are Backup Systems and Feedwater conditions.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
22	7	11	10	11	8	9	11	14	10	10	7	5	6	6	6	6	6	7	6	7	4
21	6	11	10	9	6	8	10	11	10	10	5	4	6	4	6	6	6	7	6	6	
20	7	13	11	11	8	9	11	13	9	7	5	6	5	4	4	4	6	6	5		
19	7	12	11	11	8	8	13	13	11	8	5	5	7	4	4	6	5	6			
18	9	13	12	11	9	8	11	14	12	10	7	6	4	6	4	4	7				
17	8	13	11	11	8	8	11	14	10	9	7	6	7	5	4	7					
16	9	14	12	11	8	9	11	14	11	10	6	6	3	4	2						
15	8	14	13	13	9	10	13	17	13	13	4	4	5	2							
14	7	12	11	9	6	7	11	12	10	9	4	5	5								
13	9	13	12	10	8	8	10	13	11	11	6	6									
12	6	10	10	9	6	7	11	12	11	10	6										
11	7	12	10	8	6	7	10	11	11	10											
10	9	11	11	14	10	11	16	14	9												
9	9	11	10	14	11	13	13	15													
8	12	14	12	7	7	9	11														
7	13	15	13	8	9	8															
6	9	12	11	6	4																
5	8	11	10	5																	
4	11	14	12																		
3	6	4																			
2	6																				

Figure 8.7: Hazardous events are here represented by indices in this plot (indices can be found in Table 8.1a) on each axis. The category of hazardous event is colored by x-axis only and the number in the tile represents the distance between each hazardous event. The transparency of the tiles represents the distance between each hazardous event for clarity.

Figure 8.7 identifies hazardous events that are closely related to each other across all fourteen water systems in this study. Given the range of scores present for each hazardous event across water systems, Figure 8.7 provides water stakeholders with a picture of which events are most likely to influence other events in the water system, allowing stakeholders to take preventative action before an issue arises. For example, Dosing Controls (Event 15) and Monitoring for Low Chlorine (Event 14) are closely related on this tile plot. From an operator's perspective, this is critical information: when there are concerns with dose control, increased monitoring for chlorine needs to be conducted to ensure chlorine residual does not fall below an acceptable threshold. Figure 8.7 effectively pinpoints which hazardous events can be considered indicators for other hazardous events within the water systems. While Figure 8.7 shows relationships across several water systems for one year, this analysis performed on several years' worth of data from an individual water system over time is useful for identifying key relationships within an individual water system.

8.5 Discussion

8.5.1 Communicating hazard relationships improves risk management

Analyzing relationships between hazards in a water system identifies key events that impact water safety. The benefit of completing PCA and cluster analysis is insight gained on hazardous event relationships for water system stakeholders. When one hazardous event is identified as "high-risk", understanding which hazardous events are most closely to this hazardous event allows stakeholders to manage the system more accurately. Water safety plans are focused on proactive risk management, aiming to prevent issues from occurring before unsafe water quality reaches a customer (Bartram et.al., 2009, WHO, 2012, WHO, 2018). This study has demonstrated the utility of understanding relationships between hazardous events to better alleviate issues before occurrence.

Communicating risk to all stakeholders in a water supply system is difficult as a result of varying degrees of technical understanding of the system. Tyszka and Sawicki, 2011, showed that numeric probabilities are difficult to understand; in Chapter Six of this thesis, it became clear that communication of risk from water quality data is a challenge (Tyszka and Sawicki, 2011). Research on risk assessment techniques for water systems has shown integration of multiple techniques provides better coverage of the full system than an individual analysis method (Hokstad et.al., 2009). The visualization techniques in this study demonstrate the utility of considering not only the likelihood or risk of one event, but also the interactions between events. Integrated methods such as the Bow Tie method (Groot, 2014, Guldenmund et.al., 2006) showcase methods that allow for the consideration of multiple hazards and barriers to risk. Future studies need to be aware of these factors: the communication of information about risk should consider not only risk at point sources, but risk across the water system and risk as a result of the interactions between events.

Several studies of water safety in water systems have focused on drinking water advisories and methods for predicting future advisories (Murphy et.al. 2016, Harvey et.al., 2015, Post et.al., 2018). However, while predictive modeling is useful for identifying key characteristics of advisories, it does not focus on underlying reasons advisories are issued. An advisory can be operational or related to water quality, but a drinking water advisory does not communicate why the operational concern occurred (Health Canada, 2018, Murphy et.al., 2016, Thompson et.al., 2017). The water safety plan developed in this thesis demonstrates how identification and prioritization of high-risk hazardous events better informs decision making and improvements in a system (Chapter Five, Chapter Six). This study demonstrates how modeling can be improved by examining individual hazardous events instead of the reason a drinking water advisory is issued. With a better understanding of the most closely related hazardous events, a water treatment operator can minimize operational concerns, such as pump failures or loss of pressure before occurrence. If hazardous event relationships are known, preventative measures can be taken to mitigate risk.

8.5.2 Relationships between hazards inform policy making and auditing procedures

The data analysis techniques included in this study are standardized methods that are used in other related industries (air quality monitoring, natural disaster risk modeling, flood prediction, etc.) (Idzikowska et.al., 2017). The standardized nature of these analysis methods is ideal for external auditing of water safety plan effectiveness. One of the identified challenges with WSPs still to be addressed is the lack of external auditing procedures to ensure WSP accuracy and efficacy (WHO & IWA, 2017). The hazard identification and risk assessment components of a water safety plan have been analyzed critically to determine benefits and challenges with water safety plans (Kumpel et.al., 2018, Loret et.al., 2016). However, little work has been reported to understand if results generated from a WSP are an accurate representation of risk in a water system.

Gunnarsdottir et.al., 2012 reported that potential bias can be introduced when the stakeholder completing the WSP process has extensive knowledge of the subject area, underscoring the need for external methods of evaluating WSPs (Gunnarsdottir et.al., 2012). The data analysis techniques presented in this study provide visual representations of risk that can be used to validate the effectiveness of a WSP. For example, the dendrogram method provides a visual interpretation of which hazardous events are most closely related in fourteen different systems. We would expect similar hazards to have similar relationships in other water systems. If these relationships are not present, this in an indication an external auditor should raise questions about bias introduced in the WSP and further analysis is needed to better manage risk. Using standardized data analysis in an external audit provides a new method for evaluating WSP effectiveness that has not been previously explored.

Showing how hazardous events are related across several systems provides more useful information for policy making at a regional, provincial or national level. Summerill et.al. dedicated three individual papers to the study of stakeholder buy-in to water safety plans (Summerill et.al., 2010a, Summerill, et.al., 2010b, Summerill et.al., 2011). The conclusions from these papers demonstrated the importance of buy-in at a stakeholder and water utility level, but also at a policy-making level, whether regionally or nationally. Other studies of WSPs highlighted the need for support from local agencies and stakeholders with decision making power at a regulatory level for water safety plan success (Kot et.al., 2015, Baum and Bartram, 2017, Gunnarsdottir et.al., 2012, Hasan et.al., 2011, Setty et.al., 2018). The data visualizations presented in this study clarify high-priority issues at a regional level for both municipal and First Nation water systems. For example, in chlorination procedures, relationships between chemical safety plans and subsequent treatment barriers exist for First Nation systems that are not present in municipal systems (as shown with cluster analysis). Implementing chemical safety plan training programs in First Nation communities is more likely to improve overall system performance.

The relationships between hazardous events give regional authorities, national regulators and stakeholders involved in policy making a better overall picture of how these systems operate. A water safety plan is unique in that it focuses not only on water quality monitoring but also on operational practices (WHO, 2012, Bartram et.al., 2009). The tile plots presented in Figure 8.7 and the PCA diagrams in Figure 8.3 and 8.4 show key interactions between these types of hazardous events (monitoring, maintenance and operational). Understanding these interactions leads to improved quality water monitoring programs: instead of monitoring water quality parameters dictated by regulatory guidelines, optimized sample collection is informed by how operational practices relate to water quality parameters. In small systems water safety planning, steps four through six outline steps to be taken after hazard identification has been completed (WHO, 2012). Among these steps are the optimization and follow-through of monitoring plans and improvement plans (WHO, 2012, WHO, 2018). Utilizing the data analysis techniques presented is this study, utilities and regional authorities can make informed decisions about monitoring plans.

8.5.3 Future studies

This study examined cluster analysis and PCA across fourteen water systems with the chlorination module and the distribution system module. Next steps to better understand the water system holistically need to analyze hazard relationships across modules. WSPs are designed to analyze risk from source to tap in a water system (Bartram et.al., 2009, WHO, 2012) and the analysis completed in this study needs to be extended to fully capture the entire water system. For example, inadequate monitoring of chlorine dose within a treatment facility can lead to chlorine residual degradation by the time water reaches the end of the distribution system. Analyzing both modules together gives a stakeholder in a water system a better understanding of how chlorination operations are impacting the distribution system. Future studies should include other source and treatment modules, such as sedimentation, filtration, etc. Chlorination and distribution operations were selected for this study since all fourteen systems had full data sets for these modules.

8.6 Conclusions

The objective of this study was to examine relationships between hazardous events in a water safety plan. Analysis of hazardous event relationships provides valuable data for policy making and interpretation of risks within water systems. Identifying hazardous events and risk levels alone is insufficient to design and implement appropriate monitoring programs at an individual system level and does not inform regional water quality policy making. The cluster analysis and principal component analysis completed in this study highlight the necessity of developing data analysis techniques to model relationships between risks in a water system. This analysis visually shows relationships between hazardous events and provides a new series of methods for externally auditing WSPs. Each visualization explored in this study provided different information to the key stakeholders in a water system. The dendrograms, tile plots and biplots inform operators which hazardous events are most likely to impact other events, thereby contributing to increased risk. The boxplots and dot plots provide valuable information for regulatory stakeholders, showing issues present across multiple water systems. While each plot informs a different stakeholder, the information generated allows all stakeholders to make important decisions about water system operations both at an individual and regional level. This study provided an initial exploration of data analysis techniques for identifying hazardous event relationships and continued research is needed to best understand the utility of this analysis in practice.

9 Chapter Nine – Conclusions

9.1 Introduction

This chapter provides a summary of the key findings generated from this thesis and how each hypothesis was proved or disproved by the studies presented in each chapter of this thesis. Study limitations are also explored and recommendations for future research to address these limitations are provided.

This thesis hypothesized the following three hypotheses in Chapter One:

1. Rural and remote water systems in Canada would benefit from the implementation of water safety plan frameworks.
2. A water safety plan provides more useful information to water regulators and policy makers than current water tools.
3. Water safety plan risk methodologies can be improved with the addition of quantitative water quality data.

These hypothesis statement lead to the development of the following objectives:

1. Develop and review a WSP for rural and remote water systems for use in this thesis (Hypothesis One)
2. Build a base of evidence for WSP implementation strategies in rural, remote and Indigenous water systems (Hypothesis One)
3. Review drinking water advisory and water safety plan methodologies to understand both current drinking water tools (DWA) and the current literature on WSPs (Hypothesis Two)
4. Compare the risk matrix method in a WSP to other methods or calculating probability of occurrence of hazardous events (Hypothesis Three)

In this thesis, these objectives were explored in a series of studies, presented in Chapters Two thru Eight. Chapter Two of this thesis examined the data set available from drinking water advisory reporting in three provinces, focusing on DWA characteristics and what information about risk is available. This chapter demonstrated the prevalence of operational issues in water systems, issues that cannot be addressed with current water quality regulations, pointing to the need for an improved risk management tool. The results from Chapter Two provide evidence suggesting **Hypothesis Two** is accurate. Chapter Six provides further evidence that water safety plans provide more information than current tools by comparing the information available in a system assessment report compared to a WSP. The comparison of information available in 2013 compared to 2018 (with the water safety plan) demonstrated the additional knowledge a WSP provides to a water system beyond regulatory guidelines and sampling requirements. This chapter provided clear evidence that a water safety plan provides more information, specifically about operations and maintenance of water systems than water quality monitoring alone.

Hypothesis One was explored in Chapter Three, Four, Five and Six. Chapter Four fulfilled Objective Two by developing a water safety plan specific to the rural and remote systems included in the subsequent studies. Chapter Three provided a desktop study of the added benefits of a WSP in remote communities in Nunavut, highlighting the clear need to consider local factors when designing and implementing a WSP. Chapter Five and Chapter Six provided evidence for both municipal and First Nation systems showing conditions conducive to successful water safety plan implementation. The strategies needed for a sustainable adoption of a WSP are different between municipal and First Nation systems but showing increased knowledge about the water systems in both situations after a trial of the water safety plan approach. The increased system knowledge alone is a clear added benefit of water safety planning that has been observed in previous studies, providing evidence hypothesis one is valid.

Finally, **Hypothesis Three** is explored explicitly in Chapter Seven of this thesis. Identified concerns with the risk matrix method traditionally applied in WSPs were presented in this chapter and two methods for calculating probability of occurrence based on water quality data were evaluated. Chapter Seven revealed that probability an event generated from the risk matrix approach is rarely an accurate estimation of the actual probability of occurrence calculated from water quality monitoring data. Risk calculated using a risk matrix is an underestimation or overestimation of the actual probability of occurrence in 75% of the water systems included in Chapter Seven, highlighting the need for clearer risk calculation procedures in WSPs. While water systems may not have sufficient data to completed probability calculations, in situations where data is available, these methods provide a link between the risk matrix method and a QMRA approach, focusing on operational data instead of only microbial data (WHO, 2016). “Sufficient data” is also a term that needs to be examined more closely; intermittent sampling for parameters such as arsenic in source waters does not constitute enough data to perform calculations, while having chlorine residual samples taken every minute may be too cumbersome a data set for water systems to analyze. More studies are needed to validate this result with other water quality parameters, however, Chapter Seven clearly meets Objective Four, providing evidence in partial support of Hypothesis Three. With the addition of other water quality parameters such as turbidity and temperature, and more water systems involved in the analysis, Hypothesis Three can be proved conclusively.

9.2 Key Findings

9.2.1 Key Finding One: DWAs communicate, but do not inform, risk in water systems

Evidence from Chapter Two of this thesis confirmed the prevalence of operational concerns within water systems in the Atlantic provinces, using data available from drinking water advisory records. However, while there is useful information available to communicate overall risk in water systems and highlight common concerns, the DWA alone cannot adequately address the individual issues encountered in every water system. Furthermore, inconsistent DWA reporting results in an incomplete data set across water systems. Historically, there has been a heavy reliance on DWAs as a method for communicating which water systems are most at risk for adverse water quality (Grover, 2011, Patrick, 2011, Eggerston, 2017). However, communicating risk alone does not provide regulators and policy makers with enough information to prioritize which water systems need the most urgent attention; more in depth hazard assessment is needed to better address the needs of these water systems. Chapter Two highlighted the lack of uniformity present in DWA reporting and the inability of the DWA to provide detailed information about risk in water systems. DWAs alone do not provide enough information to adequately address the multi-faceted issues prevalent across water systems, leading to the recommendation of a more substantial risk management methodology, such as water safety planning.

9.2.2 Key Finding Two: WSP development needs to move away from desktop studies and towards practical implementation studies

Outside of Alberta, there has been little to no practical implementation of the water safety planning approach in Canada. While several studies have examined strategies for sustainable WSP adoption, few have put these developed frameworks into actual practical to better understand the technical and human capacity needed to successfully implement a WSP. This thesis not only developed a tool that is a variation on WSPs for use in water systems (Chapter Four), but also solicited review of the WSP and worked with water system stakeholders to determine the factors limiting and promoting a successful WSP. Chapter Five focused on eight municipal water systems and Chapter Six evaluated WSPs in six First Nation systems. Chapter Three provided a desktop study of the theoretical hazardous events to be included in a WSP for Nunavut but did not apply these ideas to a specific community in Nunavut. In contrast, Chapter Five and Six consulted stakeholders from each community water system and actively refined the WSP developed in Chapter Four. The results from Chapter Five and Six provide more substantial information about the environment and prevailing attitudes in water systems that would hinder or aide the implementation of a WSP for policy makers and water quality regulators for better risk management strategies.

As a result, these studies reveal the importance of moving away from desktop studies of WSP applicability to water systems and moving towards more practical implementation studies in Canadian water studies. While desktop studies provide value to the overall body of literature on WSPs in Canada, without continuing studies of how WSPs will be implemented in practice, literature will not provide an accurate representation of the WSP as a risk management approach. Practical, applied studies prove the validity of considering technical capacity, funding structures and stakeholder choice in water safety planning in a way desktop studies can only theorize.

9.2.3 Key Finding Three: WSP Implementation will proceed differently in municipal and First Nation water systems

Building off Key Finding Two, studies of practical WSP implementation (Chapter Five and Six) illustrated the need for different WSP implementation strategies in municipal and First Nation water systems. Chapter Five revealed the presence of a predominant regulatory mindset in municipal water systems and demonstrated how attitudes to data collection automation and record keeping can inhibit successful WSP adoption. Chapter Six focused on First Nation systems and showed these same inhibiting factors are not present; instead, improvements in system specificity and presentation and communication of risk are needed for successful WSP adoption. The systems explored in this thesis exhibit many of the same characteristics as traditionally defined small systems, but also have lower operator turnover rates in both municipal and First Nations systems; therefore, future studies should be cognizant of how high operator turnover and a lack of record keeping procedures may change the conclusions observed in the fourteen systems included here.

The different factors inhibiting WSP implementation in these two types of water systems have not been previously explored in WSP literature. The differences between municipal systems and First Nations systems holistically are well documented, as is the importance of choosing appropriate solutions for each system based on community preference and beliefs surrounding water (Castleden et.al., 2017, Jimenez et.al., 2014). However, WSP literature, particularly in Canada, has not addressed the different strategies for WSP implementation needed for each of these types of water systems. WSPs are designed as a system specific tool (Bartram et.al., 2009, WHO, 2012) and while different characteristics between systems have been noted, this thesis provides the first analysis of the practical considerations needed to successfully introduce and sustain a WSP in both First Nation and municipal water systems.

9.2.4 Key Finding Four: Risk matrices predominantly under or overestimate risk compared to water quality data

Water safety plans, historically, have used risk matrices to evaluate risk (WHO, 2012), but studies of risk matrices have demonstrated that risk matrices have inherent issues (such as suboptimal resource allocation, lack of resolution, and poorly defined inputs) that may lead to under- or over-estimation of risk (Cox Jr., 2008). Chapter Three provided an evaluation of the descriptions of likelihood and consequence in WSP risk matrices as well as the scoring methods used in several global jurisdictions. This review showed no common risk matrix is used when developing WSPs, leading to the concern that variations in risk matrices are causing over or underestimation of risk in some jurisdictions. Chapter Seven evaluated the appropriateness of using a risk matrix by comparing the likelihood scores in the risk matrix method to the probability of occurrence calculated using water quality data, looking specifically at chlorine residual data. This study showed that data availability directly influences how accurate these calculations are as most water systems tended to overestimate or underestimate risk using the risk matrix method. The magnitude of the over- or under-estimation is also a concern, with the difference between the risk matrix and water quality data being more than three degree of magnitude in some situations. Two different probability of occurrence calculations were reviewed, and neither was able to accurately match the results from the risk matrix. This study concluded that further evaluation of risk analysis techniques for water safety plans are needed and data availability will play a key role in which water systems will be able to use these more advanced risk analysis calculations.

The identified issues with the accuracy of the risk matrix method will influence how new jurisdictions integrate water safety planning in water systems not previously using this method. The risk matrix methodology is only one of three variations of the water safety plan: the simpler version is the sanitary survey and the more data intensive version is the QMRA (WHO, 2016). However, neither the risk matrix method nor the QMRA approach use operational data such as turbidity measurements or records of pump failures to calculated risk in a water system. Given the low accuracy rate of the risk matrix compared to water quality data, it is clear that another variation on the WSP is needed, one that integrates operational data already collected in a water system to better characterize risk. The data intensiveness of a QMRA often limits small or remote water systems from applying this approach; however, a new variation of the WSP that moves to quantitative data analysis and away from the semi-quantitative risk matrix would provide a logical entry point to water safety planning for these types of water systems.

9.2.5 Key Finding Five: Risk Communication is critical to WSP effectiveness long-term

The final key finding of this thesis is the importance of communicating risk clearly to all of the stakeholders in a water system. Evidence presented in Chapter Six showed that accurate communication between stakeholders in a water system is critical to WSP adoption and the risk results generated by a WSP need to be presented in a clear and comprehensible format. Chapter Eight provided a first look at how clustering algorithms and principal component analysis could be used to extract additional information from the results generated by a water safety plan. Previous WSP case studies have only presented the results from a WSP as a table or list of prioritized hazardous events with risk levels included. This study showed that clustering analysis and the use of dendrograms may provide a usual data visualization that gives a stakeholder a better idea of how hazardous events are related in a water system. Chapters Five and Six showed there is a desire for better visualization outputs from a WSP and the dendrograms included in Chapter Eight are a first step towards a more cohesive way of relating hazardous events visually. Chapter Eight also demonstrated that principal component analysis is another analysis technique to evaluate which hazardous events most impact a water system by looking at the relationship between hazards. Both of these techniques are well documented in risk analysis literature but have not been previously applied in the realm of water safety plans. This thesis demonstrated that there is potential added value to a WSP if these techniques are utilized.

9.3 Recommendations

9.3.1 Recommendation One: Implement a management strategy that identifies and communicates risk to key stakeholders in water systems

The predominance of operational concerns identified by DWAs highlights the need for a water management strategy focused on process-related concerns in addition to water quality monitoring. The reported reason for a DWA pinpoints overall concerns, not the underlying issues that led to DWA issuance. In depth hazard identification is needed to accurately catalogue water system deficiencies, a process that can be completed using a WSP. In addition, after hazard identification is completed, communication of prioritized risk to relevant stakeholders is critical to the success of a new operational strategy. Both the identification and communications of hazards and risks in a water system is key to new and successful water management strategies. Water system stakeholders should focus on implementing such strategies to alleviate chronic operational concerns.

9.3.2 Recommendation Two: Develop Canadian WSP studies focused on community-based research

Desktop studies of WSP implementation in Canada are insufficient to adequately understand the practical challenges and benefits of the WSP approach. Prior studies have failed to actively incorporate community stakeholder input into the WSP process. Engaging with municipal and First Nation stakeholders revealed important improvements needed in the WSP process and key barriers to implementation. Personal interactions with stakeholders in a water system provides researchers with information unobtainable by examining available water system documentation alone. In addition, unclear added benefits have historically resulted in difficulty securing stakeholder buy-in to a water safety plan approach. Engaging stakeholders as both sources of information and as primary researchers in the WSP process provides the most benefit to WSP implementation studies by c. Subsequently, recommendation two advocates increased community-based research to involve all stakeholders in the WSP process.

9.3.3 Recommendation Three: Develop stepwise WSP implementation strategies, integrating appropriate regulatory stakeholders

WSP implementation requires a progressive strategy, specific to water system policies and regulatory environments. Full, immediate WSP adoption does not provide the most sustainable method to successfully change water system mindsets. Both Chapter Five and Six examined different stakeholders in a water system, highlighting the importance of an operator-informed hazard identification process and the need to include external auditing procedures to ensure WSP effectiveness. In the Canadian water governance structure, regulatory stakeholders need to play the role of external auditor. Regulatory mindsets in water systems will be difficult to overcome if WSPs are required federally or provincially; as a result, the regulator needs to have a defined role in the WSP process that supports operators in a water system. WSP implementation involves several stakeholders and successful adoption requires a stepwise strategy that actively and effectively defines a role for each stakeholder.

9.3.4 Recommendation Four: Integrate risk analysis of water quality data into WSPs to best quantify probability of occurrence

Chapter Seven demonstrated risk matrices underestimate or overestimate probability of occurrence compared to water quality data. This key finding reveals the necessity of risk analysis research tailored specifically to water quality data. The risk matrix method is a valid approach in data scarce water systems; however, as data gathering technology improves, water systems can use water quality data to determine probability of occurrence for indicator water quality parameters (such as chlorine residual, turbidity, pH, temperature, etc.). Future studies need to examine risk analysis techniques specific to water quality parameters, analysis techniques that can be integrated into the WSP process. Integration of these techniques provides the WSP method with research-based and validated risk analysis methodologies, strengthening the argument for WSP implementation globally.

9.3.5 Recommendation Five: Investigate methodologies for clear risk communication between water system stakeholders

Chapter Five and Six noted a need for risk result visualization, explored further in Chapter Eight. The overarching conclusion from all three studies is the necessity of data visualizations and tools to analyze and communicate risk to all stakeholders in a water system. Understanding relationships between hazards showcases an unexplored added benefit of the WSP process. The presence of hazard relationships better informs operational decisions in a water system and can be used to communicate priority concerns to all water system stakeholders. Chapter Five and Six highlighted the importance of understanding WSP results beyond the operator level and the need for results explanation for decision makers in the water system. Effective communication of risk bridges the gap between the multiple stakeholders in a water system and further research is needed to understand the best methodologies to do so.

9.4 Conclusions

This thesis has provided an in-depth evaluation of water safety plan development and implementation in Atlantic Canada, both from a municipal and Indigenous perspective. There are challenges to successful implementation, such as a predominant regulatory mindset, the need for better risk assessment methods and the differences between each type of water system. Successful and sustainable implementation will follow a different path for municipal and Indigenous water systems as these water systems are characterized by different attitudes to water safety planning. Calculations of probability of occurrence that used water quality data, either under or overestimated the risk calculated by a risk matrix, demonstrating a need to further consider how appropriate a risk matrix is, especially in a water system with a wealth of water quality data available. This thesis also demonstrated the clear need for better methods for communicating risk to all stakeholders within the water system. Visualization of water safety plan results is critical to the utility of a WSP: not only from a stakeholder's perspective, but as a tool to better understand how hazardous events are related in a water system. Clustering analysis and principal component analysis provide two options that were considered in this thesis and should be further explored to understand the benefits these methods could provide to a stakeholder.

The water safety planning method provides a valuable tool for managing risk in a water system but needs revision and audit to determine how this method should be best adapted to the variability inherently present in water systems.

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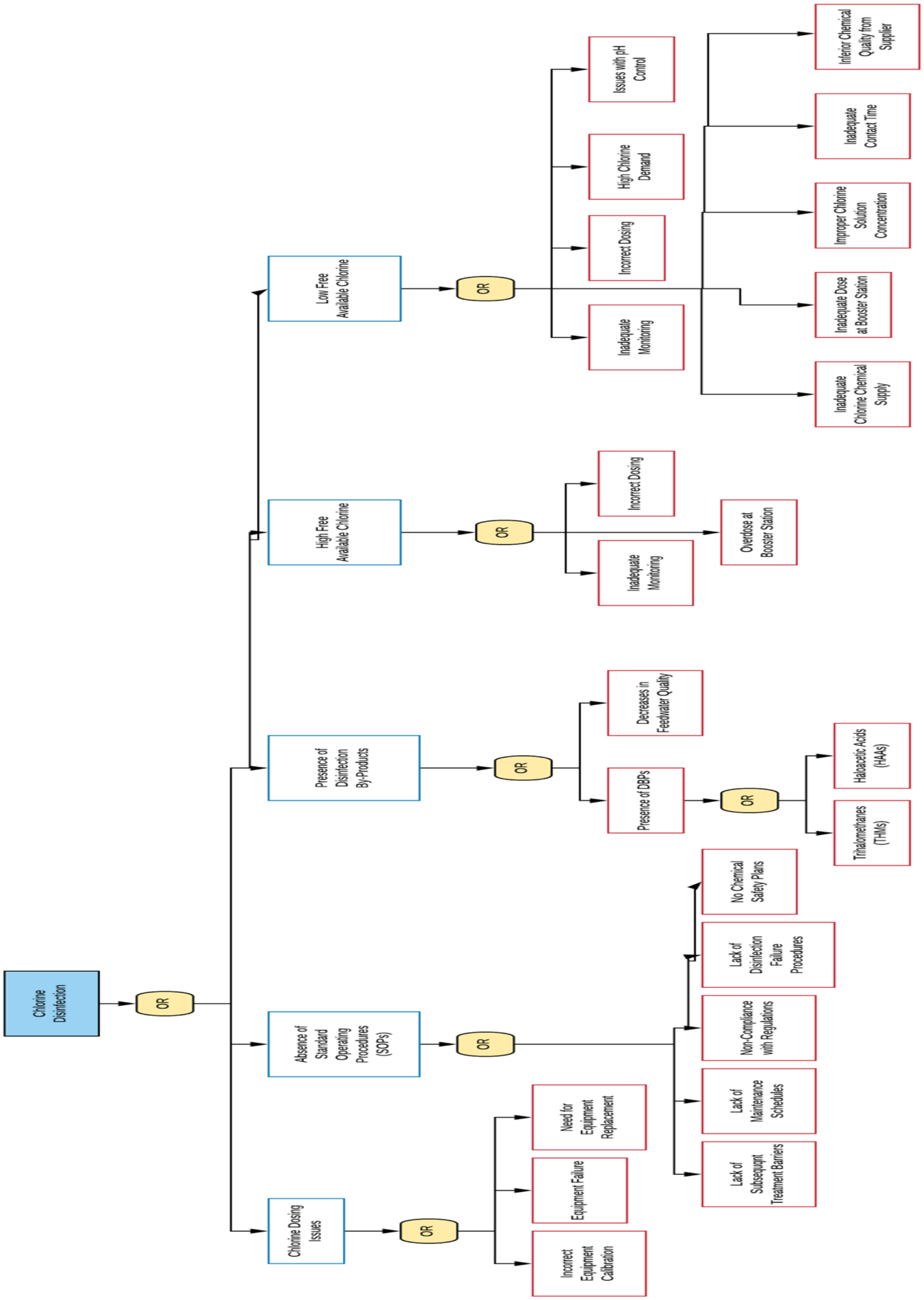
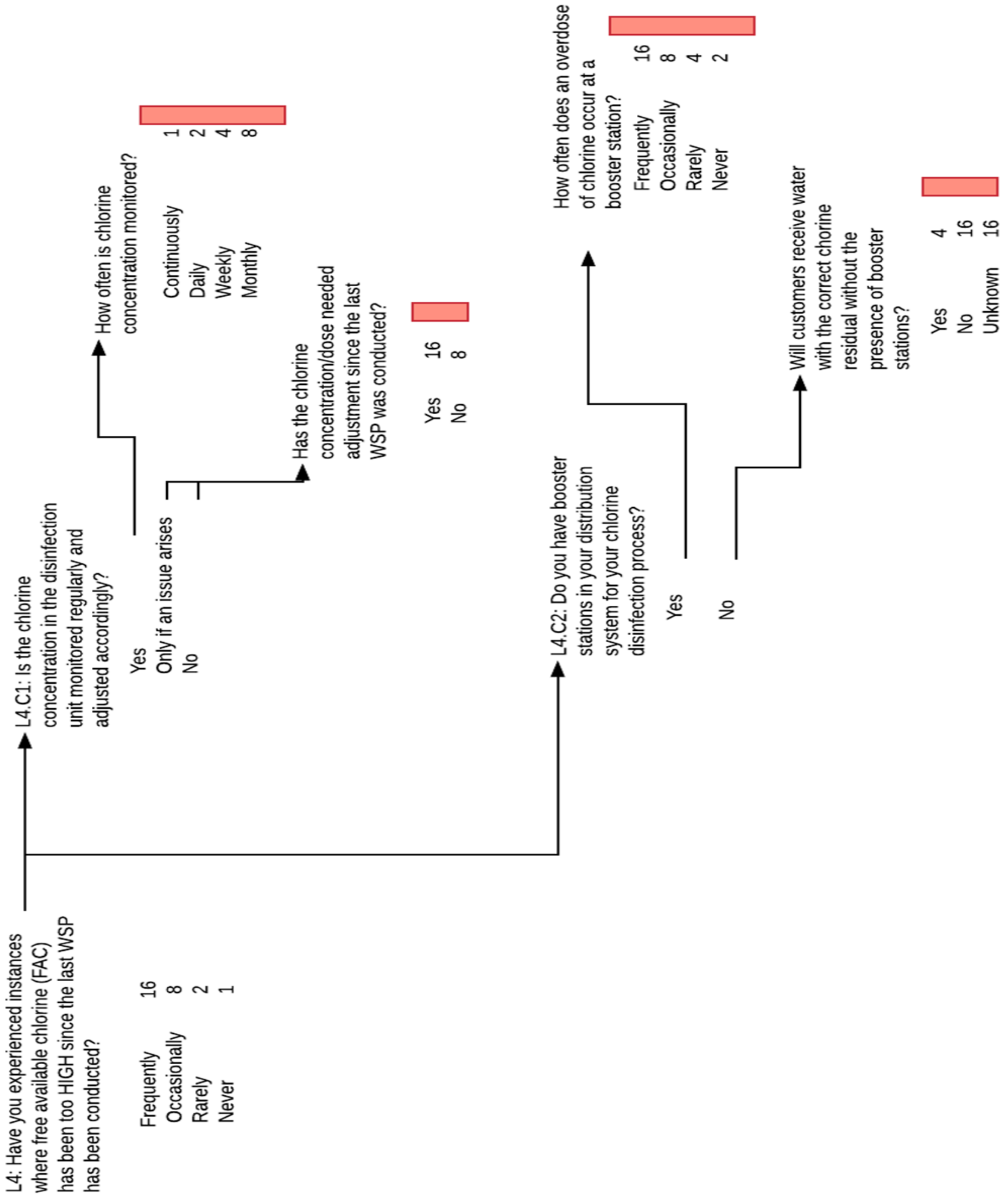
Appendix A: Chlorination Fault Tree



Appendix B: Example Survey Flowchart



Appendix C: Hazard Identification Documentation

Section of WSP: Treatment
System Process: Chlorine Disinfection

Instructions:

Please select which hazardous events have occurred since the last WSP was conducted or could possibly occur within your water supply system before the next WSP is conducted. For each hazardous event listed, please indicate the likelihood and consequence of the hazard occurring for an initial assessment of perceived risk. If a hazard or hazardous event is not present in the table presented below, there are available spaces to add system specific hazards to the table. Please review the definitions of hazard and hazardous event before adding additional system specific risks to the hazard identification table.

Definitions:

Water Supply System – The combination of source water, treatment processes and the distribution system that is used to obtain, treat and deliver water to customers.

Hazard – An identified event that poses a risk to your water supply system. Hazards are divided into hazardous events to specify the occurrence of these events within the water supply system.

Hazardous Event – An occurrence that affects water quality or water quantity produced by the water supply system and which could have impacts on customer health.

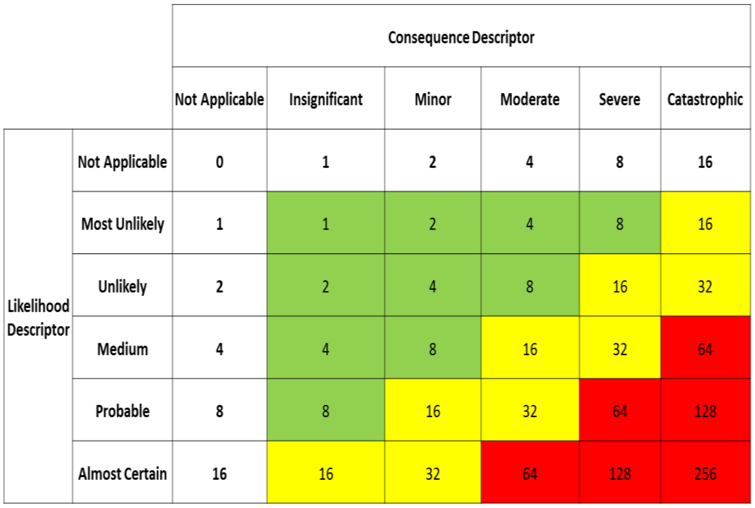
Likelihood – The probability that a hazardous event could occur within your water supply system.

Consequence – The severity of a hazardous event should that event occur within your water supply system.

Risk – The quantitative figure that describes the combined probability and severity of hazardous events within the water supply system to help an operator or WSP user prioritize improvements and align safety concerns.

Score	Likelihood	Consequence
0	Not Applicable	Not Applicable
1	Highly Unlikely	Insignifcant
2	Unlikely	Minor
4	Medium	Moderate
8	Probable	Severe
16	Almost Certain	Catastrophic

Table 1.0: Risk scoring method for hazard identification.



		Consequence Descriptor					
		Not Applicable	Insignificant	Minor	Moderate	Severe	Catastrophic
Likelihood Descriptor	Not Applicable	0	1	2	4	8	16
	Most Unlikely	1	1	2	4	8	16
	Unlikely	2	2	4	8	16	32
	Medium	4	4	8	16	32	64
	Probable	8	8	16	32	64	128
	Almost Certain	16	16	32	64	128	256

Table 2.0: Risk matrix constructed from the product of the likelihood and consequence scores given to a particular hazard.

Hazard Identification Table

System Module: Chlorine Disinfection	Likelihood	Consequence
HAZARD: Not enough free available chlorine (Low FAC)		

	Dosing malfunction		
	High chlorine demand		
	Poor dose control		
	Power failure		
	Incorrect calibration of dosing controller		
	Dose controller's setpoint incorrect		
	Chlorine chemical supply exhausted		
	Booster station failure (if applicable)		
	High pH in chlorine contact tank		
	Chlorine solution quality deterioration: sun exposure		
	Chlorine solution quality deterioration: age of solution		
	Chlorine solution quality deterioration: poor chemical quality		
	Monitoring of chlorine concentration		
HAZARD: Excessive formation of Disinfection By-Products (DBPs)			
	Organic matter (NOM) not sufficiently removed before chlorination		
	Monitoring for disinfection by-products (THMs and HAAs)		
HAZARD: Too much free available chlorine (high FAC)			
	Dosing malfunction		
	Low chlorine demand		
	Poor dose control		
	Dose controller's setpoint incorrect		
	Chlorine solution concentration too high		
	Chlorine overdose at booster station (if applicable)		
	Monitoring of chlorine concentration		
	Incorrect dose calculation		

HAZARD: Insufficient Standard Operating Procedures (SOPs) for chlorine disinfection			
	Maintenance schedules for chlorine disinfection		
	Chemical safety procedures for chlorine disinfection		
	Concerns with non-compliance with guidelines		
	Backup system or additional treatment barriers not available		
	Alarm system ineffective or not installed		
HAZARD:			
HAZARD:			

Hazard Identification

Section of WSP: Distribution System

System Process: Operations

Instructions:

Please select which hazardous events have occurred since the last WSP was conducted or could possibly occur within your water supply system before the next WSP is conducted. For each hazardous event listed, please indicate the likelihood and consequence of the hazard occurring for an initial assessment of perceived risk. If a hazard or hazardous event is not present in the table presented below, there are available spaces to add system specific hazards to the table. Please review the definitions of hazard and hazardous event before adding additional system specific risks to the hazard identification table.

Definitions:

Water Supply System – The combination of source water, treatment processes and the distribution system that is used to obtain, treat and deliver water to customers.

Hazard – An identified event that poses a risk to your water supply system. Hazards are divided into hazardous events to specify the occurrence of these events within the water supply system.

Hazardous Event – An occurrence that affects water quality or water quantity produced by the water supply system and which could have impacts on customer health.

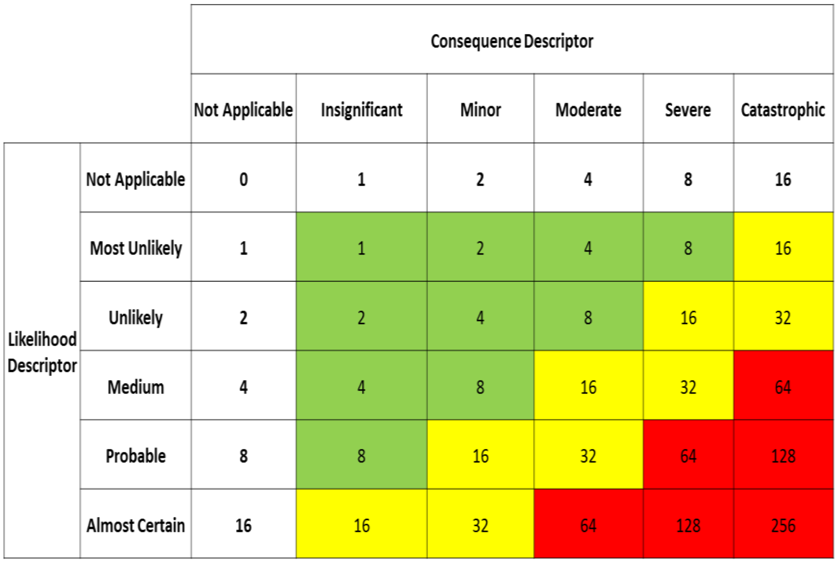
Likelihood – The probability that a hazardous event could occur within your water supply system.

Consequence – The severity of a hazardous event should that event occur within your water supply system.

Risk – The quantitative figure that describes the combined probability and severity of hazardous events within the water supply system to help an operator or WSP user prioritize improvements and align safety concerns.

Score	Likelihood	Consequence
0	Not Applicable	Not Applicable
1	Highly Unlikely	Insignifcant
2	Unlikely	Minor
4	Medium	Moderate
8	Probable	Severe
16	Almost Certain	Catastrophic

Table 1.0: Risk scoring method for hazard identification.



		Consequence Descriptor					
		Not Applicable	Insignificant	Minor	Moderate	Severe	Catastrophic
Likelihood Descriptor	Not Applicable	0	1	2	4	8	16
	Most Unlikely	1	🟩 1	🟩 2	🟩 4	🟩 8	🟨 16
	Unlikely	2	🟩 2	🟩 4	🟩 8	🟨 16	🟨 32
	Medium	4	🟩 4	🟩 8	🟨 16	🟨 32	🟥 64
	Probable	8	🟩 8	🟨 16	🟨 32	🟥 64	🟥 128
	Almost Certain	16	🟨 16	🟨 32	🟥 64	🟥 128	🟥 256

Table 2.0: Risk matrix constructed from the product of the likelihood and consequence scores given to a particular hazard.

Hazard Identification Table

System Module: Distribution System Operations			**Likelihood**	**Consequence**
HAZARD: Maintaining Distribution System Pressure				
		Insufficient water available in the distribution system		
		Leaks in the distribution system		
		Transmission pump failure		
HAZARD: Inadequate water quality monitoring in distribution system				
		Pipe breaks		
		Pipe incidents		
		System Pressure drops		
		Presence of cross connections unauthorized by the water system		
HAZARD: Presence of Sediment and/or Biofilm				
		High Flow rate entering the distribution system		
		Sediment buildup		
		Biofilm presence		
		Iron precipitation within pipes		
		Manganese precipitation within pipes		
		Chlorine residual degradation		
HAZARD: SOPs for Maintenance and Cleaning				
		Flushing procedures		
		Staff training		
		Hygenic practices for samplers		
HAZARD: Repair practices are not effective or are a potential source of contamination				
		Leak isolation procedures		
		Repair materials are of improper or poor quality		
		Bypasses are incorrectly implemented during pipe repair		
HAZARD:				

Appendix D: Example Operator Questions

Chlorine Disinfection – Hazards and Knowledge Questions

Hazard	What do we need to know?
Equipment Calibration	• How often do you calibration your chlorine analyzers • Are people trained to correctly calibrate analyzers
Equipment Failure	• How often have chlorine analyzers failed • Do you have a record of failures • Have any of your other automated pieces of equipment failed
Equipment Replacement	• Have you had to replace chlorine analyzers this year • Is any automated component in your chlorination system going to need replacement this year
Maintenance Schedules	• Do you have a DOCUMENTED maintenance schedule/plan • Is this plan according to a manufacturer's standard • How often are regular maintenance activities carried out
Compliance with Requirements	• Does your chlorination system comply with provincial and federal regulations • Has your chlorine residual ever been below the requirement (0.2 mg/L free chlorine)
Disinfection Failure Procedures	• Do you have an SOP or disinfection failure procedure for your chlorination system • Is this documented
Subsequent Treatment Barriers	• Do you have secondary disinfection • Is there a treatment barrier after disinfection (could include a clearwell for contact time or secondary disinfection)
Chemical Safety	• Do you have a chemical safety plan • Are your chemicals properly stored
Disinfection By-Products (DBPs)	• Do you measure disinfection by products (such as THMs and HAAs) in your treated water • How often do you measure DBPs • Have you ever exceeded a provincial or federal guideline for DBPs
Feedwater Conditions	• Do you monitor your raw water for any of the following: turbidity, TOC, DOC, DO or natural organic matter (NOM) • How often do you monitor raw water for these parameters
High Cl2 Monitoring	• How often are you measuring chlorine dose and residual • Has it ever been too high (this depends on what you define as too high) • Have you ever had an alarm for chlorine higher than normal
High Cl2 @ Booster Stations	• Do you have booster stations in your distribution system • Have you ever had an over dose of chlorine at a booster station
Incorrect High Cl2 Dose	• Do you monitor chlorine dose

	• Has your dose been too high in the past year
Low Cl2 Monitoring	• How often are you measuring chlorine dose and residual • Has it ever been too low (this depends on what you define as too low) • Have you ever had an alarm for chlorine lower than normal
Dosing Controls	• Is your dose automatically controlled by an analyzer or do you have to prepare doses of chemical in batches yourself • Have any chlorination pumps failed this year
Chlorine Supply	• Do you have a pump to provide chemical chlorine to a solution • Have you ever run out of chlorine chemical during operation
Chlorine Concentration	• Do you have a way of measuring chlorine concentration in your mixing or contact chamber • How often are you measuring chlorine concentration in your mixing or contact chamber
Chlorine Demand	• Have you ever had high or seasonally higher chlorine demand • Was this high demand as a result of changes in source water quality
Contact Time	• Do you monitor contact time (CT) • How often do you monitor CT
Chemical Supplier	• Do you have a reliable supplier for chlorine chemicals (chlorine, pH adjustment, etc.) • Is your chlorine supplier providing consistent chemical quality (basically, is it always a good product)
pH Control	• Do you monitor pH in your chlorine contact or mixing chamber • Do you adjust pH in your chlorine contact or mixing chamber • How often do you monitor pH in your chlorine contact or mixing chamber
Low Cl2 @ Booster Stations	• Do you have booster stations in your distribution system • Have you ever had a booster station fail (and not provide enough chlorine residual)

Notes for thinking about these hazards:

1. When we ask you survey questions, we are generally asking about what happened in this past year. Our surveys are designed to be taken 1-2 times a year as a system assessment to determine risk.
2. Unknown is an option on many of our survey questions – this will normally fall under moderate risk so its fine not to know everything
3. When we ask about “too high” or “too low”, this is in reference to your system. Whatever your operational parameters are for this parameter should be what you use to answer this question
4. Having lots of people help you answer any of these questions will be very important since everyone is going to have a different answer. We ask questions where the options are “frequently”, “occasionally”, “rarely” or “never” and how these get answered will absolutely depend on the person answering the question.

Distribution System Operations – Hazards and Knowledge Questions

Hazard	What do we need to know?
Insufficient Water Available	• Do you have water withdrawal permits • Have you ever exceeded your water withdrawal permits • Do you experience seasonal changes in how much water you are producing (is there more use in the summer vs. winter) • Do you ever have high demand that you can't meet or is really hard to meet
Leaks in System	• Do you know if any of your pipes have leaks • If you do have leaks, how quick can your staff fix them
Transmission Pump Failure	• Does the pump that transfers water from the plant/clearwell to the distribution system ever fail • If it does fail, how often • Will this pump need repair or replacement soon • Has this pump been repaired in the past year
Pipe Breaks	• Have any of your pipes broken in the past year (completely sheared or a section had to be replaced)
Pipe Incidents	• Have there been any other issues with your pipes besides leaks or breaks that have occurred (issues with corrosion, biofilm, sediment buildup, etc.)
System Pressure Drops	• Do you monitor pressure anywhere in your distribution system • At how many points in your distribution system do you monitor pressure • Have you seen any drastic drops in pressure in the past year to any of your connections
Cross Connections	• Do you know if there are any cross connections in your distribution system • Do you know if there are any unauthorized connections to your system • Do you water mains run near any wastewater mains, power cables, other cables, etc.
High Flow Entering	• Do you ever experience a higher than normal flow rate entering your distribution system • Do you monitor flow rate entering your distribution system • Do you monitor flow rate at any other points in your distribution system
Sediment Buildup	• Have you ever checked your pipes/mains for sediment buildup • Do you measure turbidity or total dissolve solids (TDS) in your distribution system – if so at how many points • Have you ever had issues with high turbidity or total dissolve solids in your distribution system

Biofilm Presence	• Have you ever checked your pipes or mains for biofilm growth (this can include doing a heterotrophic plate count (HPC) or ATP test) • Have you ever had biofilm growth in your distribution system
Iron Precipitation	• Do your measure iron in your distribution system – if so at how many points and how often • Have iron levels in the distribution system ever exceeded a provincial or federal guideline?
Manganese Precipitation	• Do your measure manganese in your distribution system – if so at how many points and how often • Have manganese levels in the distribution system ever exceeded a provincial or federal guideline?
Cl2 Residual Degradation	• Do you measure chlorine residual in your distribution system – if so at how many locations and how often • Do you have booster stations in your distribution system
Flushing Procedures	• Do you have a schedule, plan or procedure for flushing your mains/pipes • How often do you flush your mains/pipes
Staff Training	• Do you have at least one certified individual to operate the distribution system • Do you have at least one trained individual to operate the distribution system
Leak Isolation	• Do you have a procedure or plan for isolating a leak should one occur • Is your leak isolation plan documented and available for all staff members and operators
Hygienic Sampling Procedures	• Do you take samples for *E. coli*and total coliforms in your distribution system • Do you have an assigned laboratory that takes care of these samples • Do you have a trained sampler who knows the hygienic sampling procedures to avoid cross contamination in these types of sample
Repair Materials	• If a leak or break occurs, is the pipe material upgraded to a better product • If a leak or break occurs, are connections made from a material that is safe for your system (ideally will not cause corrosion)
Bypasses	• Do you have a procedure for bypasses sections of the distribution system should the need arise • Are these bypass procedures documented for all staff and operators to review

Notes for thinking about these hazards:

1. When we ask you survey questions, we are generally asking about what happened in this past year. Our surveys are designed to be taken 1-2 times a year as a system assessment to determine risk.
2. Unknown is an option on many of our survey questions – this will normally fall under moderate risk so its fine not to know everything

3. When we ask about “too high” or “too low”, this is in reference to your system. Whatever your operational parameters are for this parameter should be what you use to answer this question
4. Having lots of people help you answer any of these questions will be very important since everyone is going to have a different answer. We ask questions where the options are “frequently”, “occasionally”, “rarely” or “never” and how these get answered will absolutely depend on the person answering the question.
5. Some of these things are really hard to answer and the surveys are designed that way so that really well-maintained systems show up as low risk an those with some unknowns come up at a different level so that monitoring activities can be scaled properly

Appendix E: Letters of Support from APC

The following letter was sent to each First Nation water system during the Phase One Project with the Atlantic Policy Congress. Email and phone replies from each community were obtained from all six communities included in Chapter Six of this thesis.

ATLANTIC POLICY CONGRESS
OF FIRST NATIONS CHIEFS SECRETARIAT

Water Safety Plans Pilot Program

What is a Water Safety Plan?

Water safety planning is an approach advocated by the World Health Organization (WHO) that aims to develop a preventative framework to protect and manage drinking water from source to tap. Water safety plans (WSPs) place more emphasis on risk assessment and risk management than water quality analyses. They are designed to be adaptable and flexible; using a holistic approach with community structure and socioeconomic variables considered as high priority inputs. A WSP is meant to be a “living document”; it evolves and improves as the plan is implemented and used by the community.

What is the Water Safety Plan Pilot Program?

On May 12, 2017, a resolution was passed at the APC All Chiefs Forum to support the organization of a Water Safety Plan Pilot. This pilot will be administered by APC in partnership with Dalhousie University’s Center for Water Resource Studies (CWRS).

A phased approach will be followed to pilot WSP’s in Six First Nations communities in the Atlantic Region. The project team will work with Water Operators, Monitors to tailor generic system surveys based on the individual system and operator needs. In addition, the surveys will be peer-reviewed by Environmental Health Officers to offer a public health perspective. The system surveys will then be incorporated into a user- friendly digital interface and implemented in each community.

How will this program benefit First Nations Communities?

The outcomes of this pilot program will provide participating First Nations communities with a completed Water Safety Plan that will accurately assess the hazards, hazardous events, risks and existing control measures for each individual system. As living documents, these plans can continue to be updated and adapt to changes in the future. Furthermore, Water Safety Plans could be incorporated into drinking water regulatory development under the proposed Atlantic First Nations Water Authority.

Contact Us

James MacKinnon

Policy Analyst - Team Leader Housing &

Infrastructure

Toll free: 1 877-667-4007

Phone: 1-902-435-8021 ext.1390

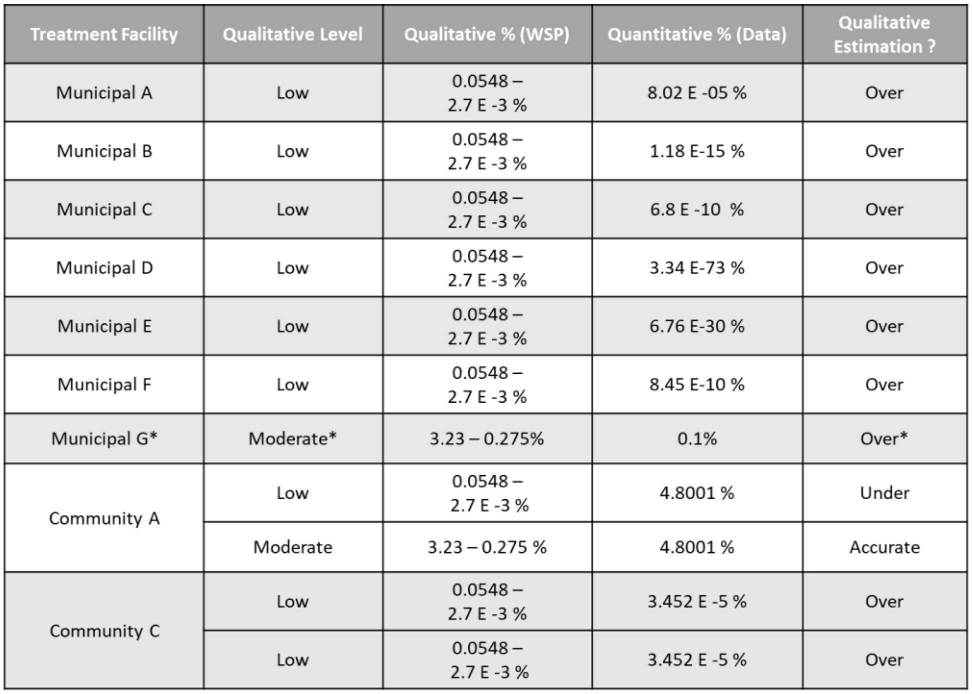
Fax: 1-902-435-8027

Email: james.mackinnon@apcfnc.ca

Appendix F: Supplemental Figures and Tables for Chapter Seven

Treatment Facility	Number of Samples	Best Fit Distribution	2nd Best Fit Distribution
Municipal A	366	Lognormal	Gamma
Municipal B	368	Gamma	Weibull
Municipal C	368	Gamma	Lognormal
Municipal D	349	Gamma	Lognormal
Municipal E	364	Gamma	Lognormal
Municipal F	369	Lognormal	Gamma
Community A	376	Weibull	Gamma
Community C	107	Gamma	Lognormal

Table F.1: First and second best fit distributions for grab sampling data for eight water systems. Municipal system G did not have grab samples available and best fit distributions could not be constructed as a result. The gamma distribution provides the best fit distribution for the majority of the water systems included, with the Lognormal distribution providing the majority of the second best fit distributions



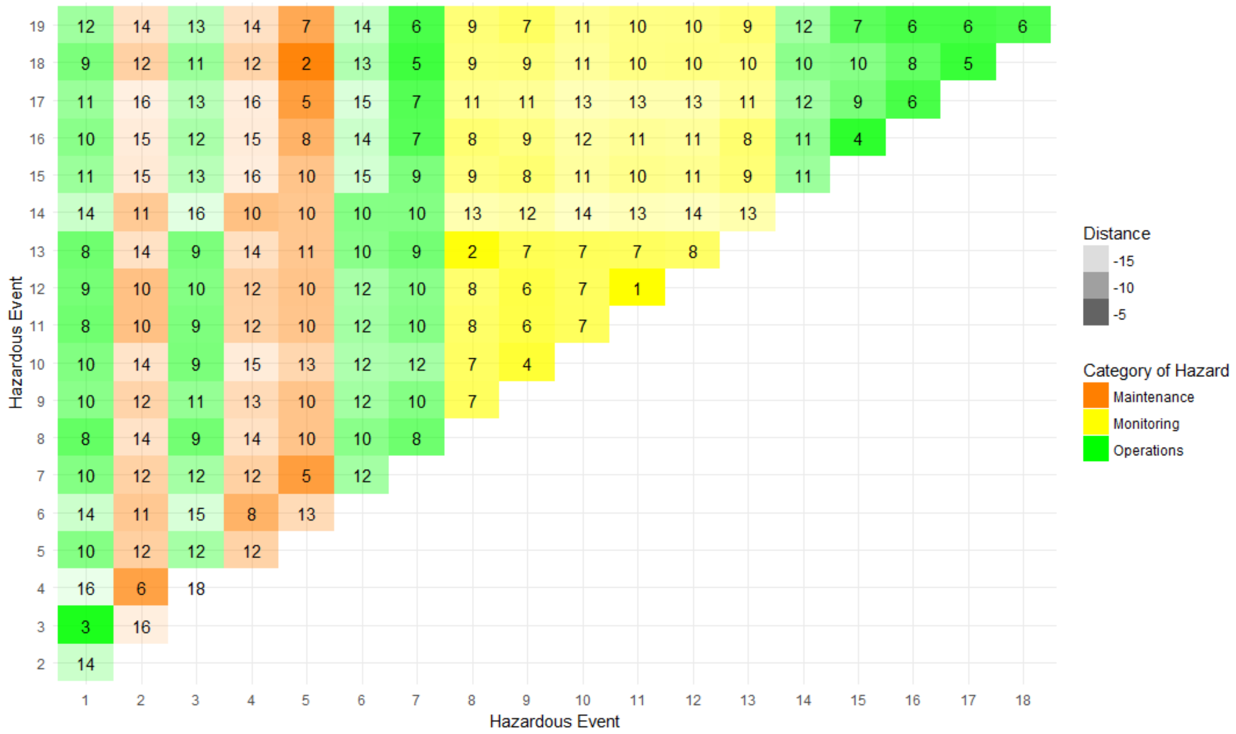
Treatment Facility	Qualitative Level	Qualitative % (WSP)	Quantitative % (Data)	Qualitative Estimation ?
Municipal A	Low	0.0548 – 2.7 E -3 %	8.02 E -05 %	Over
Municipal B	Low	0.0548 – 2.7 E -3 %	1.18 E-15 %	Over
Municipal C	Low	0.0548 – 2.7 E -3 %	6.8 E -10 %	Over
Municipal D	Low	0.0548 – 2.7 E -3 %	3.34 E-73 %	Over
Municipal E	Low	0.0548 – 2.7 E -3 %	6.76 E-30 %	Over
Municipal F	Low	0.0548 – 2.7 E -3 %	8.45 E-10 %	Over
Municipal G*	Moderate*	3.23 – 0.275%	0.1%	Over*
Community A	Low	0.0548 – 2.7 E -3 %	4.8001 %	Under
	Moderate	3.23 – 0.275 %	4.8001 %	Accurate
Community C	Low	0.0548 – 2.7 E -3 %	3.452 E -5 %	Over
	Low	0.0548 – 2.7 E -3 %	3.452 E -5 %	Over

Table F.2: This table presents the quantitative probability of occurrence using the probability density function method with grab sample data. The quantitative percentage data is calculated using this method and data set and compare the probabilities as calculated using the risk matrix approach. The final column describes if the risk matrix method is an overestimation, underestimation or accurate estimation of the probability obtained via calculation.

Treatment Facility	Qualitative Level	Qualitative % (WSP)	Quantitative % (Data)	Qualitative Estimation ?
Municipal A	Low	0.0548 – 2.7 E -3 %	0.21 %	Accurate
Municipal B	Low	0.0548 – 2.7 E -3 %	0.99 %	Accurate
Municipal C	Low	0.0548 – 2.7 E -3 %	0.139 %	Accurate
Municipal D	Low	0.0548 – 2.7 E -3 %	0.023 %	Accurate
Municipal E	Low	0.0548 – 2.7 E -3 %	0.36 %	Under
Municipal F	Low	0.0548 – 2.7 E -3 %	0.05 %	Accurate
Municipal G*	Moderate*	3.23 – 0.275 %	0.01 %*	Under*
Community A	Low	0.0548 – 2.7 E -3 %	0.01 %	Over*
	Moderate	3.23 – 0.275 %	0.01 %	Accurate*
Community C	Low	0.0548 – 2.7 E -3 %	0.013 %	Under
	Low	0.0548 – 2.7 E -3 %	0.013 %	Under

Table F.3: This table presents probabilities of occurrence calculated using the event tree method with SCADA data. The quantitative percentage data is calculated using this method and data set and compare the probabilities as calculated using the risk matrix approach. The final column describes if the risk matrix method is an overestimation, underestimation or accurate estimation of the probability obtained via calculation.

Appendix G: Supplemental Figures and Tables for Chapter Eight



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
19	12	14	13	14	7	14	6	9	7	11	10	10	9	12	7	6	6	6
18	9	12	11	12	2	13	5	9	9	11	10	10	10	10	10	8	5	
17	11	16	13	16	5	15	7	11	11	13	13	13	11	12	9	6		
16	10	15	12	15	8	14	7	8	9	12	11	11	8	11	4			
15	11	15	13	16	10	15	9	9	8	11	10	11	9	11				
14	14	11	16	10	10	10	10	13	12	14	13	14	13					
13	8	14	9	14	11	10	9	2	7	7	7	8						
12	9	10	10	12	10	12	10	8	6	7	1							
11	8	10	9	12	10	12	10	8	6	7								
10	10	14	9	15	13	12	12	7	4									
9	10	12	11	13	10	12	10	7										
8	8	14	9	14	10	10	8											
7	10	12	12	12	5	12												
6	14	11	15	8	13													
5	10	12	12	12														
4	16	6	18															
3	3	16																
2	14																	

Figure G.1: This figure presents a tile plot for the 19 hazardous events in the distribution operations assessment. The distance between each hazardous event is represented in the tile with the transparency also corresponding to the distance. The category of each hazardous event is represented by a different color and are colored based on the x-axis indices in the plot.

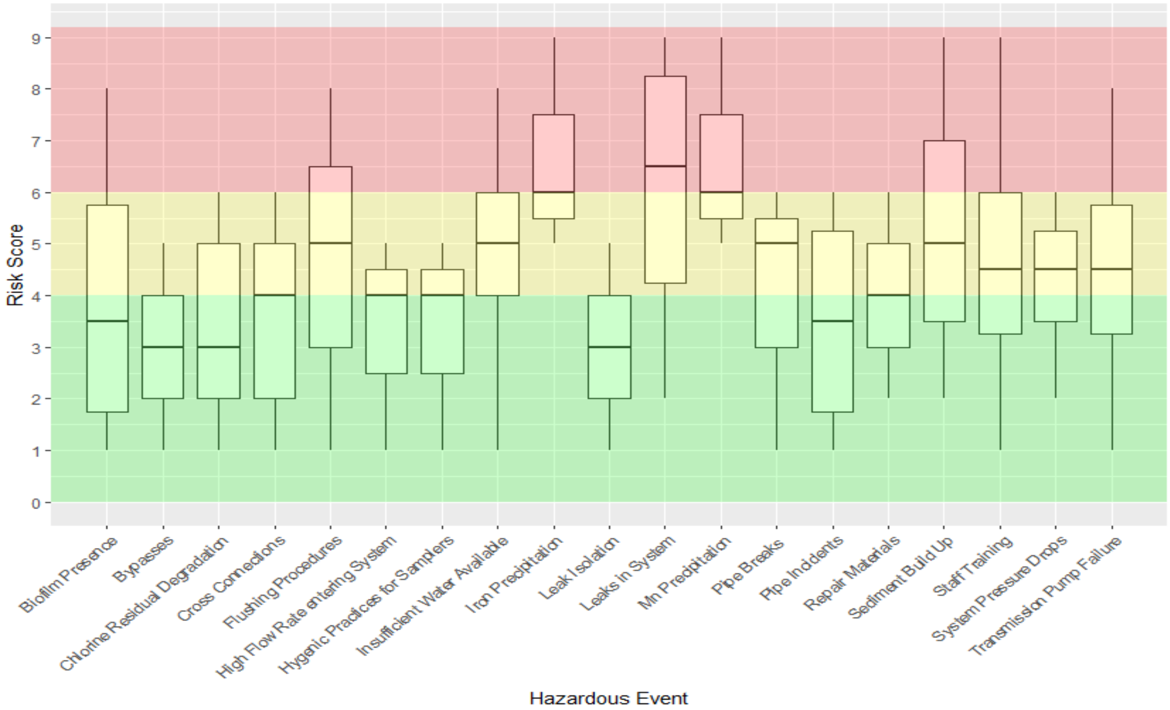


Figure G.2: Boxplot for the 19 hazardous events in the distribution system assessment. The risk levels are as follows: low risk represents a risk score 0-4, moderate risk represents a risk score 5-6 and high risk represents a score 7-9.

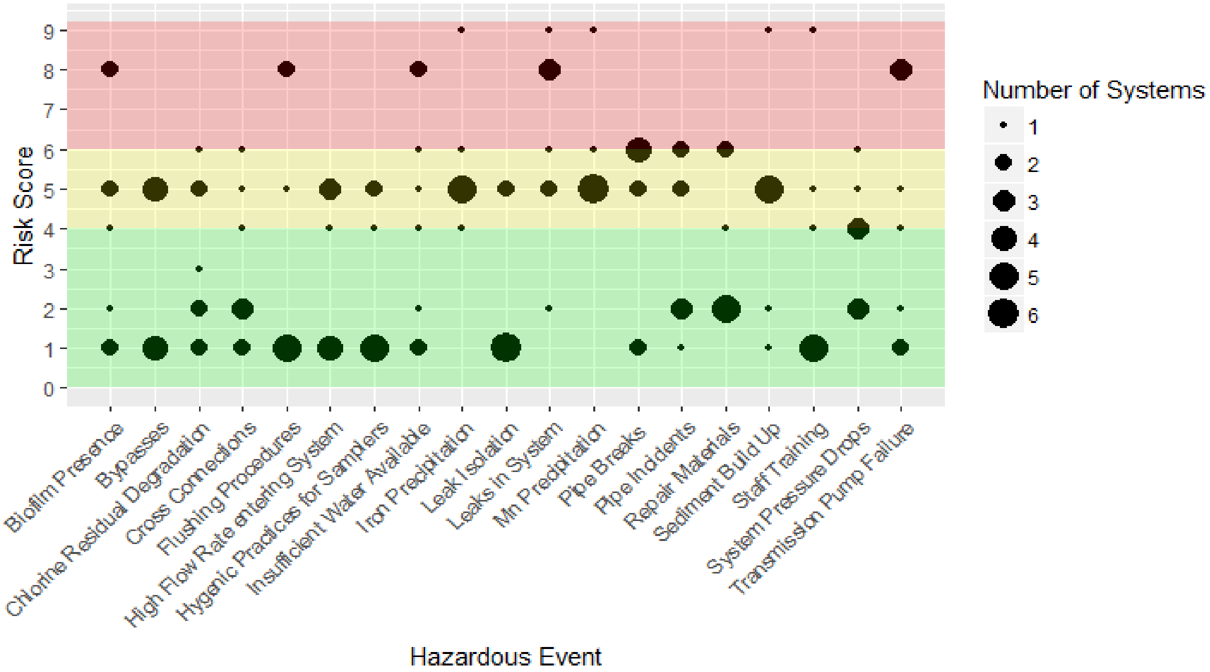


Figure G.3: Dot plot for risk scores for the 19 hazardous events in the distribution system assessment. The size of the point represents the number of water systems with the same risk score.

Appendix H: Permissions from Journals

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