PERFORMANCE ASSESSMENT OF SMALL WATER SYSTEMS IN BRITISH COLUMBIA

by

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Abstract

Delivery of safe and reliable drinking water to customers is essential to protect public health and maintain high quality of life. In Canada, provinces and territories have set their specific definitions for small water systems (SWSs), which is generally based on the population served and/or number of connections served. In this research, all water systems serving a population less than 5,000 are referred as small. The main objective of this research is to develop a performance assessment framework for British Columbia (BC) SWSs. The framework was developed focusing on the key aspects of drinking water quality management primarily related to the water distribution network (DN).

This research involved three distinct steps. First, a questionnaire was prepared and distributed to the local bodies (including regional districts, municipalities, and improvement districts) across BC. The distribution of the questionnaire resulted in responses from 66 SWSs (33%). Based on these responses, a summary of water quality issues and challenges of water systems were highlighted, which could help policy makers understand the current state of SWSs in BC. Turbidity, microbial contamination, high natural organic matters (NOMs) concentration, color, iron and manganese, high water age, low flow rate, disinfection by-product formation, residual chlorine levels, biofilm growth, and old pipes were identified as common water quality issues. Second, performance was assessed through the lens of drinking water quality management using five criteria: (1) treatment and disinfection; (2) water quality issues; (3) operators' capabilities; (4) infrastructure and funding; and (5) operational characteristics. The results indicated that the overall performance in the regional district water systems were comparatively better, followed by municipalities, and improvement districts. In all three local bodies, performance of SWS were primarily affected by the lack of advanced treatment

facilities, water quality issues in DNs, inadequate funding, and infrastructure replacement practices. Finally, a strategy based on a multi-barrier approach was proposed to ensure effective implementation of the performance assessment framework.

Findings of this study are useful for the managers of SWS to understand the strengths and weaknesses of their water systems. This comparative study is helpful in prioritizing issues for different types of SWSs.

Lay Summary

Source waters can be contaminated by various natural and anthropogenic causes. The consumption of contaminated water is detrimental to the human health. Therefore, the need for adequately treated and disinfected water is essential for the wellbeing of human beings. Chlorine is the most common disinfectant used for drinking water systems. Compared to medium and large water systems, small water systems (SWSs) are often more impacted by financial, technical, social, and infrastructural challenges. Very few studies have been conducted to understand the various water quality challenges associated with SWSs. This research aims to understand the current state of SWSs in British Columbia (BC). The findings of this study will help small water utilities to gauge own performance against similar water systems across BC. In addition, this research also provides an opportunity for SWSs owners to set baseline performance of their drinking water systems for consumers. The study indicated the need for strong communication among municipal managers, operators, and consumers to ensure safe drinking water.

Preface

I, Sarin Raj Pokhrel, have primarily conceived and developed all the contents in this thesis under the supervision of Drs. Rehan Sadiq, Manuel J. Rodriguez, and Kasun Hewage. Dr. Gyan Chhipi Shrestha has provided his valuable feedback and reviewed articles submitted to journals and conference proceedings. Some questionnaire results have been presented as a poster at the Canadian Water Summit and RES'EAU Annual General Meeting entitled with "Assessment of present status of small water systems in British Columbia" in June 2018. Questionnaire prepared for this research was approved by the Behavioral Research Ethics Board of the University of British Columbia, Okanagan campus certificate number, H17-02888.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AB	Alberta
AHP	Analytic Hierarchy Process
ANOVA	Analysis of Variance
ANN	Artificial Neural Network
AWWA	American Water Works Association
BC	British Columbia
BCWWA	BC Water & Waste Association
BWA	Boil Water Advisory
BWN	Boil Water Notice
$Ca(OCl)_2$	Calcium hypochlorite
CDWG	Canadian Drinking Water Guidelines
CFD	Computational Fluid Dynamics
Cl	Chlorine
ClO_2	Chlorine dioxide
ClO_3	Chlorate
DAF	Direct Air Flotation
DBP	Disinfection by-products
DN	Distribution network
DNU	Do Not Use Advisory
DWPA	Drinking Water Protection Act
DWPR	Drinking Water Protection Regulation

DWS	Drinking Water System
E.coli	*Escherichia coli*
ELCTRE	Elimination and Choice Expressing Reality
EOCP	Environmental Operators Certification Program
GAC	Granular Activated Carbon
GIS	Geographic Information System
HAAs	Haloaceticacids
HOCl	Hypochlorous acid
HPC	Heterotopic Plate Count
ID	Improvement district
IHA	Interior Health Authority
LSD	Local Service Districts
LWS	Large Water Systems
MCDM	Multi Criteria Decision Making
mg/l	Milligram per litre
MS Excel	Microsoft Excel
MU	Municipality
MWS	Medium Water System
NaOCl	Sodium hypochlorite
NCl_3	Nitrogen trichloride
NH_2Cl	Dichloramine
NH_3	Ammonia

NL	NewFoundland and Labrador
NOM	Natural Organic Matter
NTU	Nephelometric Turbidity Unit
PE	Prince Edward Island
pH	Power of hydrogen
PI	Performance Indicator
QC	Quebec
RD	Regional district
SK	Saskatchewan
SPSS	Statistical Package for Social Science
SWS	Small Water System
THMs	Trihalomehtanes
UDF	Unidirectional flushing
USEPA	United States Environment Protection Agency
UV	Ultra violet
WHO	World Health Organization
WSM	Weighted Sum Model
YT	Yukon

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I would also like to thank my committee member Dr. Kasun Hewage for his valuable comments and constructive suggestions. I am very thankful to Dr. Gyan Chhipi -Shrestha, my fourth unofficial advisor, and a brother, who served as a mentor throughout my tenure at UBCO. A big credit goes to Dr. Shrestha for his untiring time, efforts, and suggestions for helping me to improving my writings and providing me critical feedback on my research. My special thanks goes to Marni Turek for introducing me to the officials of various local bodies across BC. Marni’s continuous help and cooperation at the initial stage for gathering municipal contacts really helped me to collect more responses from the various local bodies. I am also thankful to Interior Health, Island Health, and Vancouver Coastal Health for sharing the contacts of the small utilities of their region. I am equally obliged to all the utility leaders, operators, engineers, directors, and managers of various regional districts, municipalities and improvement districts for spending their valuable time and providing their inputs to my questionnaire. Without their assistance, this research would not have been possible. This research also would not have been possible without the financial support from the Natural Sciences and Engineering Research Council (NSERC) and the RES'EAU WaterNET.

I would like to acknowledge my fellow researchers at the life cycle management laboratory. I appreciate the administrative staff of the School of Engineering especially Shannon Hohl, Tanya Chandra, Renee Leboe, Angela Perry, Sam Charles, Stephanie Oslund, and Barbra Hunter for their generous support. I would also like to thank Tracy, Peter, and their family for making my stay in Kelowna extremely pleasant. Although 10,000 kms away from my home, the parental care I have been receiving from Tracy's family is priceless. Special thanks to my Nepalese friends for cooking delicious Nepalese cuisine and inviting me over dinner occasionally.

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Dedication

To my mom Sandhya Pokhrel

dad Rishikesh Pokhrel

sister and brother in law, Sarina Pokhrel and Manjul Silwal, and

grandparents Bishnu Prasad Adhikari and Sumitra Adhikari

Chapter 1: Introduction

1.1 Background and motivation

Accessibility to safe drinking water is a fundamental right and basic need for humans (UN Water 2018a). The consumption of safe water not only promotes human health but can also have economic impacts (WHO 2018). Currently, 2.1 billion people across the globe do not have access to safe drinking water (UN Water 2018b). Globally, Canada is ranked third in freshwater resources with almost 7% of the world's renewable fresh water (Lui 2015). Albeit Canada is rich in freshwater resources, there are six million Canadians at risk of waterborne diseases (RES'EAU-WaterNET 2018). Furthermore, the current reinvestment level on linear assets (transmission lines, pipes, distribution network) and non-linear assets (treatment plants, pumping stations, and reservoirs) will compromise water supplies in Canada over time (Canadian Infrastructure Report Card 2016). Especially, in small communities, more than 25% of these drinking water assets do not meet the "good condition" criterion (Canadian Infrastructure Report Card 2016).

Health Canada (2013) defines a small water system (SWS) as a system serving a community with a population less than 5,000, but this definition varies from province to province. These water systems often face challenges such as insufficient funding, less availability of skilled manpower and advanced technologies, and inadequate water infrastructure, which pose a serious challenge to supplying safe drinking water to consumers (Moffatt and Struck 2011; Haider et al. 2014). Most SWSs do not use any advanced water treatments or use only chlorination as a treatment process (CBCL Ltd 2011). As a result, many SWSs that use surface water occasionally have water quality issues related to elevated colors and natural organic matter (NOM) (Patterson et al. 2012). Compared to surface water, groundwater is less vulnerable to microbial contamination, however, the risk of infiltration from agricultural runoff and contamination from human septic sources are contributing factors to groundwater (Moffatt and Struck 2011). The water quality deterioration and contamination in distribution networks (DNs) are major concerns for SWS operators. The water quality issues are potentially more severe in DNs since it is difficult to maintain an adequate concentration of residual disinfectant at the extremities of DNs (Simard et al. 2011).

The occurrence of water borne diseases in the majority of Canadian SWSs is relatively high due to poor drinking water quality resulting from inadequate treatment and disinfection practices and lack of source water protection plans (Moffatt and Struck 2011). As a result, some consumers in small communities rely on “single-use bottled water, which has economic, environmental, and social impacts far beyond the reaches of communities themselves” (Lui 2015).

Small water systems serve around 2.5 billion people across the globe, with over 30 million of those people living in North America (RES’EAU-WaterNET 2018). According to Statistics Canada (2010), there are more than 2,000 drinking water systems in Canada with almost 1,600 of these systems serving populations below 5,000 (Bereskie et al. 2017). These drinking water systems vary in size and complexity from community to community. Although drinking water systems have been studied extensively, there is a knowledge gap in assessing the performance of SWSs compared to medium and large water systems (Haider et al. 2014). Organizations such as the United States Environmental Protection Agency (US EPA) and Health Canada have set drinking water standards and guidelines to ensure safe drinking water supply to consumers. However, SWSs performance are also impacted by many other factors related to customer satisfaction, aesthetic quality, use of disinfectants, operators’ knowledge and experience, and funding availability (Bereskie et al. 2017).

The current study was primarily motivated by the following two main facts:

- The water quality issues and challenges in SWSs are greater compared to medium and large water systems (Hunter et al. 2009). However, there is very little information available on how these water quality issues affect the final quality of drinking water, especially in small communities.
- In the current study, the performance of SWSs related to treatment and disinfection, water quality issues, operators' capability, infrastructure and funding, and water quality monitoring frequency are specifically explored.

1.2 Research objectives

The main objective of this research is to determine the current state of SWSs in the province of BC, identify key challenges, develop and implement a performance assessment framework to strengthen the drinking water management systems. The specific objectives of the research are as follows:

1. Conduct a state-of-the-art review on drinking water quality management issues and challenges in SWSs.
2. Perform a questionnaire survey to highlight major water quality issues and water governance challenges in SWSs across BC.
3. Develop a framework to prioritize the performance criteria and indicators for various types of SWSs.

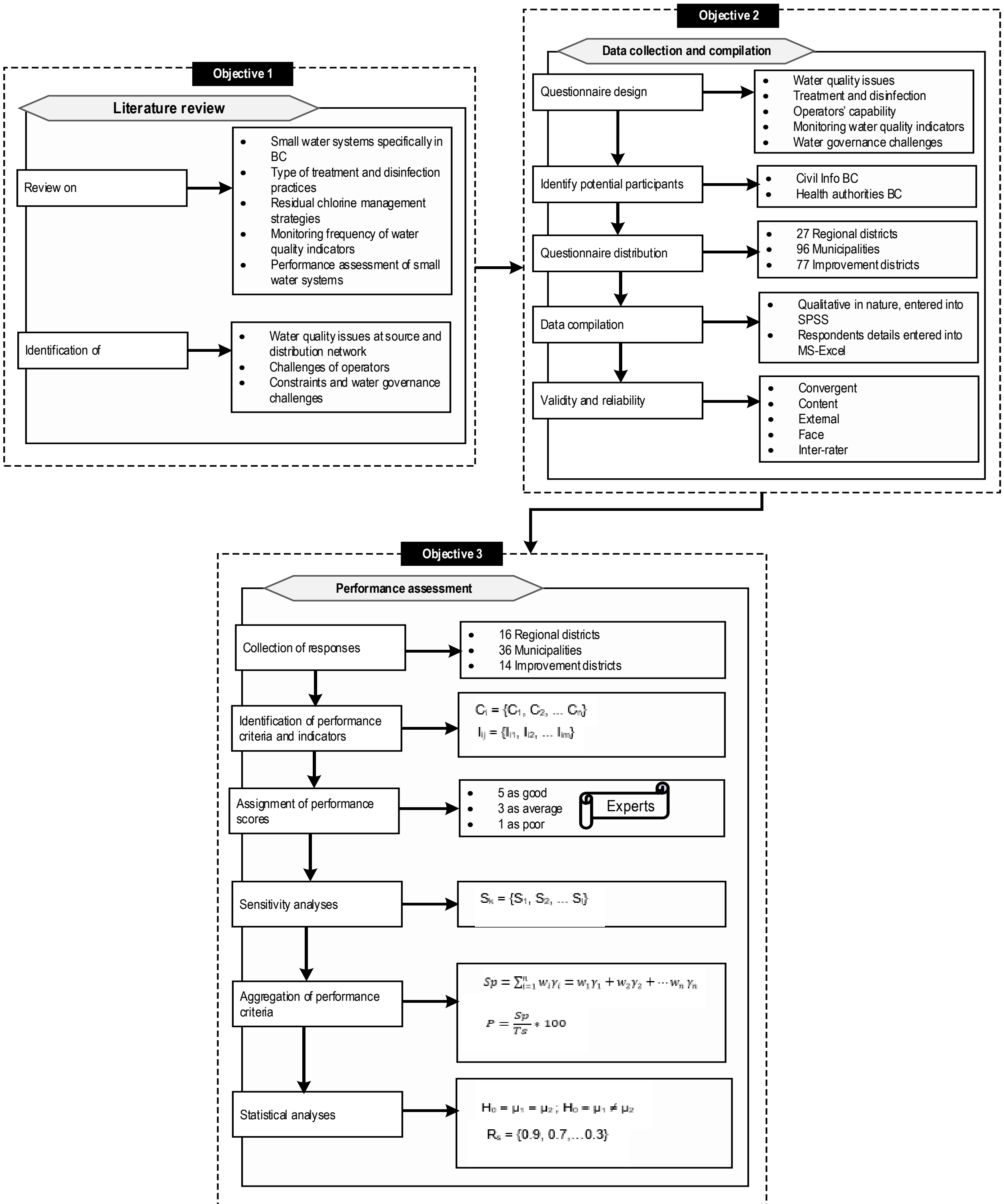
1.3 Study methodology

In order to achieve the research objectives outlined in the section 1.2, a study methodology is adopted as shown in Figure 1-1. The detailed description of each objective are discussed in the chapters 2,3, and 4, while a brief description on these objectives are explained as the following:

Objective 1 comprises of information gathered from the past literature focusing on the key issues related to the drinking water quality management in SWSs. The water quality issues associated with source waters and DNs, treatment facilities and disinfectants used, residual chlorine management strategies, water governance challenges, operators' concerns, and performance assessment of SWSs are thoroughly studied.

Objective 2 includes a comprehensive description on the data collection and compilation methods adopted for this study. A questionnaire was designed focusing on key elements of drinking water quality management. The questionnaire was distributed to 200 SWSs across BC, which comprises of three local body types namely, regional districts, municipalities, and improvement districts. Validity and reliability of the gathered responses were also investigated.

Objective 3 aims to develop a performance assessment framework. Five performance criteria and 30 performance indicators were identified for the framework development. The framework was developed using a mathematical technique to evaluate the performance level of the water systems, while statistical analyses were performed to understand the variation in the performance level of SWSs concerning different local bodies.



Note: Ci=Performance criteria, n=5,Ij=Performance indicator of criteria, m=5, Sk=weighting schemes for a specific criteria, l=6 Sp= performance of the water system, Wi= weight of the ith criteria, ¥=performance score of the ith criteria, Ts= maximum possible score, P= overall performance, H0= null hypothesis, H1=alternate hypothesis, µ= mean scores of criteria, Rs= spearman correlation coefficient.

Figure 1-1: Integration of objectives

1.4 Thesis organization

Thesis is organized into five chapters. Figure 1-2 shows thesis structure and organization related to each objective of this study. Chapter 2 presents a review on the current issues and challenges of water quality management in SWSs in Canada. Chapter 3 provides the details on data collection and proposes a performance assessment framework. Chapter 4 provides the results of the framework implementation for BC SWSs. Chapter 5 outlines main contributions of this research and makes recommendations for the future research.

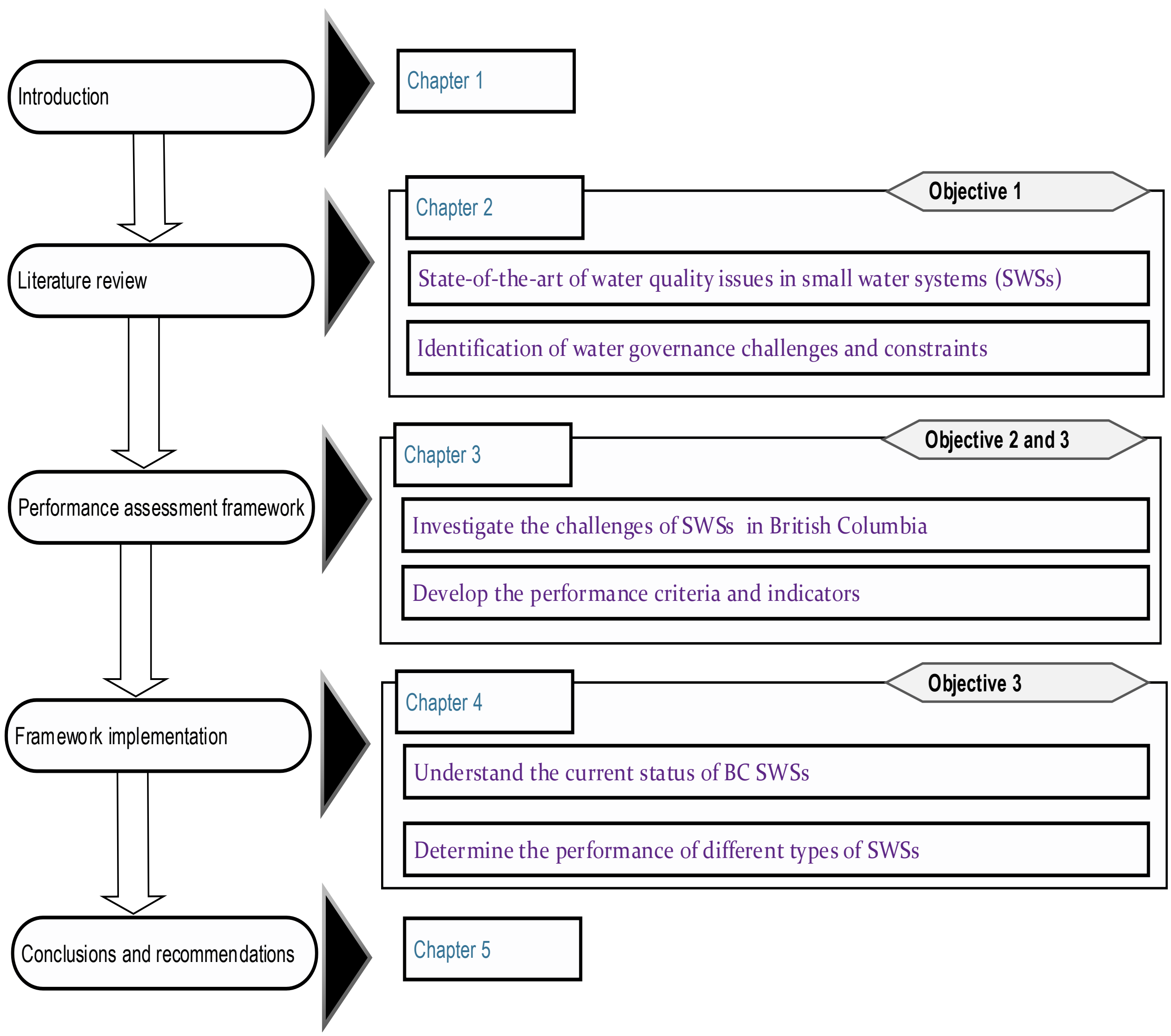


Figure 1-2: Thesis organization

Chapter 2: Literature Review

An extensive literature review was conducted to identify the current issues related to the drinking water management and water governance challenges of SWSs. Published literature and reports compiled by various governmental and non-governmental bodies, and international organizations like United States Environmental Protection Agency (US EPA), World Health Organization (WHO), Health Canada, Statistics Canada, and Interior Health in the drinking water management were used in obtaining the information. Publications made since the year 1990 in the journals were prioritized in the literature review to focus on up-to-date and high quality literature as sources of information.

2.1 Small water systems

Canadian provinces and territories have specific definitions for SWSs, which is usually based on the population and/or number of connections served. Table 2-1 shows the classification of SWSs in various Canadian provinces. For instance, in Alberta (AB), all water systems that serve populations below 500 are refereed as SWSs, while Newfoundland and Labrador (NL) considers population between 501-1,500 as *small* (0-500 as very small systems).

Health Canada (2013) categorizes water systems based on the following population criteria:

- Large systems > 5,000
- Small systems between 501-5,000
- Very small systems between 26- 500
- Micro-systems ≤ 25

Compared to SWSs, large water systems are equipped with advanced drinking water treatment technologies, greater number of resources, and a strong financial outlook (Scheili et al. 2015). Generally, SWSs rely on a simple water treatment process. They take raw water from the source (surface water or groundwater), add a disinfectant to raw water -mostly chlorine in form of hypochlorite or gaseous chlorine and distribute water to consumers. However, in some provinces, surface water and groundwater under the direct influence of surface water are made mandatory to use filtration prior to disinfection. On the other hand, medium to large water systems adopts a multi- barrier approach to provide safe water supply to their consumers. This approach takes into an account of all the threats related to drinking water by protecting source water, using effective water treatments and disinfectants, and preventing the deterioration of water quality in the DNs. Furthermore, these water systems undergo a multiple level of treatments and disinfection prior to their distribution. A majority of these water systems use conventional treatment (coagulation, flocculation, sedimentation, and filtration) prior to disinfection. The use of either chlorine, UV or ozone as a primary disinfectant, and chlorine or chloramine as a secondary disinfectant is a common practice in medium to large water systems (Bereskie et al. 2017).In this thesis, SWSs refer to all water systems that serve populations less than 5,000 people.

Table 2-1: Classification of SWSs in different provinces and territories (Pons et al. 2015)

Province/ Territory	Terminology	Definitions
Alberta (AB)	Small water system	500 or less people
British Columbia (BC)	Small water system	500 or less people
Manitoba (MB)	Semi-public water system	0-15 service connections (one connection usually serves 3 people) or public facility with own water supply
New Brunswick (NB)	Not particularly identified	N/A
Newfoundland and Labrador (NL)	Small system	501-1500 people (very small systems are defined as 0- 500 people)
Northwest Territories (NWT)	Small system	Defined based on complexity and capacity of treatment system. Small system represents the simplest systems
Nova Scotia (NS)	Not particularly identified	N/A
Nunavut (NU)	N/A	N/A
Ontario (ON)	Small drinking water system	Defined under business or premise that makes drinking

Province/ Territory	Terminology	Definitions
		water available to public but does not receive water from municipal DWS.
Prince Edward Island (PE)	Small drinking water system	100 or less people
Quebec (QC)	Small system	201-1000 people (Very small system serves population between 21-200)
Saskatchewan (SK)	Semi-private waterworks	< 18,0000 l per day of flow
Yukon (YT)	Small drinking water system	A system other than large DWS, the SWS should provide: a) Have water source or receive water from large DWS b) Equipped with infrastructure that collects, produces, treats or stores drinking water c) 0-14 service connections or up to four delivery sites

2.2 Small water system in British Columbia

In BC, all water systems that serve populations up to 500 in a 24 hour period is termed as small water system (Carter et al. 2008). As of 2013, there were approximately 4,000 SWSs in BC (Ministry of Health 2013). There is an estimation of approximately 1,000 SWSs in Northern and Interior Health regions, and 100 within Vancouver Island Health, which are yet to be identified (Carter et al. 2008). One of the main reasons for being unable to identify these water systems is unavailability of sufficient resources in these regions (Carter et al. 2008). There are 122 privately owned regulated utilities, which serve approximately 20,000 households in BC (Provincial Government of British Columbia 2018a).

In BC, all water systems must comply with the BC Drinking Water Protection Act (DWPA) and Drinking Water Protection Regulation (DWPR) (Provincial Government of British Columbia 2018a). Both these legislations include the definition of water systems, type of treatments required, minimum qualifications required to be an operator (Provincial Government of British

Columbia 2016a), monitoring water quality indicators, and water assessment plans (Provincial Government of British Columbia 2016b). These legislations are consistent with Federal Government's Canadian Drinking Water Quality Guidelines (CDWQG) (IHA 2017). All water systems are governed by the Ministry of Health, which administers DWPA and DWPR and also administer provincial policy on drinking water. Different health authorities across the province enforce DWPA and DWPR to all the water systems owners except the single-family residence. The water systems owners are obliged to report about their water quality to the respective health authorities (Provincial Government of British Columbia 2018b). Interior Health, Fraser valley Health, Vancouver Island Health, Vancouver Costal Health, Northern Health, and First Nations Health are the health authorities in BC. Drinking water is supplied to consumers through local bodies like regional districts, municipalities, improvement districts, and First Nation bands. There are also private utilities and individual homeowners who manage DWSs (BCWWA 2018). Table 2-2 outlines the classification of the local bodies considered for the current study.

Some Canadian provinces have specific challenges to supply safe drinking water to consumers. For example, in BC, different health authorities highlighted key challenges as: difficulty to transport water samples in a timely manner to the assigned laboratory, cost incurred in getting staff out to remote systems, and accessibility of some systems by only boat or seaplane in rural areas (Carter et al. 2008). The BC Ministry of Health (2013) reported that there were altogether 29 water-borne disease outbreaks between 1980-2004 in BC. Among all the Canadian provinces, BC records the most boil water advisories (BWAs) in small and medium water systems (Chhipi-Shrestha et al. 2017). This problem is also evident through a report from Interior Health Authority (IHA 2017), which states 80% of BC SWSs in IHA's jurisdiction had an average of around 100 days of BWAs over a period of five years. The reasons for BWAs to be placed in these communities include: contamination of source water, inadequate treatment and disinfection, broken water mains or maintenance work on the DN, power and equipment failure, and water systems dealing with non-compliant issues.

Table 2-2: Classification of local bodies in BC

Local body type	Number	Services	Provincial grants	References
Regional districts (RD)	28	• Recreational facilities • Manage regional services (e.g. regional parks) • Local services such as water and fire protection • Generate revenues through taxes	Yes	(Provincial Government of British Columbia, 2018 c ; Carter et al. 2008)
Municipalities (MU)	162	• Water, police, fire, transportation, land use planning, and regulation • Generate revenues through taxes	Yes	(Provincial Government of British Columbia, 2018 d ; Carter et al. 2008)
Improvement districts (ID)	215	• Water and /or fire • Maintenance and operation cost for the services completely depend on taxation and user fees	No	(Carter et al. 2008)

2.2.1 Drinking water treatment objectives in British Columbia

In British Columbia, the surface water and ground water at risk of pathogens are expected to meet the following treatment objectives, referred as “4-3-2-1-0 drinking water objectives” (Ministry of Health 2013).

- 4-log (99.99%) reduction of enteric viruses: Chlorine is usually used to inhibit the viruses in drinking water. Some water systems also practice UV but the viruses (especially adenovirus found in human fecal matter) are very resistant to UV. A higher dosage of UV with the combination of another disinfectant is recommended for the complete inactivation of viruses.
- 3-log (99.9%) reduction of Giardia and Cryptospordium: Giradia and cryptosporidium are protozoa, which are easily introduced by domestic and wild animals in the source water. Albeit large dosages of chlorine, ozone and chlorine dioxide with long contact time inactivates Giardia, Crytpospordim is extremely resistant to chlorine. To resist Cryptospordium, filtration (less than 1 micron) is recommended, which is depended on the source water conditions, method of filtration, and operation.
- 2 treatment process: CDWQG recommends all water systems to practice filtration and at least one form of disinfectant to meet the drinking water treatment objectives.
- 1 or less than 1 NTU of turbidity: The turbidity of treated water should be less than 1 NTU, which is also the accepted limit by the CDWQG.
- 0 detectable *E.coli*, fecal coliform and total coliform: *E.coli* are generally found in human faeces and other animals, whereas the other forms of total coliform are naturally found in soil, water, and vegetation. Under, DWPR, there should be no detection of *E.coli*, fecal and total coliform in the treated water. (Ministry of Health, 2013).

2.2.2 Drinking water advisories

Drinking water advisories are the messages circulated by the health authorities to consumers about the actions they should take to protect people from the health risks related to drinking water supply. As of 2015, 78% BWAs were issued in Canada (this percentage do not include "do not consume" and "do not use advisories") (Environment and Climate Change Canada 2016). Out of 1838 drinking-water advisories, there are 544 advisories in BC. The Environment and Climate Change Canada (2016) report suggests the a majority of BWAs were issued between 2010-2017 in the communities serving a population of 500 or less. Annually 50% of these BWAs are reported because of the broken water mains or maintenance work in DNs and the majority of these advisories take place in the community with population less than 5,000 (Environment and Climate Change Canada 2016). The drinking water advisories can be administered in three ways which are discussed as below (IHA 2017):

a) Water Quality Advisory (WQA): This type of water advisory is usually administered when there is a certain risk associated with drinking water but does not have sufficient evidence or risk to warrant more stringent notices like BWA, do not use or do not consume (IHA 2017).

b) Boil Water Advisory (BWA): This type of water advisory is administered when a water system is evident of having positive *E.coli* result or any serious water quality issues but can be mitigated through boiling of water. This is the most common water advisory administered in the small communities (IHA 2017).

c) Do Not Use Advisory (DNU): This type of water advisory is administered when drinking water is extremely contaminated and the health risk cannot be mitigated by boiling the water. The example could be a chemical contamination, intentional break, and tampering at a reservoir (IHA 2017).

2.3 Water quality issues

The quality of drinking water is influenced by the type of source water, which is dependent on various natural and artificial factors. The natural factors include: soil type, hydrology, precipitation, climate, wildlife, whereas anthropogenic factors are closely linked with land management practices, discharge from point sources, and non-point sources. Compared to the groundwater, surface water contain more organic materials and are more vulnerable to the microbial contamination, thereby requiring extensive treatment practices (EPA 2011). The type of treatment depends on the quality of source water, number of people served by a water system, and availability of financial and human resources (Moffatt and Struck 2011). Figure 2-1 shows the basic water treatment processes for surface water and groundwater.

The water quality in DNs is a major concern for SWS operators. The water quality issues are potentially more severe in DNs since it is difficult to maintain an adequate concentration of residual disinfectant especially at extremities of DNs (Simard et al. 2011). The DNs are also affected by physical attack, cyber disruption, biological and chemical intrusions (Khanal et al. 2005).

The water quality issues disturb physical, hydraulic, and water quality integrity of a DN. Several cases of water borne diseases outbreak have been recorded due to contamination intrusion during repair and replacement of physical infrastructure such as pipes, main lines, and service lines (NRC 2006). The installation of contaminated pipe components and absence of critical physical components of DN also degrade the water quality. Inadequate pressure in pipes, failure of pumps and valves, loss of water through leakage disturb the hydraulic structure of DNs. Low flow in pipes allows sediments to deposit and bacteria to multiply fast. These deposition of sediments not only increase the roughness of pipe wall but also increase the pumping cost. The formation of biofilm reduces the concentration of disinfectant residuals, contributes to corrosion, and forms disinfection by-products (DBPs). Although the presence of iron and manganese and leaching in DNs are not considered as a public health concern, bad taste and odor from these issues might invite various water quality complaints from the consumers (NRC 2006).

In the context of drinking water for SWSs, past studies have focused on identifying various water quality issues at source, treatment plant, and DN. Coulibaly and Rodriguez (2003) studied microbial and physico-chemical characteristics of source water, treated water, and distributed water in ten small Quebec utilities. Six utilities not complying with some drinking water quality standards were referred to as problematic, while four were unproblematic showing rare or zero signs of microbial contamination. The results suggested that apart from trihalomethanes (THMs) concentrations, the concentration of all other water quality indicators were higher for problematic utilities. Minnes and Vodden (2017) studied the interrelated elements of drinking water systems, which include source water quality and quantity, aging of water infrastructure, social, political, technical, and financial constraints associated with rural and SWSs in Newfoundland and Labrador. Kot et al. (2011) examined the status of rural and small Canadian communities in Atlantic Canada. The results indicated that SWS operators face serious problems in complying water quality guidelines and customer satisfaction, and also lack financial, managerial, and human resources to address the issues.

Thus, all studies clearly depict that SWSs usually encounter various problems in drinking water, which hinder safe water supply to consumers in small communities.

The water quality issues at source and DNs are controlled with an adequate treatment and disinfection. The treated and distributed water must be monitored well. In addition, these monitored indicators are recommended to follow the guidelines set by their respective provinces/ drinking water authorities. These regulatory guidelines enable safe water supply to consumers. For instance: adoption of guidance on total coliform rule protects DN from microorganisms (Islam et al. 2015). Table 2-3 outlines regulations for different indicators.

Table 2-3: Guidelines on water quality indicators

Water quality indicators	Guidelines	References
Disinfectant residual	0.2 -0.5 mg/l at the point of delivery in the treatment plant, 2 mg/l for clear water (turbidity less than 10 NTU), 4mg/l to turbid water (>10 NTU). Should not exceed 4 mg/l in DN for chlorine and chloramine residual and 0.8 mg/l for chlorine dioxide. (Stage 1 Disinfectant/ Disinfection By-Product Rule.)	(EPA 2007)
Turbidity	Depends on type of treatment. Conventional and direct filtration: ≤ 0.3 NTU, slow sand & diatomaceous earth filtration: ≤ 1NTU, membrane filtration: ≤ 0.1 NTU. Overall water entering DN should have turbidity less than1 NTU.	(Health Canada 2017)
Temperature	AO: ≤ 15°C	(Health Canada 2017)
pH	7 – 10.5	(Health Canada 2017)
Trihalomethanes (THMs)	0.1 mg/l	(Health Canada 2017)
Haloacetic acids	0.08 mg/l	(Health Canada 2017)
Escherichia coli (E. coli)	None detectable per 100 mL	(Health Canada 2017)
Total coliforms	None detectable per 100 mL in water leaving treatment plant and in non-disinfected groundwater leaving the well	(Moore 1998)
Total Organic Carbon (TOC)	4 mg/L for source water, 2 mg/L for treated water	(Health Canada 2017)
Iron	AO: ≤ 0.3 mg/l	(Health Canada 2017)
Manganese	AO: ≤ 0.05 mg/l	(EPA 2013; Richardson et al. 2007; Earth Tech 2005)

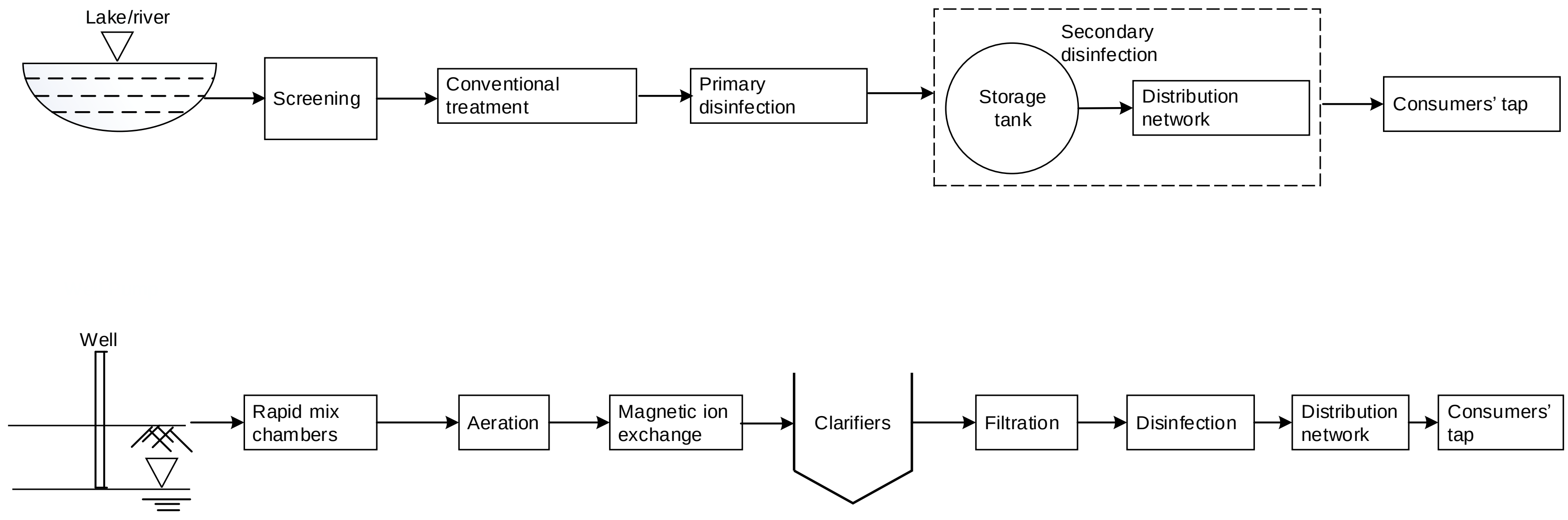


Figure 2-1: Common surface and groundwater treatment process

2.4 Disinfection

Disinfection is the most important step in distribution of safe water to consumers. Disinfection of water is achieved in two ways – primary disinfection and secondary disinfection. Primary disinfection (chemical or physical) kills or inactivate microorganisms present in source water, whereas secondary disinfection aims at maintaining an adequate concentration of residual disinfectant in the DNs (Government of Canada 2009). An appropriate concentration of disinfectant (usually chlorine) is added to the distributed water to maintain an adequate amount of residual throughout the DNs. Chlorine is unstable and its reaction with organic and inorganic contaminants in bulk water and pipe wall results in the consumption of the chlorine in the DNs (Xin et al. 2003) Figure 2-2 shows the basic process of chlorine consumption mechanism.

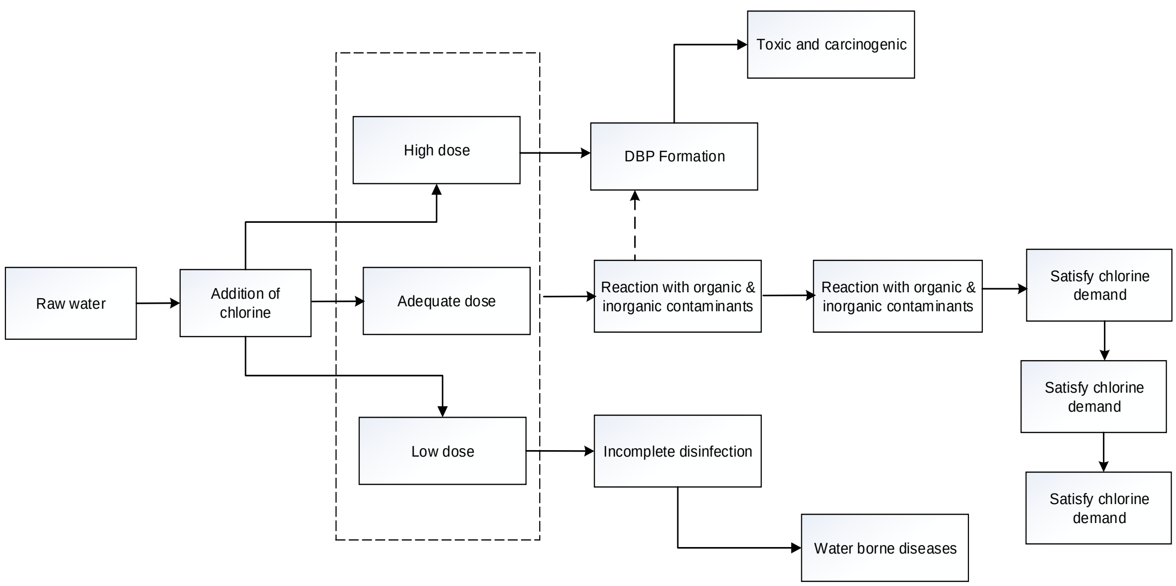


Figure 2-2: Chlorine management process

Some common forms of disinfectants are discussed in the following sections:

2.4.1 Chlorine

Chlorine is the most popular disinfectant because of low cost, affordability, and easy availability. It is extremely effective against viruses and bacteria but is not effective against Cryptosporidium, a protozoa (Earth Tech 2005). Chlorine can be used both as primary and secondary disinfectant. Chlorine is available in three forms, which are described in the following sections.

2.4.1.1 Hypochlorite solution

Hypochlorite solution is commonly used as a disinfectant However, it contains various compounds of oxyhalide groups such as bromate, chlorite, chlorate (ClO_3^-), and perchlorate. Among these species, the former three compounds are considered as regulated DBPs, while later component falls under the category of unregulated DBPs (Stanford et al. 2011). Despite no regulations have been set for the perchlorate, it has human health effects disturbing the normal functioning of thyroid gland (Greer et al. 2002). Different factors such as temperature, ionic strength, and pH affect the performance of hypochlorite solution. pH between 11-13 should be maintained for the less decomposition of the hypochlorite ions in the solution. Higher pH acts as catalyst for the ionic strength and also supports perchlorate formation. Increase in ionic strength and high temperature also degrade the solution faster (Snyder et al. 2009; Stanford et al. 2011). Hypochlorite solutions can be managed properly by the following ways (Snyder et al. 2009)

i) dilution of hypochlorite solution during the storage after delivery

ii) storage of hypochlorite solution at a low temperature, onsite generation of hypochlorite should not be stored for more than 1-2 days

iii) maximum use of fresh hypochlorite solution as it contains higher concentration of hypochlorite.

Basically, two types of hypochlorite solutions are used in the form of disinfectants in drinking water, which are summarized as follows:

Sodium hypochlorite solution

Sodium hypochlorite (NaOCl), also known as liquid bleach , constitutes 12.5 to 17 % of free available chlorine at the time of manufacture (Metcalf and Eddy 2015). It is an excellent oxidizing agent and is usually added in the final stage of the treatment system. However, in some instances, it is also added in the first or middle stage of the oxidizing agent (Asami et al. 2009). According to American Water Works Association (AWWA) 2000 report, 18% (population under 10,000 for this research) of SWSs used NaOCl as a major disinfectant in their water systems. Over 80% of Japanese treatment plants use NaOCl as disinfectant residual (Asami et al. 2009). One of the major concerns of using NaOCl as a disinfectant is its property of getting easily degraded. There are several factors responsible for the degradation of liquid bleach, which includes the presence of metal ions such as copper, nickel, iron, cobalt, exposure to heat and sunlight, and long term storage condition (EPA 2013). NaOCl in drinking water treatment results in the formation of ClO_3^- . This can be attributed to the decomposition of HOCl and OCl and the quality of raw water. (Gordon et al. 1997). The chemistry of NaOCl can be illustrated as follows (Metcalf and Eddy 2015):

$$NaOCl + H_2O \Longrightarrow HOCl + NaOH$$

Ionization of HOCl takes place in the similar manner as gaseous chlorine.

Calcium hypochlorite solution

Calcium hypochlorite ($Ca(OCl)_2$) is a solid powder and contains 70% of free available chlorine. It is available in both dry and wet form. Mostly, it is used to boost the concentration of chlorine in the reservoir and sometime used for chlorination purpose at small systems (EPA 2013). According to AWWA (2000) report, 9% of SWSs (population under 10,000 for this research) used $Ca(OCl)_2$ as a major disinfectant. Although, $Ca(OCl)_2$ requires moderate storage area, less transportation cost, and have moderate chance of degradation, it is highly corrosive in nature, extremely sensitive to sunlight, bears additional chemical cost compared to gaseous chlorine, and is also considered as an explosive hazard if not handled properly (Shah and Qureshi 2008). The chemistry of $Ca(OCl)_2$ can be illustrated as follows (Metcalf and Eddy 2015).

$$Ca(OCl)_2 + 2\ H_2O \Longrightarrow 2\ HOCl + Ca(OH)_2$$

Ionization of HOCl takes place in the similar manner as gaseous chlorine.

2.4.1.2 Chlorine gas

Chorine gas (Cl_2) is the one of the most common forms of chlorine used in DNs. According to AWWA (2000) report, 89% of SWSs (population less than 10000 for this research) used chlorine gas as major disinfectant. It is greenish yellow in color and weight about 2.48 times heavy as air (Metcalf and Eddy 2015) The popularity of Cl_2 gas can be attributed to its 100% presence of free chlorine, less transportation and operational cost compared to sodium and calcium hypochlorite, requirement of small storage area, does not degrade over time, and operationally reliable. However, Cl_2 gas is highly toxic, corrosive, excessive sensitive to light, and also requires skilled manpower to run the chlorinator system. Furthermore, Cl_2 gas possess great health risk to the operators (Shah and Qureshi 2008). The chemistry of Cl_2 gas can be illustrated as follows (Metcalf and Eddy 2015).

Addition of chlorine in water results in the hydrolysis and ionization. Chlorine initially forms hypochlorous acid (HOCl) in reaction with water, which is called hydrolysis. The chemical reaction can be shown as follows;

$$Cl_2 + H_2O \leftrightarrow HOCl + H^+ + Cl^-$$

Further, the ionization of HOCl results in the formation of hypochlorite ion. The chemical reaction can be show as follows;

$$HOCl \leftrightarrow H^+ + OCl^-$$

The microbial efficiency of HOCl is 40 to 80 times greater than that of OCl and hence should be effectively used in DNs. The disinfection efficiency is more prominent at a pH below 7 compared to the pH above 7.

2.4.2 Chloramines

Chloramine is a popular disinfectant used in DN. Although, chloramines are slow reacting, they are more stable than chlorine and maintain a residual disinfectant in DNs. They form less halogenated DBPs compared to chlorine. (Earth Tech 2005). Chloramines are available in three forms. The chemistry behind the formation of chloramines is shown as below: (Metcalf and Eddy 2015);

$NH_3 + HOCl \Rightarrow NH_2Cl$ (monochloramine) + H_2O

$NH_2Cl + HOCl \Rightarrow NH_2Cl_2$ (dichloramine) + H_2O

$NHCl_2 + HOCl \Rightarrow NCl_3$ (nitrogen trichloride) + H_2O

2.4.3 Chlorine dioxide

Chlorine dioxide is a powerful disinfectant and is effective against bacteria, viruses, and protozoa. The disinfection efficiency of chlorine dioxide is better than chlorine and chloramines. However, it is less stable and it is difficult to maintain a residual disinfectant in DNs. Although, this form of disinfectant does not form any halogenated DBPs, the formation of chlorites is a major concern. Similarly, chlorine dioxide must be generated on-site, chemical cost is high, and also can be explosive at high temperature and pressures (Earth Tech 2005).

2.4.4 Ozone

Ozone is a powerful disinfectant and its disinfection efficiency is greater than chlorine dioxide. It is effective against bacteria, viruses, and protozoa. The color and taste of water can be controlled using ozone, while it also oxidizes iron, manganese, and sulfides. Ozone is usually used as a primary disinfectant as it has a short half-life. However, in the presence of secondary disinfectant like chlorine and chloramines, the overall disinfection efficiency of a water system is strengthened. Although, ozone does not form any halogenated DBPs, in the presence of bromides, the formation of bromate is a concern (Earth Tech 2005). The operation and maintenance cost using ozone is high and hence it is not a common form of a disinfectant in small systems.

2.4.5 Ultraviolet light

UV does not use chemicals for the disinfection purpose. It is widely used to inhibit bacteria, viruses, and protozoa. A high dosage of UV is required to inactivate the viruses but compared to chlorine dioxide and ozone, less cost is incurred in attaining same germicidal efficiency. The UV light does not form DBPs (both halogenated and non-halogenated). As UV is not stable, this form of disinfectant cannot be used as a secondary disinfectant. One of the principle disadvantages of UV is that it is difficult to monitor the equipment performance and the water with high concentration of turbidity, organics, iron, hardness and hydrogen sulfide cannot use UV light as a disinfectant. (Earth Tech 2005). Similar to ozone, high equipment cost makes UV unpopular disinfectant in small systems.

2.5 Water governance challenges

The challenges of SWSs is associated with financial constraints, inadequate treatment, aging infrastructure, and retaining certified operators, and social and political issues (Ministry of Health 2013). Some of the major challenges are discussed in the following section:

2.5.1 Technical capability

The technical capability is defined as an ability of operators' skills, knowledge, and experience required for the proper management and safe supply of water to consumers (Minnes and Vodden 2017). SWSs usually lack sufficient technicians to understand the system, which can cause technical difficulties to operate treatment plants and carry useful functions of DNs (Union of BC Municipalities 2013). Minnes and Vodden (2017) research on the rural water systems of NL reported that there is lack of knowledge among the operators to understand the issues related to the source water protection. Absence of technical knowledge to reduce the formation of DBPs in public water systems also seems to be a major concern for SWS operators (Minnes and Vodden 2017). They further suggested that the certified operators are hard to find in small communities and local level managers are not adequately aware of the water quality issues in their respective regions (Minnes and Vodden 2017). A majority of SWSs lack a multi-barrier approach and advanced water treatment installations at their plants, which lead to suggest that the small system operators should be extra cautious about the quality of drinking water distributed to consumers (Scheili et al. 2016b).

One of the main challenges operators encounter in SWSs is shouldering multiple responsibilities by a single person. According to the study carried out by Kot et al. (2011) in the ten rural communities of Atlantic Canada, researchers found that an operator alone was involved in taking care of water and wastewater treatment facilities, basic maintenances of town, event planning, and few public works. However, salary provided to the operators remained the same despite their multiple responsibilities (Kot et al. 2011). Some SWS operators work on part time basis. Once old operators retired from their job and it has always been challenging for new operators to understand the water system. However, aged operators often have trouble in understanding new technologies (Kot et al. 2011). In few communities, operators are not provided with sufficient training. Few instances, even if they get an opportunity to take part in training, they might not get chance to participate due to the absence of back up operators (EPA 2006).

The role of operators cannot be undermined in the context of safe water supply (Galar et al. 2011). Personal factors such as motivation, attitude, and experience play a vital role in increasing the productivity. For instance, it is observed that most of the experienced treatment plant operators working for medium to large water systems quickly identify problems in DNs and in most cases immediately recommend the possible alternatives. However, the situation is entirely reversed for small systems as they hardly have operators working in plant continuously even for couple of years (Galar et al. 2011). Maintaining a good working environment at a work place is important, which is achieved through the proper division of responsibilities among the staff. For example, the amount of work loads operators is shouldered might frustrate them at times. Few works like adjusting chlorine residual in DNs may not be physically difficult but could be complex, which underscores the importance of adequate knowledge and training among the operators (Galar et al.2011). Addressing water quality complaints efficiently and support from consumers enhances productivity of operators. In a nutshell, it can be concluded that trained operators have sufficient ability to monitor water systems and report the testing results regularly to the respective authorities' ensuring the safe supply of water to consumers (IHA 2017).

2.5.2 Financing

Small systems are often surrounded by the financial constraints. First, as the size of community is small, infrastructures are expensive and are extremely difficult to operate on per user basis. Second, the tax and revenues collected by these systems at times may not be sufficient even to bear the operating costs of treatment (Brown 2004). Third, funds are not enough to provide training to employee and keep track of state of infrastructure, operation, and maintenance cost (Health Canada 2013).

In the small communities, source water cost may be affordable but lot of funds are required to counter issues related to aging infrastructure, water quality testing, regular maintenance, and operational cost, which deteriorates the performance of SWSs (Union of BC Municipalities 2013). Following this, many of the SWS owners never revise their rates and are often seen reluctant to share their financial information (Brown 2004). This results in the inefficient planning for the sustainability of the water systems (Brown 2004). A majority of SWS owners do not charge bills in an accordance to the volume of water used, which may cause water to use wastefully. Assigning flat water price to consumers is an alternative for SWS owners instead of pricing and meter reading, however, this shall incur more economic burden to the system (Dore 2015).

According to one of surveys carried by Dziegielewski and Bik (2009) in the US- Mid-West, the primary reasons for the financial crisis in SWSs were: improper record keeping of resources, lack of accountability, unsystematic use of revenues collected, and insufficient amount of reserve funds available in difficult conditions. Also, it is reported that appropriate funding in SWSs has always been a concern. Some SWSs even do not qualify to apply for funds. For instance, in BC improvement districts (IDs) are not eligible to apply for grants. IDs should maintain their water system through the tax collection, user fees or in some cases the loans granted by municipalities (Carter et al. 2008).

2.5.3 Social aspects

The flexibility and reliability to access safe water in SWSs depend primarily on the social status of a particular community. In some small communities, the practice of using chlorine as a disinfectant could be relatively new (Kot et al. 2011). For instance, according to a 2008 report on “Sustainable options for drinking water quality”, five of Local service districts (LSDs) in NL turned off their water systems due to the aesthetic issues of chlorine. (CBCL Ltd 2011). In such areas, consumers are often seen complaining about the taste and odor of chlorine in their drinking water. Despite several efforts from the operators to promote tap drinking water, people still tend to consume bottled water (Kot et al. 2011). This kind of mistrust among people frustrate operators. In order to overcome these kinds of disbeliefs, operators in few communities tried to generate awareness through various community programs and newspaper articles (Kot et al. 2011). In some cases, residents considered their water is naturally clean, abundant, and cheap. As a result, the drinking water owners do not receive appropriate support and investment from the government to upgrade the water infrastructure (IHA 2017).

It is extremely important for local community and politicians to better understand the need of upgrades in water infrastructure. The local community must be well informed about the performance of their water system, how funds have been used for quality water service, and implications of health hazards in the absence of adequate water treatment and disinfection (IHA 2017). Lack of education among public in regards to water quality issues, importance of treated water, source water protection and monitoring facility, insufficient participation of local government in water sector, and unawareness among people about the introduction of BWAs in their community are some of the major social issues associated with SWSs (Minnes and Vodden 2017).

2.6 Disinfection practices and adopted strategies

Chlorine is considered as the most popular method of disinfectant in DNs. It is widely used because of its ability to fight against bacteria and viruses, simplicity and cost efficient. However, it is not resistant against the *Cryptosporidium*, a protozoa (AWWA 2008). The practices and adopted strategies for safe supply of water to consumers are discussed as follows:

2.6.1 Common practices

In Canada, many SWSs do not use any sophisticated treatments rather use only chlorination as a treatment strategy (CBCL Ltd 2011; Scheili et al. 2016a). Usually, SWSs undergo limited treatment processed compared to medium and large water systems. For instance, 75% of Canadian municipalities below the population of 1,000 use water treatment processes to treat water, while the percentage climbs up to 99.6% of the municipalities with the population over 500,000 (Environment Canada 2011). According to the report of (CBCL Ltd 2011) for the Government of NL, there were 86% of BWAs in the community serving a population less than 500. Five out of six systems in these communities even lack basic water treatment facilities, which means that the water systems did not receive any kind of treatment. The overall picture of disinfection practices in Canadian drinking water system implies that 96% water treatment systems using surface water as a source used chlorination as both primary and secondary disinfectants. Twenty-two percent of systems used ozonation, while 25% used UV as a primary disinfectants (Statistics Canada 2013).

In the United States, AWWA conducted surveys on disinfection practices for SWSs. As a part of their survey, all water systems that serve population less than 10,000 was referred to small. It can be clearly stated from Figure 2-3 that 89% of water systems used chlorine gas in 2000, while 64% systems used gaseous chlorine in 2007. The percentage of SWSs using sodium hypochlorite and chloramine as a disinfectant observed a very slight increase in the percentage in the year 2007 compared to 2000, while SWSs using calcium hypochlorite observed a small reduction. Ozone and UV were only used as a disinfectant in SWSs in the year 2007. Followed by chlorine gas, sodium hypochlorite and chloramine were widely used in the year 2007 (AWWA 2000; 2008).

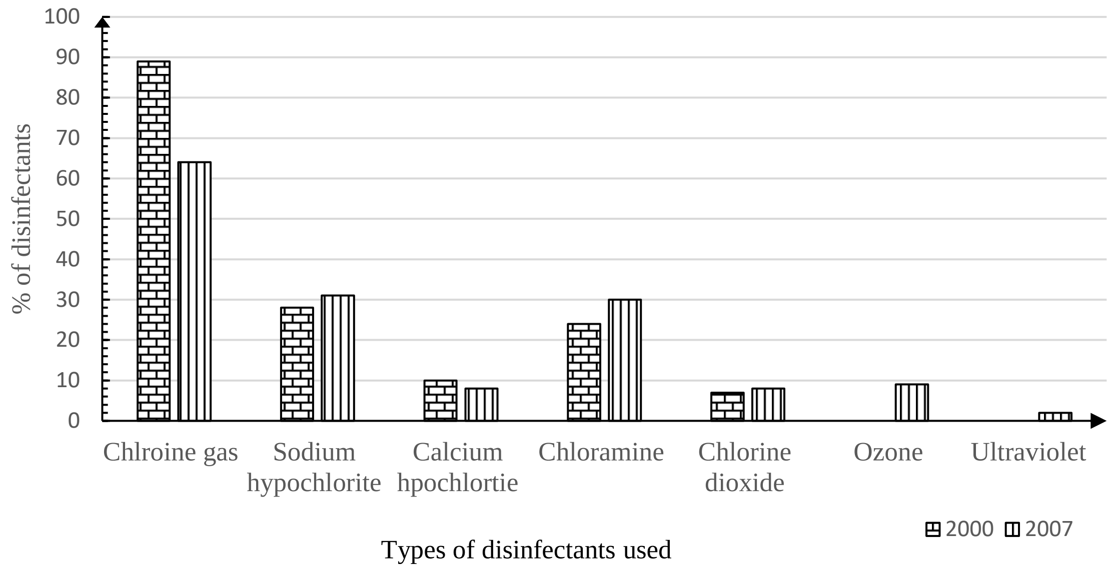


Figure 2-3: Trend of disinfectants used (AWWA reports 2000 and 2007)

2.6.2 Improvement strategies

2.6.2.1 Quality of source water and treatment

Quality of source water plays a significant role to ensure safe disinfection of drinking water. As such, source water protection is a fundamental unit in drinking water quality management, which ensures safe water supply to consumers. Source water protection is defined as the protection of drinking water suppliers like watershed and aquifer (Patrick et al. 2008). The use of local expertise and experience based on the local level knowledge is the most effective way of source water protection legislation (Hirokawa 2011). For instance, in BC, it was found that " joint water committees, information dissemination to water users, and local purveyor representation on professional drinking water associations, such as the Water Supply Association of BC, offer effective tools for operationalizing source water protection on the ground"(Patrick et al. 2008). Similarly in Quebec, Sylvestre and Rodriguez (2008) identified key strategies for the groundwater protection in small utilities. Researchers findings stressed on support from provincial government to carry studies on protection area delineation and vulnerability determination, and helping municipal government to implement Groundwater catchment regulation effectively in small communities.

Source water with high concentration of organic and inorganic contents needs pre-treatment prior to the application of regular treatment method and disinfection (EPA 2011). The use of membrane filters is an alternative to the traditional filtration, which can be adjacently used along with coagulation, adsorption, oxidation or combination of one or other. The use of ultra-filtration/nano filtration have been extremely effective in the small communities of Nova Scotia removing high levels of color and organic carbon in their water. This technique has also been successful in reducing DBPs formation (CBCL Ltd 2011). One of the major advantages of integration of coagulation with membrane filtration include effective removal of NOM along with reduction in membrane fouling (Keucken et al. 2017). Other methods like oxidation process (e.g. combination of either ozone with filtration, biological filtration, slow sand filtration, and advanced oxidation processes) also help in reducing intense colored NOM compounds into the less colored ones however, the formation of DBPs could be an issue (CBCL Ltd 2011).

Although, granular activated carbon is efficient to remove NOMs but due to its high installation and operation cost, this technique is not preferred in small communities. Another study suggested that nano filtration membranes are effective to reduce color, microbial pathogens, and NOM in small communities serving population less than 500 (Patterson et al. 2012).

Victoreen (1974) listed main breaks, cross connection, disaster operation, new construction, open reservoirs, and insufficient treatments as contributing external factors potentially deteriorating the water quality. Sadiq et al. (2004) reported that regrowth of bacteria takes place when injured bacteria from treatment plant enters into DN. This regrowth leads to the formation of slim layer at the surface of pipe which is known as biofilm. Biofilm not only cause an increase in disinfectant demand, promotes corrosion but also higher concentration of disinfectant in DNs results in the formation of DBPs (NRC 2006). Hence, it is important to overcome the above listed issues to supply safe water to consumers.

2.6.2.2 Residual chlorine management

Municipalities and water utilities pose a great challenge to maintain an adequate concentration of residual chlorine in DNs. The task becomes more difficult at the extreme ends of the DNs as chlorine starts to decay right after treated water starts to flow from treatment plant along the DN before it reaches to consumers tap (Simard et al. 2011). Indeed, there are several factors responsible for the consumption of chlorine residual in the DNs (Vasconcelos et al. 1997). Vasconcelos et al. (1997) reported that residual chlorine consumption is based on a) reaction between organic and inorganic materials during the flow b) biofilm growth on the wall of pipes c) corrosion process in pipes d) transportation of chlorine and other reactants between bulk flow and pipe wall.

The concentration of residual chlorine in DNs also varies type of disinfectant used, treatment process, and seasonal variation. Dyck et al. (2015) analyzed the survey of 49 SWSs (serving less than 3,000 people in their definition) in the province of Quebec from 47 municipalities. The result showed that the concentration of residual chlorine was more noticeable temporally, when the water systems used an additional treatment along with chlorination. The concentration of residual chlorine was observed to be the highest during winter and the lowest in spring when chlorination was only the method of disinfectant. Inversely, the concentration of residual chlorine was found to be similar for the months of winter and spring, autumn and summer when chlorination along with an additional treatment was applied. Most of the surveyed SWSs in their study do not use any physiochemical treatment, which leads their operators to add higher dosages of chlorine in their DN as a part of disinfection. This often results in high formation of DBPs. Finally, this situation presents one of the challenges in managing adequate concentration of residual chlorine in the SWSs (Dyck et al. 2015).

Another study by Coulibaly and Rodriguez (2003) in small Quebec municipal utilities demonstrated that during summer, high chlorine dosages were preferred in treatment plants before the distribution compared to winter. It was also noted that the high concentration of chlorine dosage was supplied to drinking water in order to equalize the decay of residual chlorine, which is largely associated with rise in temperature. Furthermore, the researchers observed that the high chlorine dosages (1.44 mg/ L) were applied to the untreated water compared to the utilities having treatment where an average chlorine dose of 1.12 mg/L was added prior to the distribution of water to consumers. However, the utilities using surface water with only chlorine as a primary disinfectant with no prior treatment applied a high dosages of chlorine up to 1.66 mg /L on an average. As a result, DBPs formation were favored.

The residual chlorine in SWSs can be managed by the following ways:

Reduce water age

The time taken by water to reach the consumers' tap through the DN is known as water age. The water age for a particular DN vary with number of people served and the distance a water main is stretched over. On an average, the water age varies between 1-3 days (AWWA 2002). High water age leads to formation of DBPs like THMs and HAAs, reduce the concentration of chlorine residual, increases microbial growth, occurrence of nitrification issues, and also degrades the aesthetic quality of water adding the problems related to taste and odor (AWWA 2002).

In order to maintain an adequate concentration of residual chlorine in DN, it is imperative to reduce water age. As such, flushing is one of the most convenient methods to reduce the effects of water age especially in SWSs. Flushing improves water quality issues such as microbial growth, corrosion, taste and odor, consumers complaints, and also helps to maintain an adequate concentration of residual chlorine in pipes (Chadderton et al. 1993). In SWSs, unidirectional flushing program can be conducted that includes hydrant maintenance and valve exercising (prepare maps, emergency responses) .Unidirectional flushing is generally carried out in every six months to three years unless drinking water officers suggest some changes especially keeping seasonal changes into an account (BCWWA 2004). Water age can be reduced by improved hydraulics and storage management, which includes pipe looping, manage valves, bypass oversized pipes, installed dedicated transmission, and eliminate excess storage and tanks in series. All these methods are useful, however, special attention must be given at the time of design and implementation. For instance, although looping reduces water age but if two pipes with low demands are looped together then the water gets stagnant for a long time, which can eventually form high levels of DBPs (EPA 2010). Also increase in tank's turnover reduces the water age. Furthermore, the reduction in the storage volume of a tank can play a significant role in reducing water age. For this purpose, water in a tank must be filled in such a way that it is just enough to maintain diurnal supply along with meeting fire flow requirement (Cruickshank 2009). The water in the storage tank must be mixed properly and different tools are used to predict water mixing characteristics of tank that includes desktop evaluations, computational fluid dynamic modeling, temperature measurement, and disinfectant residual online monitoring (EPA

2010). The computational fluid dynamic modelling, desktop evaluations, and the measurement of disinfectant residual may not be possible due to financial constraints, less manpower, and limited water infrastructure.

Predicting and managing residual chlorine through modeling

One of the major concerns of water quality in DNs is to efficiently manage residual chlorine concentration in the DN. Several studies have been carried out to set the optimal concentration of residual chlorine in DN. Sadiq and Rodriguez (2004) concluded that residual chlorine concentration should lie between 0.04 mg/l – 4 mg/l at DNs since it is difficult to maintain even 0.2 mg/of free residual chlorine especially at the end of extremities. Similarly, Islam et.al (2013) suggested residual chlorine levels range between 0.2-0.8 mg/l in the DNs. Several researchers have proposed different models and strategies for the management of residual chlorine in DN. In addition, several researchers have proposed different models and strategies for the management of residual chlorine in DN. Table 2-4 gives a brief outline of different models proposed.

2.6.2.3 Design and operation of water infrastructure

Building a proper infrastructure is key for safe supply of drinking water to the residents of a community. The need of strong infrastructure in DNs is the most important as it is the final barrier before water reaches to consumers' tap.

Aging of infrastructure must be taken into a greater consideration as large sum is required for replacement and rehabilitation. Old pipes are vulnerable to corrosion, which enhances growth of biofilm in pipe wall, promotes iron particles creating discolored water, forms scales, which reduces pressure in pipes creating more head loss resulting maximum consumption of energy. All these issues have negative impact on water quality, which hinder the efficiency of disinfectants in DNs and also consume bulk amount of disinfectant residual (Sarin et al. 2004).

Past studies have shown that internal corrosion could be controlled with the use of chlorine inhibitors like phosphates to the water along in combination with pH adjustment and alkalinity control. Pipe materials including ductile- iron and steel pipes are provided with linings, which reduces the frequency of leaks in pipes thereby preventing the internal corrosion (NRC 2006). External corrosion can be controlled selecting appropriate pipe materials according to the nature of soil, application of external metallic corrosion prevention materials during manufacturing process, use of barrier coatings, galvanic cathodic protection ,and polyurethane encasements in the field (Romer et al. 2004). Sufficient mixing of tank and maintaining tank volume turnover upgrades the quality of water. The proper design of storage tank plays a vital role in enhancing disinfection efficiency improving overall water quality. This could be achieved through hydraulic models, which can accurately determine size of a tank the community needs (Davee 2016). Unfortunately, as a majority of SWSs are supplied with limited human resources and insufficient infrastructures, computer modeling techniques can be a huge task.

2.6.2.4 Water quality monitoring

Majority of medium and large communities have regular monitoring practices at source and treatment plant. However, it is equally important to monitor water quality in DNs to ensure that water is free from contaminants (Islam et al. 2015). Generally, SWSs are not often equipped with proper infrastructures to carry the water quality monitoring regularly. This clearly indicates that SWSs not only lack infrastructures but also are unable to get a real picture of their water quality (Scheili et al. 2016a). The development and implementation of proper monitoring programs is necessary, which include monitoring of water quality indicators, sampling methods, location and sampling frequency, well equipped laboratory for testing samples, interpretation, validation, and communication of results (WHO 2011). The monitoring of various physical, chemical, and microbiological water quality indicators helps the water utilities to periodically assess the quality of their drinking water. In case of water quality degradation, the disinfectant residuals can be adjusted such that human health is not compromised. The regular monitoring of water quality is vital for distribution of safe water supply to consumers.

Table 2-4: Models proposed for management of residual chlorine

Modeling residual chlorine	Conclusion	Reference
Empirical model	Artificial Neural Network (ANN) gives better prediction of various water treatment conditions such as high and low chlorine dose compared to linear autoregressive model with external output (ARX). Forecast chlorine only at one single point in DN.	Rodriguez and Sérodes (1998)
EPA NET MSX toolkit	Observed change in residual chlorine concentration through the lens of microbial contamination. Application of chlorine sensors to predict occurrence of any intrusion in DN.	Helbling et al. (2009)
Network hydraulic model	Estimates time variation in pipe flow and storage tanks.	Propato and Uber (2004)
Consideration of multiple factors (consumption of chlorine with biofilm, corrosion with pipe & mass transfer of chlorine from bulk wall and pipe wall)	Observed spatial and temporal variation in chlorine decay. State loss of chlorine residual influenced by velocity of flow, pipe material, roughness diameter, pipe age, and activation energy.	Xin et al. (2003)
Mass transfer model	Prediction of chlorine decay using first order reaction. Smaller the diameter of pipe, faster is the decay rate.	Rossman et al. (1994)
Greedy algorithm	Appropriate placement of booster station helped to maintain required level of residual chlorine. Recommended to place one booster station for small systems while 3-4 for medium.	Islam et al. (2017)

2.7 Performance assessment

Performance assessment is defined as "any approach that allows for the evaluation of the efficiency or the effectiveness of a process or activity through the production of performance measures or indicators" (Alegre and Coelho 2014). Performance indicators (PIs) are defined for performance assessment. Performance indicators are defined as "measures of the efficiency and effectiveness of the water utilities with regard to specific aspects of the utility's activity and of the system's behaviour" (Alegre 1999). In many cases, such PIs are usually developed only for medium and large water systems (Haider et al. 2014). The need of drinking water quality management is essential, particularly for SWSs since these systems lack multi-barrier approaches and advanced water treatment installations (Scheili et al. 2016b).

Many studies have been carried out by various organizations to assess the performance of DWSs based on service quality, financial condition, service coverage, environmental impacts, customer experience, and public health and safety (ADB 2012; OFWAT 2008; Danilenko et al. 2014). However, there have been few studies, which involve the development of PIs for SWSs. Haider et al. (2014) established PIs that could be used for SWSs in developed and developing countries. The authors categorized PIs into three groups: start-up (with limited data), additional (if more data can be collected), and advanced (with sufficient resources) to assess the performance of water systems. Coulibaly and Rodriguez (2004) developed a PI-based performance assessment system, which was applied to ten small utilities in Quebec City (Canada). The assessment method calculates a total score using the weighted sum model (WSM), which can be used to compare various water systems. In their study, indicators were selected based on operational, infrastructure, and maintenance criteria. Sadiq et al. (2010) proposed a performance assessment method using ordered weighted averaging. The assessment system constitutes source water, treatment, infrastructure, and operational and maintenance characteristics of water utilities. The authors applied their framework to small municipalities in the Canadian province of Quebec. Suzuki et al. (2014) developed a performance assessment method for small to medium DWSs in Japan based on four criteria and their respective indicators. The criteria include, an overall evaluation of the plant (age of intake, water intake capacity, pump station's earthquake resistibility, and emergency power generator capacity), individual evaluation for a facility (water quality, pressure, aging, operation and maintenance, earthquake crisis management), necessity of improvements (influence on plant, customers and social activities, number of people affected, situation of degradation and time required to restore service), and selection of optimal improvement (finance, effectiveness, policy of waterworks).

Chapter 3: Performance Assessment Framework

In this thesis, performance assessment framework was developed based on the questionnaire designed, while the information provided by utility managers, engineers, and operators of 66 water systems across BC were used in the framework implementation. The objective of this framework is to understand the current status of small water systems and help operators identify the strengths and weaknesses of their respective water systems. The process of the framework development is further explained as the following:

3.1 Data collection and compilation

The performance assessment framework starts with collection of data from operators and utility managers of water systems. In this study, questionnaire was used as a medium of data collection. Questionnaire is relatively an inexpensive tool and can reach to wide range of respondents. However, collecting responses is a big challenge involved in conducting questionnaire (Trochim and Donnelly 2008). Questionnaire is a common data collection method in water quality management related research. Several researchers have used questionnaires in the field of drinking water quality management to understand the state of drinking water in their respective regions. Sylvestre and Rodriguez (2004) used the results from a questionnaire to identify different strategies adopted for the protection of groundwater sources in the context of emerging regulations in small municipalities of Quebec. Scheili et al. (2016a) used a questionnaire to document the impacts of human operational factors on drinking water quality in small systems.

3.1.1 Questionnaire design

Holyk (2011) indicated nine major steps that needs to be considered in designing the questionnaire. The nine elements are listed as below;

i. Defining the goals and objectives: The primary objective of the questionnaire was to identify the current status of drinking water quality issues, disinfection practices, monitoring practices, residual chlorine management strategies, and overall challenges of SWSs in the province of BC. The importance of this questionnaire was highlighted at the beginning of survey so that the participants could exactly realize the motif behind the questionnaire.

ii. Definition of key concepts: The questionnaire was designed in such a way that all the basic concepts related to water treatment and disinfections were thoroughly studied.

iii. Generation of hypotheses and proposed relationship: In this study, no hypotheses were assumed.

iv. Choice of survey mode: The survey can be conducted either through mail, email, and interviews (Trochim and Donnelly 2008).

v. Question construction: Holyk (2011) stressed on the importance of length of questions being designed. The questions should be designed in such a way that they should not serve as a burden for the respondents to read. In addition, the longer questions had a higher chance of rejection. Similarly, the questionnaire should be easily understandable. Therefore, in this study the questions were structured in simple English. The questionnaire was of seven pages.

vi. Sampling: The sampling method used for the questionnaire was systematic sampling i.e., the exact number of questionnaire that had to be sent was known prior to its distribution.

vii. Questionnaire administration and data collection: Questionnaire can be administered as open-ended questions and close-ended questions. Open-ended questions work better with interviews. Although, the information derived from this sort of questionnaire is comprehensive, it is always challenging to code correct set of information and it is also time consuming. Close-ended questions are mostly preferred. However, sometimes the respondents can be biased in their views by the pre- determined thinking of what are considered "appropriate" answers (Holy 2011). Majority of the questionnaire administered in this research were close-ended. The data collected was generated through email and mail. The hard copies of documents are stored in a locked room and the computer files are password protected.

viii. Data summarization and analysis: The results obtained from the questionnaire was thoroughly studied and have been properly summarized and analyzed. The comprehensive description is discussed in the Chapter 4.

ix. Conclusion and communication of results: This research identified some key conclusions that might be helpful to the utility managers of small systems and decision makers. The results and conclusions are discussed comprehensively in the chapter 4. The results are shared with the participants once published in the journals

In this study, the questionnaire was designed through a comprehensive literature review of peer reviewed journal articles and municipal reports across Canada. Organizational reports were also reviewed, which includes Health Canada, US EPA, and WHO reports. A majority of questions administered in this study were closed-ended. For some questions, respondents were required to assign a rank. The respondents were required to rank the challenges faced in their water systems in a descending order (e.g. 1 as a major challenge and 5 as a minor challenge). The questionnaire was divided into four categories as shown in Table 3-1.

Each category addresses the corresponding issues related to their specific objectives. Fifty-nine questions were included in the questionnaire. Among them, ten questions were related to water quality issues. Twelve questions dealt with the type of treatments and disinfectants used. Seven of those questions were focused to understand the management of hypochlorite solution. Seventeen questions were framed to identify the residual chlorine management practices. These questions were related to understand the variation in chlorine dosages based on the season, monitoring frequency and location of residual chlorine testing, challenges to maintain chlorine concentration at the extremities, methods of residual chlorine testing, and gathering information on water age within DNs. Three questions were asked to understand the monitoring frequency, types of samplings, and location of tests performed for various physical, chemical, and microbiological indicators of water quality. Fifteen questions dealt with various water governance challenges i.e., financial, technical, social, managerial, political, and operators. Among them, nine questions were designed to understand the operators' behavior (number of operators, training, education level, responsibilities, experience, and the challenges operators encounter).

3.1.2 Identification of potential participants

Once the questionnaire was designed, the following steps were carried out to distribute the questionnaire to the potential participants:

Gather contacts: The majority of contact details (respondent's name, email address, telephone number) for BC government bodies were pulled from the official website of CivicInfoBC (www.civicinfo.bc.ca/about-us). However, the website did not provide information on the population status of the government bodies (i.e., regional districts, municipalities, and improvement districts). To identify the population status of each community, a manual search was completed through Google search for 28 Regional Districts, 162 Municipalities, and 215 Improvement Districts. In addition, a request was sent as a Freedom of Information Request to all the health authorities across BC to acquire contact details of SWS operators. Interior Health, Island Health, and Vancouver Coastal Health shared their list of SWSs available in their respective databases.

Questionnaire distribution: The need of ethics approval is a must while conducting any kind of social science related or engineering survey. Prior to distribution to SWS operators, the questionnaire was approved by the Behavioral Research Ethics Board at the University of British Columbia (UBC), Okanagan campus. A consent form and recruitment letter were sent to the respondents before their participation in the study. After receiving their consent, the questionnaire was sent to the potential participants. The questionnaire was distributed among 200 local bodies, including 27 Regional Districts, 96 Municipalities, and 77 Improvement Districts. Although there are 215 Improvement Districts, most of the contact information was not available on government websites, while some contact details shared by health authorities were either incomplete or incorrect. Similarly, out of 28 Regional Districts, 27 qualified for this research based on population size (i.e., < 5,000 people).

Method of questionnaire responses: Questionnaire respondents could reply via email, telephonic interview, one-to-one interview, or by mail. The questionnaire was designed to take between 15 and 20 minutes to complete.

Table 3-1: Categorization of questionnaire

Category	Objective	Questions related to
Water quality issues	Understand the water quality issues	Source water quality Causes of water quality failure and customer complaints Instances of BWAs Water quality issues at source and DNs Compliance of water quality guidelines.
Treatment and disinfection	Understand the existing treatment methods and disinfectants used	Water treatment processes employed prior to disinfection Types of disinfectants used Types of chlorination employed Management of hypochlorite solution.
Water quality monitoring	Understand monitoring frequency of water quality indicators and residual chlorine management strategies	Monitoring frequency of water quality indicators Methods of flushing Temporal variation of chlorine decay Challenges to maintain residual chlorine Methods to test residual chlorine in DNs.
Operators' capability	Understand challenges related to operators	Training and certification Number of operators Experience and knowledge Shoulder additional responsibilities
Other challenges	Understand water governance challenges	Challenges related to financial, technical, social, political, and managerial

3.1.3 Data compilation

After data collection, the responses obtained from the questionnaire were entered into Statistical Package for Social Sciences (SPSS) software version 24. As a majority of the questionnaire responses were qualitative in nature, SPSS was used to compile the data. Each of the questions along with their respective options were assigned a "number", and descriptive statistics were performed. The statistical analysis was carried out using MINITAB 2018.

3.1.4 Validity and reliability

Validity measures the highest degree of truthfulness leading to the valid conclusions, whereas reliability assumes to produce similar output over and over again with conditions remaining the same (Trochim and Donnelly 2008). In order to assess the validity of this research, external, face, content, and convergent validity were used, while the inter-rater reliability test was performed to check the reliability of the responses. In addition to the inter-rater reliability, there are different types of reliability as the following (Trochim and Donnelly 2008):

i. Test-retest reliability: This type of reliability measures the consistency of measure from one time to another. As the current study is not time variant, this reliability was not applicable for the particular study.

ii. Parallel-forms reliability: This type of reliability assesses the consistency of results of two tests constructed in the similar manner from the same content domain. As our study performs only one type of test i.e., for small water systems', this type of reliability was not applicable to the study.

3.2 Performance assessment

In this study, performance assessment is defined as a process that evaluates the performance level of water systems by establishing suitable criteria and indicators. A five step process is followed to the assess the performance level of water systems in three local body types i.e., regional districts, municipalities, and improvement districts.

3.2.1 Collection of responses

The first step for the performance assessment is to gather data from the local bodies across BC. Based on their responses, the performance criteria and indicators are defined.

3.2.2 Assignment of performance scores

In this study, performance score is defined as a score assigned to each indicator in each criteria. The performance scores are assigned as 1,3, and 5. In order to represent the performance scores of various criteria, radar diagrams were used. A radar diagram provides a visual representation of performance scores making it easy to identify the highest and the lowest scores for the respective indicators in a criterion. Indicators with scores close to the border of radar diagrams are considered to have higher performance, whereas the performance decreases as the indicator deviates away from the border. These scores were plotted in the radar diagrams by calculating mean of the performance scores achieved by indicators under each criterion. Mean scores were preferred over the median scores because there were no outliers in the performance scores. Generally, in the absence of outliers, mean scores provide better measure of central tendency compared to medians.

3.2.3 Identification of performance criteria and establishing indicators

The first step for the development of performance assessment framework is to identify the performance criteria. The main purpose of developing performance criteria is to help operators and managers improve/understand the performance level of water systems based on the selected number of measures established. While developing the performance criteria, at least four indicators should be included (UNEP GEMS 2007). The performance criteria and indicators were selected based on the following requirements:

- the operators could easily use these measures to assess the performance of their systems at any given time
- they should represent drinking water challenges occurring in the SWSs.

In this study, five criteria were identified. These criteria were treatment and disinfection (C_1), water quality issues (C_2), operators' capabilities (C_3), infrastructure and funding (C_4), and operational characteristics (C_5). Each criterion was composed of six indicators. Indicators were rated using qualitative scales: "poor", "average", and "good". The rating scales were developed based on literature, technical reports, and expert opinions. In addition, Appendix A provides rationale behind the rating scores. The experts included engineers, utility managers, and academics. The ratings were transformed to performance scores of 1, 3, and 5 respectively (Yin et al. 2005). The possible range of scores that one criterion can achieve was between 6 and 30. Based on respondents' questionnaire results, responses were converted to scores. For example, if a water system had operators with experience over 10 years, then a score of 5 was assigned. The score was reduced to 3 with operators having experience between 5-9 years, while a score of 1 was assigned with operators with experience less than 5 years. Table 3-2 outlines the detailed classification of different criteria, indicators, and their ratings.

3.2.4 Sensitivity analysis

Sensitivity analyses were performed to understand the variance in performance scores of water systems when priority of one criteria changes to another. Furthermore, this form of analysis helps operators and managers to identify the most vulnerable criteria in order to take necessary actions to improve the performance level of their respective water system.

In this step, the criteria were divided into six weighing schemes. The six schemes were: "baseline" (S1) "treatment technology-priority" (S2), "water quality-priority" (S3), "operators' capabilities-priority" (S4), "infrastructure and funding-priority" (S5), and "monitoring frequency-priority" (S6). In the baseline schemes, equal weights were considered (i.e., each criterion were given 20% weightage). The weighting criteria for the rest of schemes were different. For instance, in S2, C1 was given a "high" importance, thus was given 60% weightage and the rest of the criteria in this scheme were each given 10% weightage. The high importance refers to a 60% weightage, whereas a "low" importance corresponds to a 10% weightage. Table 3-3 outlines the weighting schemes for sensitivity analyses.

Table 3-2: Rating of the indicators

Indicators	Good (5*)	Average (3*)	Poor (1*)	Source
Criteria 1: Water Treatment and disinfection (TD)				
Processes employed prior to primary and secondary disinfection	Conventional (coagulation, flocculation, sedimentation and filtration)	Only Filtration	No treatment	(EPA 2011)
Disinfectants	Primary and secondary disinfection	Primary disinfection	No disinfection	(EPA 2013)
Type of Chlorination at treatment plant	Post chlorination / Both pre chlorination and post chlorination	Pre/ inter chlorination	No chlorination	
Seasonal variation in chlorine decay	Low		High	(Fisher et al. 2011; Scheili et al. 2015a)
Follow WQ guidelines	Yes		No	(Government of Canada 2016a).
Cleaning of water mains	Yes (Unidirectional flushing)	Yes (Conventional flushing / blow off)	No flushing	(NRC 2006; Newmarket 2018)
Criteria 2: Water Quality Issues (WQI)				
Quality of source water	Good	Moderate	Bad	(EPA 2011)
WQ issues at source	No		Yes	(Chowdhury 2018)
WQ issues at DN	No		Yes	(Chowdhury 2018)
Water quality failure	Never	Once in last five years due to leakage/mains breakage or any other reasons	Every year on seasonal basis	(WHO 2011)
Customer Complaints	Never	1-5 in the last 5 years	6 or more in the last 5 years (Kot et al. 2011)	(Kot et al. 2011; Minnes and Vodden 2017)
Instances of Boil water advisory	Never	1-2 in the last 5 years	Currently	(Chhipi-Shrestha et al. 2017; IHA 2017)
Criteria 3: Operators' capabilities				
Training	Yes		No	(Scheili et al. 2016;. Minnes and Vodden 2017)
Experts advice	Monthly / whenever needed	Annually	No advice	
Certification	Yes		No	
Experience	≥ 10 years	5-9 years	≤ 5 years	

Number of operators	2 or more Full time equivalent (FTE)	1 FTE	No operators	(Minnes and Vodden 2017)
Additional responsibilities	No- operator is available full time for key duties	Yes-operator is sometimes assigned other duties	Yes- operator is always assigned multiple roles	(Kot et al. 2011)
Criteria 4: Infrastructure and Funding (IF)				
Age of treatment system (years)	< 15	16- 40	> 40	(Vieira et al. 2008)
Infrastructure replacement	5 rank obtained from survey	3-4 rank obtained from survey	1-2 rank obtained from survey	(Minnes and Vodden 2017)
Age of Distribution Network (years)	Less than 25 years	26-50 years	More than 50 years	Vieira et al. 2008)
Use of modern technologies (GIS)	Yes		No	(Oikonomidis et al. 2015)
Availability of funding	5 rank obtained from survey	3-4 rank obtained from survey	1-2 rank obtained from survey	(Suzuki et al. 2014; Minnes and Vodden 2017)
Small population base	5-6 ranked from survey	3-4 rank obtained from survey	1-2 rank obtained from survey	(Brown 2004)
Criteria 5: Operational characteristics (Frequency of monitoring)				
Turbidity (Source)	Daily/continuous	Weekly/ Monthly	No monitoring	(Health Canada 2013).
Organic content (TOC) (Source)	Weekly/ monthly	Quarterly /annually	No monitoring	(Chowdhury 2018)
Turbidity (Distributed water)	Daily/continuous	Weekly/ monthly	No monitoring	(Government of Canada 2013)
Residual chlorine (Distributed water)	Daily/continuous	Weekly/ monthly	No monitoring	(Government of Canada 2016b)
THMs (Distributed water)	Quarterly	Semiannually/ Annually	No monitoring	(Health Canada 2013)
HAAs (Distributed Water)	Quarterly	Semiannually/annually	No monitoring	(Health Canada 2013)

Table 3-3: Weighting schemes

Performance criteria	Equal weight (S1)	Treatment technology-priority (S2)	Water quality-priority (S3)	Operators' characteristics priority (S4)	Infrastructure and funding-priority (S5)	Monitoring frequency-priority (S6)
Treatment and disinfection	0.2	0.6	0.1	0.1	0.1	0.1
Water quality issues	0.2	0.1	0.6	0.1	0.1	0.1
Operators' capabilities	0.2	0.1	0.1	0.6	0.1	0.1
Infrastructure and funding	0.2	0.1	0.1	0.1	0.6	0.1
Operational characteristics	0.2	0.1	0.1	0.1	0.1	0.6

3.2.5 Estimate overall performance level

Performance level is defined as a rating, which classifies water systems into different categories based on the scores achieved by the criteria in each weighting scheme. The baseline scheme gives the overall performance level of water systems. Figure 3-1 shows the thermometric representation of the performance levels in this study.

Performance level was determined using a WSM. This method is preferred over other methods because it is an easy method to use and is less severe than the weighted multiplicative method, which is based on geometric means (Couillard and Lefebvre 1986; Coulibaly and Rodriguez 2004). WSM is one of the most common multi-criteria decision making techniques and is based on the additive utility assumption. It is widely used in single dimensional cases where all units are the same. The assumption suggests that each alternative is the product of the sum and its corresponding weights (Evangelos Triantaphyllou 2000). The basic formula used for the WSM is as follows (Coulibaly and Rodriguez 2004):

$$Sp = \sum_{i=1}^{n} w_i \gamma_i = w_1\gamma_1 + w_2\gamma_2 + \cdots w_n \gamma_n \qquad \text{(Equation 1)}$$

where Sp is the performance of the water system; w_i is the weight of the ith criteria; γ_i is the performance score of the ith criteria which is equal to the sum of scores of all indicators in the ith criteria; $n = 5$.

The performance of a SWS in each criteria is calculated based on the percentage as following:

$$P = \frac{Sp}{Ts} * 100 \qquad \text{(Equation 2)}$$

where P is the overall performance expressed as a percentage; Sp is the observed performance score; and Ts is the maximum possible score (i.e., 30).

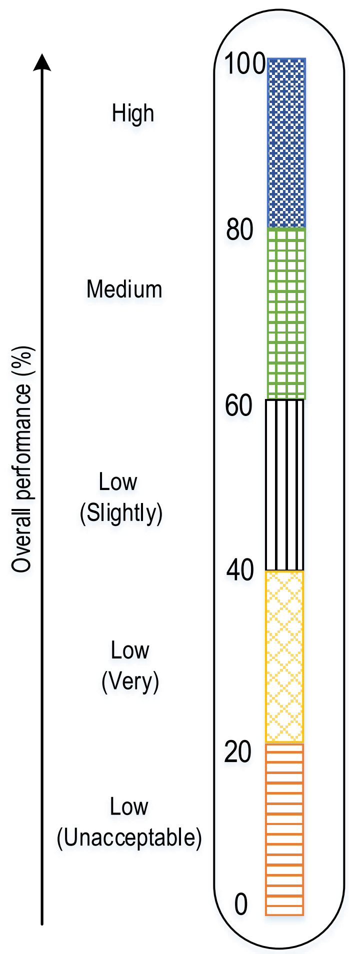


Figure 3-1: Performance levels

3.2.6 Statistical analysis

Statistical analysis is important to understand the variation and relationship among different variables, which help to assess the performance level of any systems (for e.g., water system in the current study). Some studies like Senduran et al. (2018)assessed the performance of a pocket wetlands in treating highway and railway runoff using ANOVA analysis, Kruskal-Wallis analyses, and Spearman correlation. One of their results suggested that total suspended solids and total organic carbon were partially affected by different temperatures and pH range. The former two analyses were also performed by Wanda et al. (2017) to understand the seasonal variation in the occurrence of emerging micro pollutants in their water.

In the current study, the difference in mean performance level of water systems representing three local bodies were evaluated using one-way ANOVA (Analysis of Variance) for the normally distributed data and Kruskal-Wallis (non-parametric) for non-normal data. In some cases, although, the mean difference in the performance level might be significant among three local bodies, the difference might not be significant between two local bodies. Therefore, Post–hoc tests (H-test and Tukey test) were performed to understand the significance of differences between two local bodies.

The relationships among various criteria [C_1, C_2 …C_5] under each weighting scheme was compared by a Spearman correlation analysis. The assumptions of Pearson correlation were not met by two schemes (i.e., S_1 and S_3), which resulted the use of Spearman correlation analysis (Bishara and Hittner 2012). The Spearman correlation coefficient measures the strength and weakness of relationship between criteria pairs under a given scenario. For example, if a strong negative correlation is established between water quality issues and operators' capabilities, the result highlights the importance of operators in minimizing water quality related issues. Table 3-4 outlines a commonly accepted standards for interpreting the value of a correlation coefficient.

Table 3-4: Interpretation of correlation coefficient values

Correlation coefficient	Interpretation of correlation
$0.9 < x \leq 1$	Very high
$0.7 < x \leq 0.9$	High
$0.5 < x \leq 0.7$	Medium
$0.3 < x \leq 0.5$	Low
$x \leq 0.3$	Very low

Chapter 4: Framework Implementation

4.1 Collection of questionnaire responses

The questionnaire responses highlight the issues and challenges of water systems in BC. Sixty-six participants responded and returned the questionnaire. The response rate was 33%. A majority (55%) of respondents were from municipalities. Regional districts and improvement districts represented 24% and 21% of respondents respectively. The questionnaire respondents consisted of drinking water operators, managers, technicians, utility leaders, and engineers of the respective local bodies. Operators are responsible to sample water quality indicators, monitor water systems, and take necessary actions if threshold values of these water quality indicators does not meet. Technicians deal with various technical difficulties observed in the water treatment systems and distributions. Utility leaders oversee the operators' duties and take decisions associated with safe water distribution to consumers. Managers usually check overall activities on daily basis, involve in planning programs to improve water quality, and work closely with the governments to address water quality issues. Engineers are involved in planning and designing of various components of treatment plants and distribution networks. Engineers are also responsible to assess water quality results.

Among them, 43% of the respondents were operators, 26% were managers, 13% played the role of both operator and manager, 10% were utility leaders, 6% were technicians, and only 2% of the respondents were engineers. Ninety-one percent of respondents answered the questionnaire through email, while 6% mailed their information, and 3% participated through a telephonic interview. The telephone interviews lasted for 10-15 minutes. The responses from the questionnaire are discussed in the following sub sections:

4.1.1 Water quality at source and distribution network

The results showed that a majority of water systems supply water to consumers, with 55% relying on surface water, while 33% rely on groundwater. A few systems used mixed sources with a mix between lakes and wells, and river and wells. Figure 4-1 outlines the current water sources for the respondents.

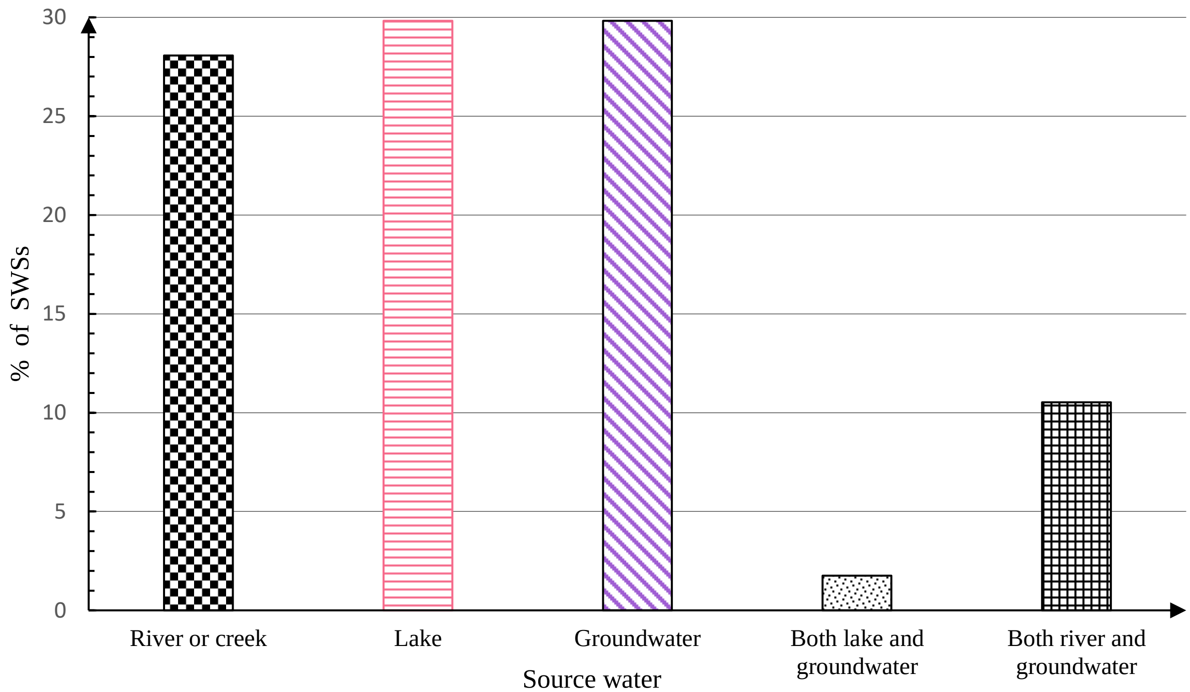


Figure 4-1: Type of source water

Regarding the quality of source water, respondents were required to identify their source water as "good", "moderate", and "bad" based on their own experience and judgement. Fifty-three percent of respondents considered their source water as "good", while 26% rated their source water as "moderate", only 2% reported the quality of source water as "bad", 16% did not respond to this question, and 3% rated their source water both as "good" and "moderate".

Respondents were asked to rank the causes of water quality deterioration as a challenge at extremities of DNs (outlined in Figure 4-2). A large percentage (27%) of respondents rated low flow rate as a major challenge followed by high residence time (14%), high DBP formation (12%), microbial contamination (10%), contamination other than microbiological (8%), low concentration of residual chlorine (6%), and taste and odor (5%). As water flows in DNs, the chemical deposits slowly start to build up due to a reaction between the minerals in the water and pipe itself (Vasconcelos et al. 1997). These deposits are observed closer to DN extremities, which can cause flow rates to decrease (NRC 2006). These low flow rates create a favorable environment for bacteria to grow. As a result, water quality becomes poor.

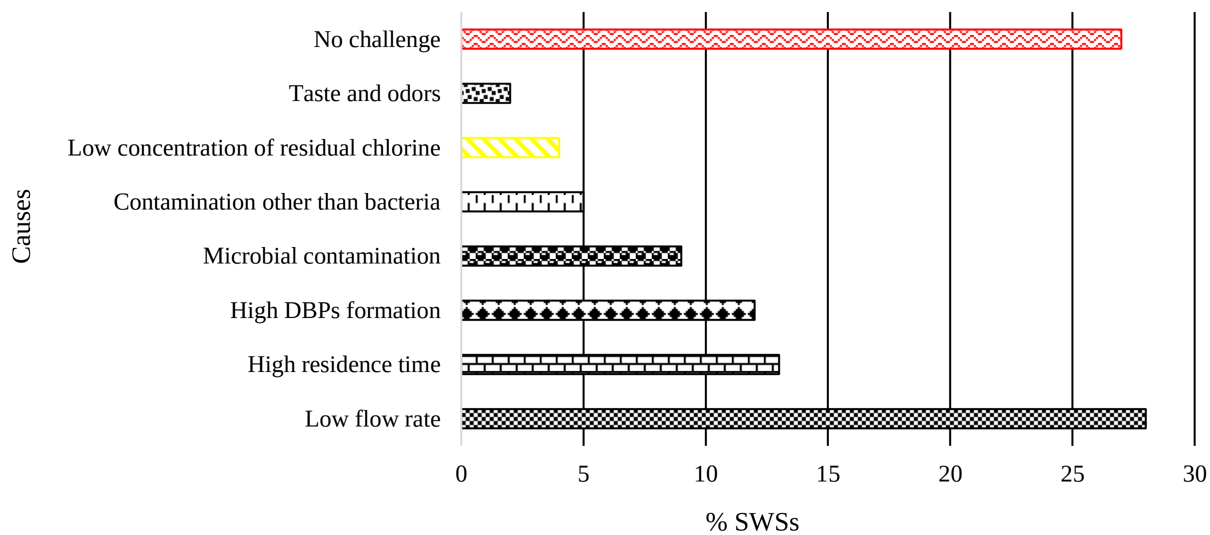


Figure 4-2: Causes of water quality deterioration

Small communities are more susceptible to water quality failures, which is defined as the "exceedance of one or more water quality indicators from an established threshold values either self-imposed or established by the water regulators" (Sadiq et al. 2007). Twenty-one percent of water systems reported water quality failure in their DNs, and the reported frequency of failure ranged between once in every few weeks to once every couple of years. The effect of failure on consumers varied from "less than an hour to a couple of hours" and "lasted for a week to ten days". Table 4-1 outlines factors responsible for water quality failure in DNs as reported by the respondents.

Table 4-1: Reasons for water quality failure

Reasons for failure	Description
Main breaks	Pressure drops and high turbidity from main breaks
Water leakage	Loss of water, difficult to maintain optimum pressure
Power outages	This leads to intermittent supply of water, increases water age which eventually contributes to failure
System upgrade and disruption of service	Contaminants intrude pipeline during construction or field work
Ignorance of operators	Not keeping an eye on water infrastructure/system leads to failure and invites BWN
Water system malfunction	Damage on various systems of water infrastructure, including faulty gaskets, valve malfunction, and negative pressure in pipes
Unable to meet standard guidelines	High concentration of DBPs in source water and DN, high turbidity
After flushing and super chlorinating DN and reservoir	Improper method of flushing and excess dosage of chlorine

Based on the questionnaire responses, it was common for operators to receive complaints related to the distributed drinking water. A significant portion (51%) of respondents reported that they received complaints about poor water quality from consumers annually. Out of the 51% of complaints, 58% of respondents did not use any treatment but used only disinfectants, and 19% of complaints were reported by the respondents who practiced only filtration and used disinfectants. The same percentage of complaints (19%) were reported by the respondents who used both conventional treatment (i.e., combination of coagulation, flocculation, sedimentation, and filtration) and disinfectants. Only three percent of complaints were reported by the respondents that neither used any treatments nor used any disinfectants. The largest percentage of respondents (25%) rated chlorine related taste and odor as a major complaint followed by aesthetic (20%), taste and odor other than chlorine (12%), color of water (10%), and non-compliance with water quality guidelines respectively (8%).

Sixty-three percent of respondents reported that they manage their water systems as per the water quality guidelines set by various organizations. Most of these water systems followed the guidelines imposed by BC Interior Health Authority, while 35% of water systems adopted the guidelines developed by Health Canada, American Water Work Association, and different BC health authorities (Vancouver Coastal Health, Island Health, Fraser Health). The Interior Health and other health authorities in BC follow the same guidelines as CDWQG (Interior Health Authority 2017). For some water systems, following the same stringent guidelines set for medium and large water systems can be challenging especially with limited resources and funds. Thirty-two percent of respondents reported that they are either currently or were under BWAs in the last five years. The BWAs were placed in some water systems only during heavy rainfall since their source water gets extremely turbid.

4.1.2 Treatment methods and disinfection practices

Respondents were required to identify the type of treatment prior to disinfection, and the type of disinfectants that are currently being applied. A large proportion (58%) did not use any treatment prior to disinfection, out of which 52% of water systems relied on groundwater. A similar study was conducted in Newfoundland and Labrador (NL), which reported that 54% of small municipalities (defined as a population < 1,000 in their study) used only basic screens for filtration (Minnes and Vodden 2017). In this current study, the results revealed that only 17% of water systems used conventional treatment methods. Eighteen percent of water systems used only filtration as a treatment process prior to primary and secondary disinfection. Seven percent of water systems used other treatment methods like Direct Air Flotation and pre-treatment using

$KMnO_4$. Seventeen percent of water systems neither treated their water nor used any disinfectants. Albeit having no treatment and disinfectants, these water systems had no water quality issues reported so far. One possible explanation could be; these water systems might have a very good source water. All these water systems used groundwater as their source water. Second, in small communities, as many people are more concerned about taste and odor of water (Kot et al. 2011), the absence of disinfectants (for e.g. chlorine) might have resulted in no water quality complaints.

In regards to the disinfectants used, the use of sodium hypochlorite (39%) in the form of chlorine was the most common. The higher use of hypochlorite over other disinfectants is understandable because of its ease of use, availability, affordability, and the use of less skilled manpower. Compared to chlorine gas, the handling and storing of hypochlorite solution is simple. However, the American Water Works Association (2007) study on SWSs (defined as population $< 10{,}000$) concluded chlorine gas as the most popular disinfectant (AWWA 2008). This implication clearly suggested that the use of disinfectants vary between different locations. Based on the questionnaire in the present study, 53 % of water systems used only chlorine (chlorine gas, sodium hypochlorite) as a disinfectant, while 23% used more than one type of disinfectant, which included the combination of sodium hypochlorite and UV, mixture of calcium hypochlorite and UV, and the combination of chlorine gas and UV. The use of chlorine only as a treatment process is understandable in small communities given the various financial constraints these communities face in their water systems. The lack of sufficient funds also leads to the unavailability of advanced treatment facilities. Comparing the disinfectants usage to the overall picture of disinfection practices in Canadian water systems, 96% of these water systems using surface water as a source used chlorination as both primary and secondary disinfectants. Twenty-two percent of these systems used ozonation while 25% used ultraviolet radiation as a primary disinfectant (Statistics Canada 2013). Figure 4-3 shows the different types of disinfectants used in the current study.

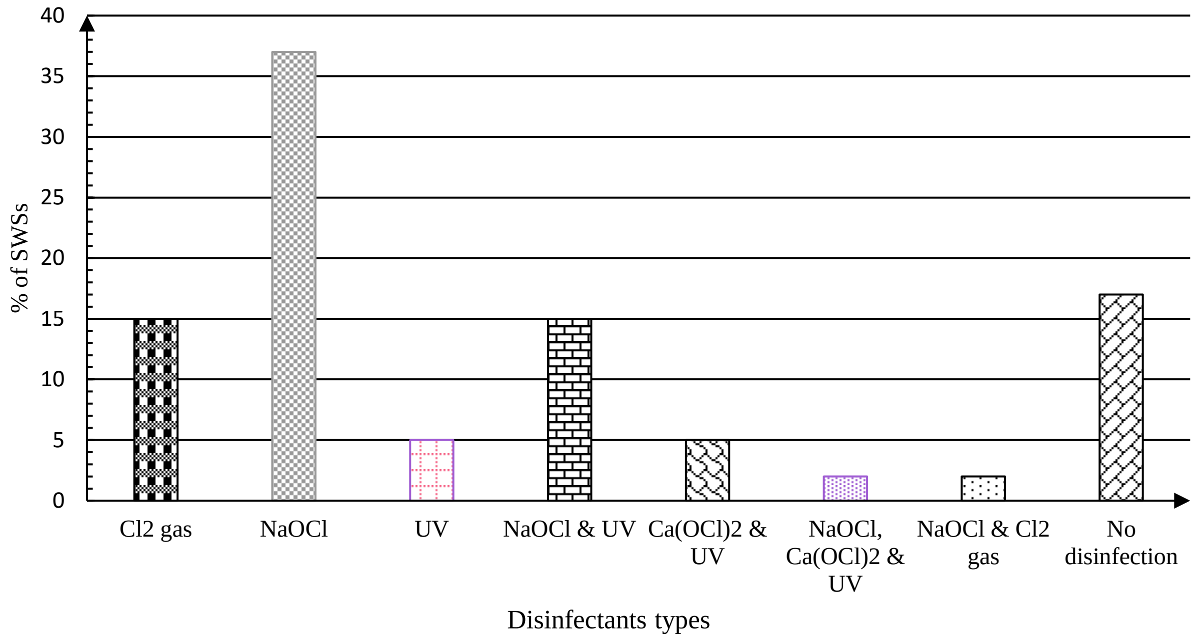


Figure 4-3: Types of disinfectants used

Eighteen percent of the surveyed water systems did not own any treatment plants, out of which 82% of water systems used groundwater as their source. As many as 21% of the treatment plants were less than 10 years in age. The results also indicated that an average age for the treatment systems was 19 years, while the average age of DNs was 44 years. Three DNs were more than 100 years old, while two DNs had been constructed in the last 12 years. Figure 4-4 compares the age of DNs between the current study and DNs across Canada. The majority of DNs were aged between 40-59 years in the current study, while the majority of Canadian DNs aged between 20-39 years in the small communities (Canadian Infrastructure Report Card 2016).

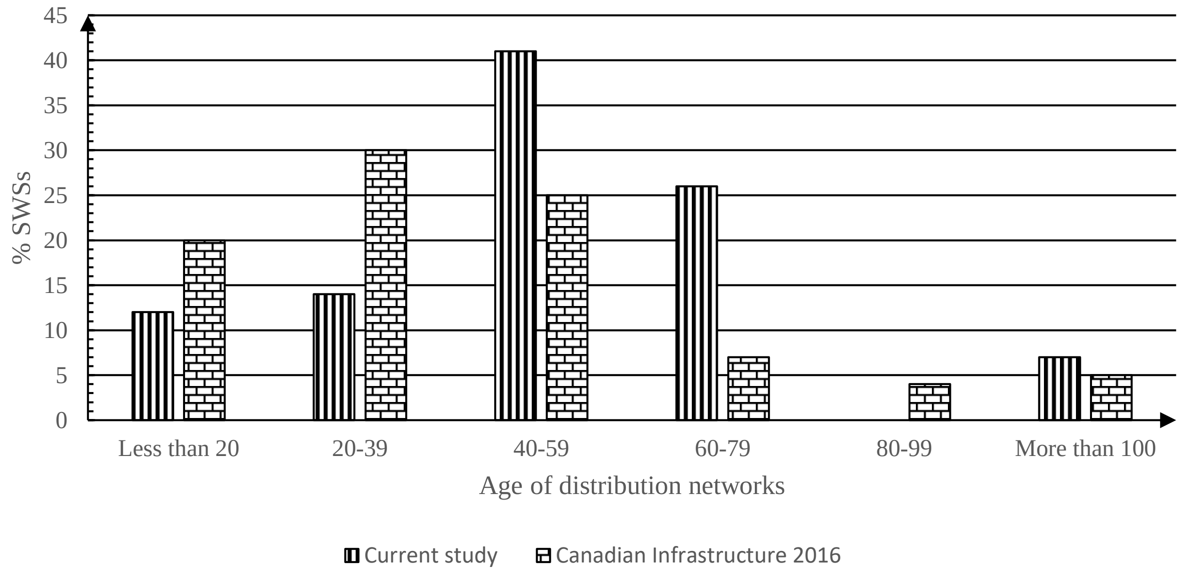


Figure 4-4: Comparison of the age of distribution network between current study and Canadian Infrastructure (2016)

4.1.2.1 Management of hypochlorite solution

Hypochlorite solutions must be properly managed to avoid contamination or loss of solution concentration (EPA 2011). Respondents were asked to rank the challenges associated with hypochlorite solution. A large percentage of respondents rated maintaining an adequate concentration of solution during storage (25%) as a major challenge followed by health risk of hypochlorite solution (e.g. formation of by-products, 22%), increase in storage time (15%), controlling pH (12%), and maintaining temperature (10%). The long storage time of hypochlorite solutions leads to the formation of inorganic by-products such as chlorate, bromate, and perchlorate, which are hazardous to human health (EPA 2011). Hypochlorite solutions must be stored at a low temperature since the decay of hypochlorite is faster at higher temperatures. During storage, pH should be maintained between 11-13. The pH levels below 11 cause the hypochlorite to decompose faster, which promotes the formation of chlorate and perchlorate (Snyder et al. 2009).

When surveyed about the location of the storage of hypochlorite solutions, respondents reported that solutions are stored in heated storage rooms, pump houses, treatment buildings, and public work yards. Ten percent of respondents generated sodium hypochlorite solution onsite. The duration of replacing and refilling hypochlorite tanks varied. Some water systems replaced and refilled tanks between 3-5 days to 7 -10 days, while others performed the same action anywhere between three weeks to six months. Usually, it is recommended to fill the tank on a monthly basis since the hypochlorite solution decays over time. The largest percentage of respondents carried out replacing and refilling activities as per the demand of their respective water systems. The results also revealed that 18% of respondents purchased hypochlorite solution monthly, while 13% purchased quarterly. Fewer than 10% of the respondents bought solution bimonthly, half yearly, annually, and quarterly. Fifty-five percent of respondents verified the purchase (receipt of purchase, quantity of solution purchased), and a majority (42%) of respondents did it while receiving the product. Some respondents carried out the verification monthly, while very few respondents did not verify their purchase.

Thirty-two percent of the respondents cleaned their hypochlorite solution tank before adding the hypochlorite solution, while 17% diluted with the previous solution. Less than 10% of respondents reported that cleaning and dilution of solution in the tank take place as per the demand. Some respondents cleaned their tanks only after the appearance of accumulated particles.

4.1.2.2 Residual chlorine management

Respondents were asked to identify the various stages of chlorination applied in their water systems. The results revealed that 40% of water systems used post chlorination (addition of chlorine at the end of treatment plant), while only 5% used inter chlorination (addition of chlorine at different strategic points in treatment plant). Twelve percent of water systems used pre chlorination (addition of chlorine to raw water), and 2% adopted both pre and post chlorination.

Based on the results, 33% of respondents reported the decay of chlorine varied with season. This decay is notable especially during the summer, while some respondents also observed the decay during spring and fall. As a result, operators find it difficult to maintain an adequate residual chlorine level in their DNs. During winter, respondents revealed that they apply chlorine dosage between 0.4-2.3 mg/L and 1.4-9.0 kg/day in their DNs. The chlorine dosage ranged between 0.5-2.5 mg/L and 1kg/day-200 kg/day in the summer. In some water systems, the addition of large doses of chlorine is carried out to meet the chlorine demand. For example, during spring, the concentration of NOMs in some source waters increases and operators may add more chlorine to meet the chlorine demand. However, this high dosage results in the formation of DBPs. The population in some small communities vary between summer and spring. During fall, some communities have fewer people residing due to which the water remains stagnant for long period of time in DNs increasing the water age. This further reduces the chlorine level in DNs. During summer, the decay of chlorine increases with increasing temperatures.

When surveyed about various strategies adopted for chlorine management in DNs, 63% of respondents considered "mains cleaning (flushing)' as the most suitable method. Ninety-three percent of respondents reported that they cleaned their water mains. Table 4-2 outlines different flushing methods practiced. Twenty-three percent of respondents were in the opinion of “reducing water age”, whereas 15% of respondents preferred the ‘’use of booster station’’ to maintain an adequate disinfectant residual in their DNs. Low water age not only helps to maintain the chlorine level but also inhibits microbial growth, thus, improving the final quality of water. The use of booster stations in small communities is not very common because of the small population, and water can be easily distributed to consumers.

Table 4-2: Flushing methods

Flushing types	% of participants
Unidirectional	43
Conventional	25
Unidirectional and conventional	8
Unidirectional, conventional and continuous blow off	13
Continuous blow off and conventional	7
Continuous blow off and unidirectional	3

Apart from these strategies, the respondents suggested the use of automated water flush systems, extra sampling on dead ends, manual addition of chlorine in tanks, variable solution strength, continuous flow of water at extremities of DNs, and constant monitoring as adopted methods to maintain an adequate concentration of residual chlorine in DNs.

In regards to maintaining residual chlorine levels, the findings revealed that 72% of respondents adjusted dosage according to residual changes. Forty-three percent of respondents adjusted chlorine dosages according to water quality changes at the upstream dosing point while 17% adjusted the dose according to change in temperature.

Based on the questionnaire findings, 45% of respondents used calorimetric method (Diethyl paraphenylene diamine [DPD]) as a method to test residual chlorine in DNs. Eighteen percent of respondents relied both on DPD and membrane covered polarographic sensors, while 12% of respondents used DPD and potentiometric as primary methods to test residual chlorine. The results indicated that 38% of respondents used both manual methods and sensors to monitor residual chlorine, while 33% relied only on manual sampling. In small communities, the majority of respondents using one or two methods to check residual chlorine concentration is a welcomed step. Residual chlorine is a good sentinel to reduce the probability of microbiological contamination and, the wise monitoring of residual chlorine is important from a human health perspective.

4.1.3 Water quality monitoring

Adequate monitoring of water quality indicators followed by immediate controlling action as required ensure safe water supply to consumers. Respondents were asked to report the frequency of monitoring various water quality indicators in source water, in treated water (leaving treatment plant), and in distributed water. The water quality indicators were divided into three categories (i.e., physical [refers to the characteristics of water that are determined by touch and sight], chemical [refers to the characteristics of water that are determined by chemical properties], and microbiological [refers to the microbial content in the water]). Turbidity and temperature were considered as physical indicators. pH, organic content, THMs, and Haloaceticacids (HAAs) were considered as chemical indicators. Heterotrophic plate count (HPC) and residual chlorine were considered as microbiological indicators. The frequency of monitoring for all three indicators varied among daily, weekly, bi-weekly, monthly, quarterly, semi-annually, annually, to once in every five years. The majority of water quality indicators were monitored daily. Table 4-3 outlines the most common monitoring frequency of three water quality indicators at three different locations.

Turbidity was the most monitored physical indicator. Turbidity was measured in source water, treated water, and distributed water by 67%, 61%, and 62% of respondents respectively. pH was the most monitored chemical indicator followed by organic content (organic carbon), THMs and HAAs at all three locations (except for THMs and HAAs in source water). pH was monitored in source water, treated water, and in distributed water by 71%, 58%, and 58% of respondents respectively. Residual chlorine (62%) was the most monitored microbiological indicator followed by HPC, (32%) in distributed water. Appendix B shows the detailed monitoring frequency of all three water quality indicators.

Table 4-3: Monitoring frequency of water quality indicators

Indicators	**Point of measurement**		
Physical			
	Source water (%)	Treated water (%)	Distributed water (%)
Turbidity	35^{D}	42^{D}	26^{D}
Temperature	29^{D}	34^{D}	22^{W}
Chemical			
pH	29^{A}	18^{A}	18^{W}
Organic carbon	43^{A}	28^{A}	29^{A}
THMs		21^{A}	27^{A}
HAAs		13^{A}	15^{A}
Microbiological			
Residual chlorine			31^{D}
HPC			12^{W}

Note: Daily: D, weekly: W, annually: A

Respondents were also required to identify the sampling methods (online, manual, automatic, a mix between online and manual, online and automatic, automatic and online, or a mix of all three). The results indicated that among all three water quality indicators, the largest percentage of respondents sampled pH (82%), followed by temperature (67%), turbidity (64%), residual chlorine (62%), THMs (57%), HPC (55%), and HAAs (38%) using one of the above sampling methods. The largest percentage of respondents used manual sampling methods to sample THMs (57%), HPC (55%), pH (45%), turbidity and temperature (28%).

The data clearly supports the assumption that there is a lack of monitoring programs in SWSs. Similar to BC, the earlier research conducted in NL reported only 17% of Local Service Districts and 55% of small municipalities conducted regular monitoring in their water systems. Similarly, only 6% of Local Service Districts and 20% of small municipalities were aware about the formation of DBPs in their water system in the past four years (Minnes and Vodden 2017).

The CDWQG suggests minimum monitoring frequency of different water quality indicators. For instance, CDWG recommends at least four bacteriological samples, three samples of residual chlorine per month, and daily samples of turbidity both at source and in DNs for the water systems that serves populations < 5,000. The guidelines also suggest that the number of samples could be reduced in water systems serving populations less than 500 (Government of Canada 2013). Compared to medium to large water systems, the rate of sampling is fewer in SWSs. For example, some medium to large water systems take more than 500 samples of various water quality indicators in source water and distributed water on a monthly basis (COK 2017). This practice of low monitoring frequency of water quality indicators in SWSs might be difficult for the identification of possible contamination events and it does not provide a clear picture of drinking water systems. Therefore, it is recommended to increase the number of collected water samples for ensuring safe water supply to consumers.

4.1.4 Issues and challenges of small water systems

Table 4-4 represents the issues and challenges observed among the surveyed water systems. Table 4-5 summarizes various water quality issues associated with source water, DNs, residual chlorine management, financial, technical, and managerial challenges. The issues are categorized into three classes (frequent, common, and occasional). These classes are differentiated in terms of percentages.

The following key points were derived from the study:

- Of the 33% of water systems facing source water quality issues, 45% of respondents identified turbidity as their major challenge.

- Of the 67% of water systems facing DNs water quality issues, 21% of respondents rated old pipes as their major challenge.
- Of the 62% of water systems regarding residual chlorine management as a challenge, 50% of respondents rated “dead ends” as their major challenge.
- Of the 77% of water systems considering financial, technical, social, political, and managerial challenges, 55% of respondents rated financial issues as their major challenge.
- Of the 87% of water systems facing financial issues (includes major and minor challenges), 55% of respondents rated “small population base” as their major challenge.
- Of the 77% of water systems facing technical issues (includes major and minor challenges), 17% of respondents rated infrastructure replacement as their major challenge.
- Of the 64% of water systems facing managerial issues (includes major and minor challenges), 17% of respondents rated lack of community support as their major challenge.

Table 4-4: Issues and challenges in SWSs

Issues	Class	%
Distribution network Financial Technical	Frequent	>67
Source Residual chlorine management Managerial	Common	>33-67
Social Political	Occasional	< 33

4.1.4.1 Source water

Turbidity was a common source water issue for both water systems supplied by surface water and groundwater. Based on the results, turbid source water condition (45%) was classified under a “common” class. The causes of turbidity listed were: location of source adjacent to steep ravines (which are more vulnerable to mass wasting events during heavy rainfall and seismic events), algal formation, and high sediment loads. The sharp spike in turbidity levels during heavy rainfall was a major area of concern. In addition, spring runoff also contributed to source water with a high turbidity. Other surface water issues include: algal formation, colored water, high concentration of NOM in dry seasons, and sand and silt contamination. The presence of total dissolved solids, sodium content, hardness, colored water, and low pH were some of the reported groundwater issues. The high concentration of iron and manganese were major source water issues for groundwater-sourced systems. One possible explanation could be the reduced level of dissolved oxygen concentration in groundwater systems (i.e., shallow and deep wells). The organic matter present in such anaerobic conditions make water more acidic, which provides the most suitable condition for increased iron and manganese concentrations. All issues discussed in this paragraph, except turbidity, were classified as "Occasional" in terms of frequency.

4.1.4.2 Distribution network

A large proportion (47%) of respondents considered "water age" as a common DN issue for both surface water and groundwater. The high water age in DNs is obvious especially in small communities since the water does not get sufficiently used. Old pipes and cracks were major contributors of DN issues for surface water. These issues were classified under a "common" class. Biofilm growth was a major DN issue for groundwater-sourced systems. Both biofilm growth and corrosion along with various physio-chemical and microbiological issues at DNs were classified under the "occasional" class. The physio–chemical issues associated with DNs issues were low pH, faulty gaskets, sampling error, and lack of flow through mains, line breaks, turbidity, hardness, organic matter, formation of DBPs, and chemical deposits. The occurrence of bacteria in the DNs clearly suggests that the concentration of residual disinfectant is not adequately managed. The presence of less microbiological issues does not support the normal assumption that SWSs succumb to microbial contamination. This situation can be attributed to the low monitoring frequency of microbiological indicators in DNs as reported by the respondents.

Table 4-5: Summary of issues and challenges in SWSs

Issues	Common	Occasional	
Source water	Turbidity	pH Color NOM Hardness Iron & manganese	Algal blooms Sodium content Sand contamination
Distribution network	Old pipes	Physio-chemical indicators Microbiological indicators Biofilm and corrosion	
Residual chlorine management	Dead ends	Remoteness High residence time Lack of infrastructure Lack of monitoring	
Financial	Small population base Revenue insufficiency	Insufficient funds for operators training Lack of loan approvals Low per capita income Low water price	
Technical		Inadequate source water supply Infrastructure replacement Lack of regular maintenance sufficient technicians system knowledge	
Managerial		Lack of community support experience among managers external linkage ownership and accountability operators	

Note: Social and political issues do not have sub criteria. These issues are listed under occasional class.
Financial, technical, and managerial challenges and their corresponding causes are classified as classes based on the respondents rating these issues as major challenge.

4.1.4.3 Chlorine management practices

In order to identify the challenges in maintaining an adequate concentration of residual chlorine in DNs, the respondents were asked to rank the challenges. A large percentage of respondents rated dead ends as a major challenge followed by high residence time, lack of infrastructure, remoteness, and lack of monitoring respectively. Since water remains stagnant at dead ends, chlorine consumption is high. Hence, it is important to build loops in DNs such that the flow of water is continuous. Apart from dead ends (common class), the rest of the challenges were classified under the "occasional" class. Table 4-6 outlines the various challenges to maintaining chlorine concentrations in DNs.

Table 4-6: Challenges to maintain residual chlorine in distribution network

Challenges	Rank order distribution						
	1	2	3	4	5	6	No challenge
Dead ends	50	13	12	3	5	2	15
Remoteness	12	10	10	8	25	5	30
High residence time	15	17	17	5	7	8	31
Lack of infrastructure	12	18	8	10	18	10	23
Lack of monitoring	5	2	10	8	25	17	33

Note: Rank 1 to 6 and no challenge refer to the percentage of small water systems

4.1.4.4 Water governance

The challenges associated with SWSs are not only limited to water quality issues, but also they deal with various financial, technical, operator, social, and managerial issues. In this study, these issues are considered as water governance issues. These issues were also studied by the previous researchers in NL, Nova Scotia, and New Brunswick. The results suggested that small municipalities have always found it difficult to overcome these issues in their water systems (Minnes and Vodden 2017; Kot et al. 2011). Respondents were required to rank financial, technical, political, social, and managerial issues. The largest percentage of respondents rated financial issues as a major challenge followed by technical, political, social, and managerial issues respectively. As fewer people reside in small communities, the taxes collected by the local bodies in these communities are not sufficient enough to build necessary infrastructures or maintain the existing ones. The insufficient funds and limited staff lead to low monitoring frequency of water quality, which hinders the supply of safe drinking water. In some instances, the lack of funds compels operators to spend their own money to take part in training and keep themselves updated with current standards set by the provinces. This situation is evident among a few of the surveyed water systems. Thus, it is important to distribute funds properly to meet the needs of communities of 5,000 residents or fewer. Apart from managerial challenges (common class), the rest of the challenges were classified under the "frequent" class. A comprehensive summary of collected challenges is shown in Table 4-7.

Table 4-7: Water governance challenges

Challenges	Rank order distribution					
	1	**2**	**3**	**4**	**5**	**6**
Financial	52	13	2	13	7	13
Technical	32	25	5	3	12	23
Managerial	10	3	3	15	33	35
Political	22	10	15	12	20	22
Social	17	8	18	15	18	23

Financial issues: Respondents were required to rank the financial issues. Overall, the largest percentage respondents identifying financial issues as their major challenge rated small population base followed by revenue insufficiency, low per capita income, low water price, lack of loan approvals, and insufficient funds for operator training respectively. Small population bases (55%) and revenue insufficiency (43%) were classified under a "common" class, while the rest of remaining challenges were classified under a "occasional" class.

Technical issues: Respondents were required to rank technical issues. The largest percentage of respondents rated infrastructure replacement as their major challenge followed by inadequate source water supply, lack of system knowledge, lack of regular maintenance, and lack of sufficient technicians. All these challenges were classified under the "occasional" class.

Managerial issues: Respondents were required to rank managerial issues. The largest percentage of respondents rated lack of community support as their major challenge followed by lack of experience among managers, insufficient operators, lack of external linkage, and lack of ownership and accountability respectively. All these challenges were classified under the “occasional” class. In order to gather good community support, it is the responsibility of concerned local bodies to keep consumers updated about the quality of water being distributed to their taps. Moreover, consumers should be made aware about importance of treated drinking water and negative health effects of unsafe water.

4.1.4.5 Operators role

In an absence of advanced water treatment installation in SWSs, the role of operators becomes more important to supply safe water to consumers as the quality of drinking water depends heavily on an operator’s ability to control water quality changes (Scheilli et al. 2016). The questionnaire revealed that on average, water systems have only two operators. This number of operators is low compared to medium to large water systems. The less availability of operators also presents great challenges since the responsibilities may not be managed efficiently among staff in the water systems. Ninety percent of operators were trained and the average work experience among the operators is 11 years. Operators received training from different institutions and government organizations. This includes BC Water and Waste Association, diploma degree from various colleges, on-job seminars and courses, on job-training programs, and small water systems operator’s programs. The operators received training on water quality and sampling, water distribution level 1, 2, 3, and 4, water treatment level 1 and 2, waste water treatment level 1,2, 3, and 4, and cross connection control. Some respondents also suggested that they did a lot of readings and research on their own to understand issues related to water quality.

In BC operators responsible for water systems serving population less than 500 are not required to be certified. Drinking water officers might require certified operators depending on the complexities of the systems (Provincial Government of Birtish Columbia 2018b). Apart from these operators, all other operators need to be “Environmental Operators Certification Program (EOCP)” certified. EOCP refers to “the program of classification and certification for water supply system operators established in BC by Environmental Operators Certification Program society(Provincial Government of British Columbia 2016b). As such, this study revealed 83% of operators were certified. Since the majority of operators were trained and certified, the current study provides an evidence of increasing awareness about the importance of operators’ knowledge in small communities. This result is similar to the study conducted in NL, where 25% of the operators in small communities were not certified (Minnes and Vodden 2017). The respondents reported that the majority of their operators were EOCP certified, while few were civil and mechanical engineer technicians.

When surveyed about the responsibilities of an operator, 70% of the respondents reported operators shouldered at least five different responsibilities in treatment plants and DNs. The responsibilities included taking and recording the measurements of water quality indicators, maintaining and repairing of equipment in treatment plant and DNs, ordering and purchasing of chemicals and equipment, sampling of water in treatment plant and DNs, and interpreting and assessing water quality results. Thirty-five percent of respondents identified additional responsibilities other than listed above. On call duties, preparing budgets, long-term planning of treatment plants and DNs, hold and participate in annual stakeholder meetings, and respond to water quality complaints were some of the additional responsibilities of the operators as reported by the respondents. Clearly, these responsibilities should be divided among different staff in the water systems. The lack of sufficient staff in these water systems have added extra burden on the operators.

Based on the results, managing limited resources only (28%) was the most challenging part of operator's work, while 17% of respondents regarded meeting water quality guidelines difficult. Few water systems (15%) considered customer satisfaction, meeting water quality guidelines and managing limited resources as areas of concern, while 8% of the respondents reported meeting customer satisfaction only as an issue in their water systems. The lack of available resources (finance and manpower) has been one of the biggest problems in SWSs. The operators also find it difficult to comply with water quality guidelines, which is obvious given their resource capacity restraints. In small communities, consumers give more importance to aesthetic quality of water. These consumers are quick to complain in case of discolored water, however, the presence of bacteria can sometimes go unnoticed. While the colored water has no direct health effects, the microbial contamination in drinking water can have catastrophic implications to human health.

Other challenges reported by the respondents were preventing BWAs, dealing with staff, on call after hours, unfamiliarity with updated guidelines, maintaining contacts throughout the province in sought of funding for resources protection, meeting expectations of EOCP with very limited training and EOC credits, and determining accountability for sustainability of watershed.

4.1.5 Respondents' perspectives

Respondents were required to suggest the possible solutions to overcome the challenges associated with SWSs. The solutions proposed by the respondents were focused on allocating sufficient funds, building strong community relationships, maximizing resources, improving training for operators, monitoring water system infrastructure, and gaining government support.

Table 4-8 illustrates the comprehensive summary of various solutions proposed by the operators to overcome these challenges.

4.2 Validity and reliability

In order to establish the validity and reliability of the findings obtained from the questionnaire, the following methods were used (Trochim and Donnelly 2008):

i. *External validity* refers to the generalization of ideas such that the conclusions obtained from one study are valid for different locations and SWSs. In this study, the questionnaire was sent to different small communities across BC and, to a large extent similar outputs were achieved in regards to water quality issues, disinfection practices, and water governance challenges of water systems.

ii. *Face validity* refers to the degree of accuracy of a study such that the measurement meets the required criteria. In order to verify the face validity, telephonic interviews were conducted with engineers (expert) outside BC and, their responses matched with majority of responses collected from the questionnaire.

iii. *Content validity:* To verify the content validity, questionnaires were shared and discussed with five experts working in the water resource engineering. These experts include professors from the University of British Columbia, Okanagan campus and municipal engineers. These individuals agreed with all the subjects addressed in the questionnaire.

iv. *Convergent validity* was validated with operators, technicians, water utility managers, and engineers providing similar responses to the majority of the questions. However, some of the operators were more critical, while responding to questions related to the challenges of operators' responsibilities. The majority of water systems covering all the regions across BC agreed turbidity as the main source water quality issue. The increase in turbidity level was observed maximum after the heavy rainfall.

The questionnaire's reliability was verified using inter-rater reliability. Five graduate students were asked to rate the water governance challenges. The observation showed that the financial constraints followed by technical issues were critical from the perspectives of both graduate students and questionnaire respondents.

Table 4-8: Respondents perspective to overcome water governance challenges

Existing problem associated with	Solutions
Treatment plant	Establish new treatment plant that uses sodium hypochlorite and UV in the system
Finance	Attainment of grants to upgrade DN Allocation of sufficient funds to build water infrastructure and fix broken pipes Access to infrastructure grants and more funding to replace old infrastructure Affordable water price Enough funding to support operator training which costs a lot of money Sufficient funds to hire more staffs and operators
Social	Expanding buildings and surrounding areas to attract more residents to collect maximum revenue Better communication with residents about current state of WQ Public awareness and community support
Operators	Need of more PLCA and SCADA training, Better education of youth and more opportunities for water operators Priority among operators to maintain system vs additional management teams
Managerial	Hiring more staff and sufficient operators to oversee work related to water systems Increase in number of resources to keep up with increased regulations and treatment requirements Time management among operators Team work
Technical	Regular maintenance and monitoring Appropriate location and design of intake towers Upgrade on leaks Introduce sensors
Political	Support from government Few regulations for SWSs No political play in water utilities and closely work with operators to supply safe water Need for EOCP to adjust its goals, Low cost for certification and training

4.3 Performance assessment

The proposed performance assessment framework provides an approach for operators and managers to compare performance levels of their water systems with similar water systems in BC. Furthermore, the proposed framework can assist in the prioritization of important criteria and corresponding indicators based on the requirements of a particular local body type.

4.3.1 Performance scores

The results of radar diagrams are shown in Figures 4-5a-4-5e. The first criteria, “treatment and disinfection” (C_1; Figure 4a) showed that water systems had comparatively high scores for two indicators, *cleaning water mains* and *following regulatory guidelines*. The weakness of water systems in C_1 were related to *no prior treatment to disinfection*, and *high seasonal variation in chlorine decay*. Second criteria, “water quality issues” (C_2; Figure 4b) represented *customer complaints* and *water quality issues in DNs* as major indicators that weaken the performance of this criteria. The *instances of boil water advisory* and *quality of source water* were the strength of this criteria with high scores. Third criteria, “operators’ capabilities” (C_3; Figure 4c) had fairly constant strength (i.e., mean scores above 3.85) in all the indicators except the *additional responsibilities*, which had relatively low strength (compared to the rest of indicators) in C_3 with the mean score of 3.1. Fourth criteria, “infrastructure and funding” (C_4; Figure 4d) had relatively lower scores (i.e., mean score less than 2.95) compared to other indicators with the highest mean score of 3.07 for the *age of treatment system*. Fifth criteria, “operational factors” (C_5; Figure 4e) exhibited the highest mean score of 3.49 for *monitoring frequency of turbidity in source water,* while the lowest two mean scores of 2.41 and 1.85 were recorded for *monitoring frequency of THMs and HAAs*.

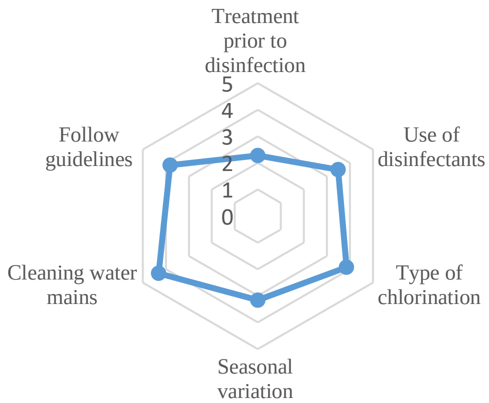


Figure 4a: Treatment and disinfection

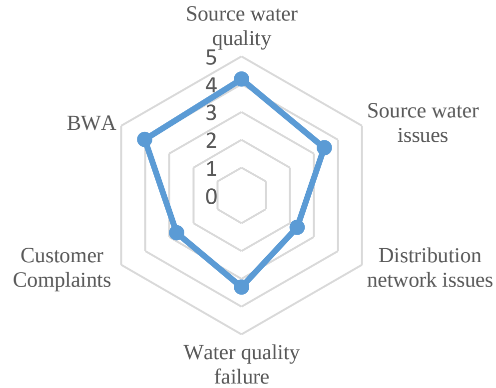


Figure 4b: Water quality issues

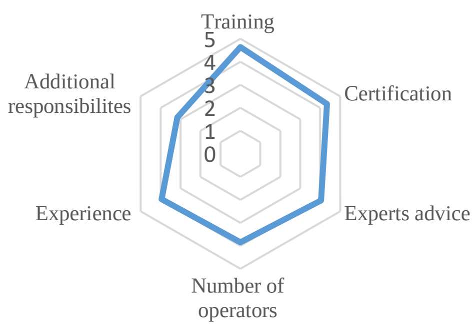


Figure 4c: Operators' capability

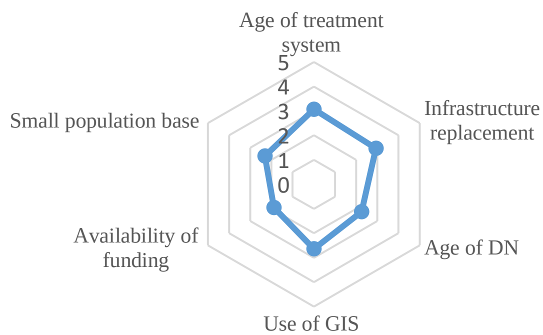


Figure 4d: Infrastructure and funding

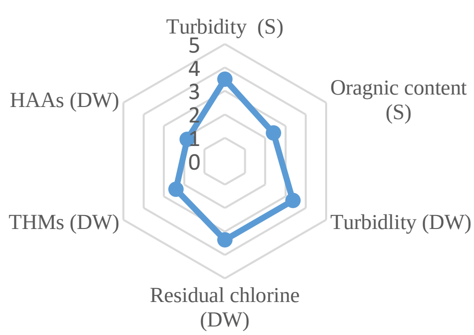


Figure 4e: Operational characteristics

Figure 4-5: Performance scores of water systems under different criteria

4.3.2 Performance level assessments

Above mentioned results are further categorized based on the variation in the performance level of three local bodies. This type of assessment provides a clearer picture related to a specific type of local body. The operators and managers can differentiate the performance level among two or more criteria to better understand their respective water systems.

4.3.2.1 Regional districts

In regards to the overall performance level of water systems, 69% of regional districts water systems had a "*medium*" performance level. This situation is attributed to the fact that a majority of water systems showing a "*low*" performance level for two criteria, C_4 (infrastructure and funding), and C_5 (operational characteristics). The weakness of C_4 was associated with insufficient funding and a low population base, while a low monitoring frequency of turbidity in DNs and organic content in source water weakened the performance level of C_5. Table 4-9 outlines the detailed rank order distribution of the indicators. The majority of water systems had a "*high*" performance level only for C_3 (operators' capabilities). Thirty- five percent of water systems had a "*medium*" performance level for C_2. The performance level was also "*high*" representing the same percentage of water systems for C_2. Sixty-three percent of water systems had a "*medium*" performance level for C_1 (treatment and disinfection).

The results of sensitivity analyses showed a slight difference in performance levels. Apart from water system under S_4 (operators' capabilities-priority, "*high*"), a majority of regional district water systems had a "*medium*" performance level for all other schemes; S_2 (treatment and disinfection-priority, 62%), S_5 (funding and infrastructure-priority, 63%), and S_6 (monitoring frequency-priority, 69%). Thirty-eight percent of water systems had a "*medium*" as well as "*high*" performance level for S_3 (water quality-priority). The regional districts water systems performed better when S_4 was given the maximum priority. The results indicated that 69% of water systems had a "*high*" performance level under S_4. Conversely, the performance level of water systems was worst when the maximum priority was given to S_5 (where 31% of water systems had a "*low*" performance level).

Table 4-9: Rank order distribution of indicators

	Rank order distribution		
Indicators	**Regional districts**	**Municipalities**	**Improvement districts**
Process employed prior to disinfection	6	6	6
Use of disinfectants	5	5	5
Type of chlorination at treatment plant	4	2	2
Seasonal variation in chlorine decay	2	4	4
Follow water quality guidelines	1	1	3
Flushing water mains	2	3	1
Quality of source water	1	3	1
Water quality issues at source	2	3	2
Water quality issues in distribution network	6	5	6
Water quality failure	2	2	4
Customer complaints	2	5	5
Instances of boil water advisory	5	1	3
Training	1	1	1
Certification	1	2	2
Experts' advice	3	3	3
Number of operators	6	4	5
Operators' experience	4	5	5
Additional responsibilities	5	6	4
Age of treatment systems (years)	1	5	1
Infrastructure replacement	3	1	6
Age of distribution network	4	6	5
Use of modern technologies (GIS)	2	3	4
Availability of funding	6	4	3
Small population base	5	2	2
Turbidity (Source)	1	2	4
Organic content (TOC, source)	5	6	3
Turbidity (distributed water)	6	3	2
Residual chlorine (distribute water)	3	1	1
Trihalomethanes (distributed water)	4	4	5
Haloacecticacids (distributed water)	2	5	6

4.3.2.2 Municipalities

The overall performance level of a majority of municipality water systems (60%) was "*low*". Apart from C_3 ("*high*"), a majority of water systems had a "*low*" performance level for the remaining criteria (i.e., C_2, C_4, and C_5), whereas 35% of water systems under C_1 also had a "*low*" performance level. The large customer complaints and water quality issues in DNs weakened the performance level of C_2, whereas aging infrastructure (i.e., treatment systems and DNs) is the major cause of low performance levels for C_4 (see Table 4-9). The weakness of C_5 was associated with a low monitoring frequency of organic content in source water and DBPs, which includes THMs and HAAs in distributed water (see Table 4-9).

The results of the sensitivity analyses showed a slight difference in performance levels. A majority of water systems under S_2 (59%), S_4 (66%), and S_6 (56%) had a "*medium*" performance level. The remaining two schemes, S_3 (52%) and S_5 (66%) had a similar performance level to the overall performance level ("*low*"). Of all the weighting schemes, the municipalities water systems performed better when the highest priority was given to S_3. The performance level of water systems was worst in S_5 where only 6% of water systems had a "*high*" performance level and 66% of water systems had a "*low*" performance level.

4.3.2.3 Improvement districts

A majority of improvement districts water systems (69%) had a "*low*" performance level in regards to the overall performance level of water systems. The reason behind this low performance level must be attributed to a majority of improvement district water systems showing a "*low*" performance levels for all criteria (C_1, C_2, C_4, and C_5), except C_3. The weakness of C1 was associated with water systems not employing any treatment prior to disinfection and lack of use of disinfectants in their water systems. The high rate of water quality failure and frequent customer complaints resulted in the low performance level for C_2. Aging of DNs and lack of infrastructure replacement were responsible indicators for C_4's low performance. Similar to municipalities, lack of monitoring frequency of DBPs weakened the performance level of C_5 (see Table 4-9).

Similar results were obtained under the sensitivity analyses. Apart from water system under S_4 (77%), which had a "*medium*" performance level, improvement districts water systems had a "low" performance level for all other schemes: S_2 (56%), S_3 (54%), S_5 (77%), and S_6 (69%). Of all the weighting schemes, the improvement districts water systems performed better when maximum priority was assigned to S_3 since 8% of water systems had a "*high*" performance level in this weighting scheme.

4.3.3 Statistical analyses

In the current study, the results of ANOVA and Kruskal-Wallis analyses showed that the performance levels of SWSs were statistically significantly different for the three local body types. Appendix C shows the graphical representation (i.e., probability plots) for Kruskal-Wallis analyses and appendix D demonstrates the graphs (i.e., probability plots) for ANOVA analyses. Performance levels were always highest for regional districts followed by municipalities, and then improvement districts under all scenarios. Apart from the baseline scheme, all remaining five schemes were ranked in the same order for both regional districts and municipalities; the order from the highest to the lowest rank was as follows: S4, S3, S2, S6, and S5. Improvement districts water systems had a "*high*" performance level only under two weighting schemes (i.e., S3 and S4).

When equal weights were considered for all criteria (i.e., baseline), the final performance scores were not normally distributed for all three types of local bodies. The final performance score is the summation of individual performance scores obtained for each scenario. The median final performance score of 71.5 was found for regional districts, whereas in municipalities and improvement districts, the final performance scores were 61.0 and 59.0, respectively. The median final performance scores among local bodies were found to be significantly different (p = 0.004). Similar tests were also performed for the remaining scenarios, as outlined in Table 4-10. Although statistically significant differences were observed in performance levels among the three local bodies, the variation was not always significant when one local body type was compared to another (see Table 4-10). The results indicated that the performance level between municipalities and improvement districts were only significant for S_6. The difference in performance levels was also not significant between regional districts and improvement districts for S_3 and S_6. The difference in performance levels was significant between regional districts and municipalities for all scenarios.

All the indicators were considered and included in the analyses to determine correlations between the criteria. The results were same for all the weighting schemes. A Spearman correlation analysis revealed that the statistically significant (at α = 0.01 and 0.05) criteria pair were C_1 and C_3 for regional districts and C_1 and C_2 for improvement districts. C_2 and C_5 and C_1 and C_3 were significant for municipalities. Table 4-11 outlines the Spearman correlation coefficient for three types of local bodies.

4.3.4 Overall performance level of water systems

The overall performance of regional district and municipality water systems in decreasing order in various criteria from the highest to the lowest rank as follows: C_3, C_2, C_1, C_4, and C_5 (Figure 4-6). Although, the rank order distribution of indicators is the same, the variance in the performance levels between these local bodies was extremely different, as evidenced by the results reported in section 4.3.2. The overall performance level for the improvement district water systems for the same order was slightly different as follows: C_3, C_2, C_4, C_5, and C_1 (Figure 4-6).

Regional district water systems treat and disinfect their water, flush the water mains, and take regulatory guidelines into consideration in a greater frequency compared to the rest of the local bodies. This is evident as a majority of improvement district water systems (70%) had a “low” performance level, while only 35% of municipalities and 18% of regional districts had the same performance level for C_1 (Figure 4-7).

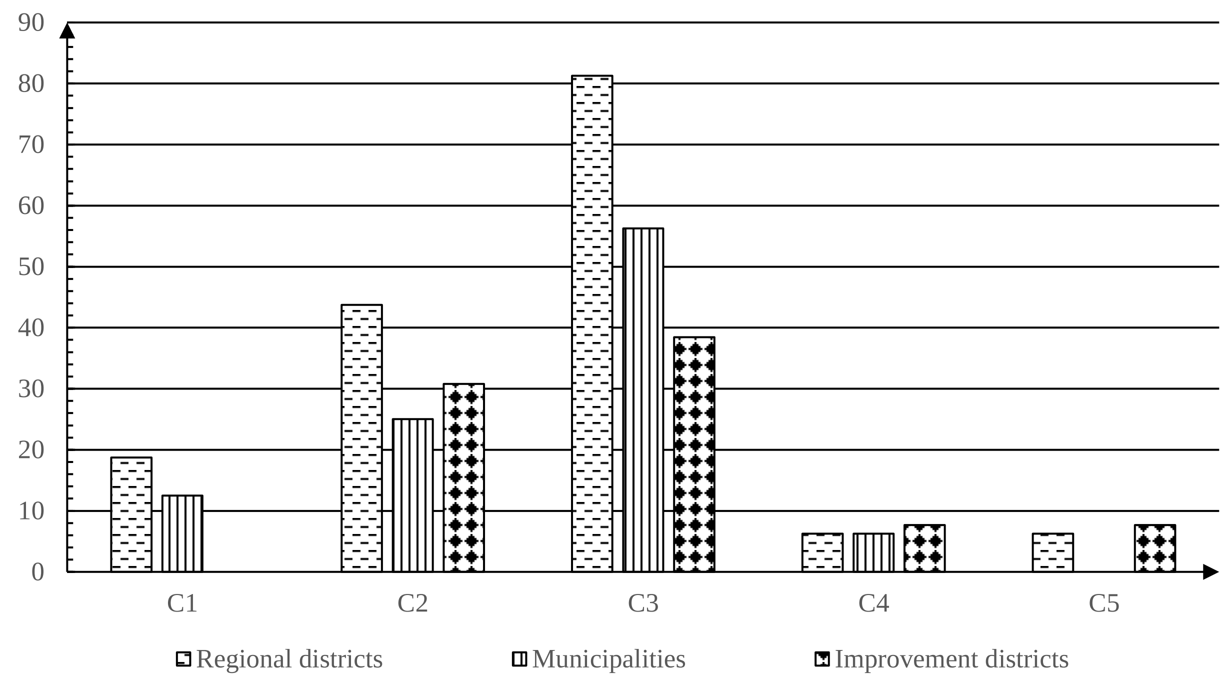


Figure 4-6: Proportion of local bodies under a “high” performance level

Similar results were observed when compared to a “medium” performance level of the local bodies, as a majority of regional district (63%), municipality (53%), and improvement district (30%) water systems fall under this category (Figure 4-8).

Furthermore, 77% of improvement districts, 56% of municipalities, and 44% of regional district water systems did not employ any treatment process prior to disinfection. Interestingly, taking regulatory guidelines as a reference do not necessarily guarantee the improved quality of drinking water. The water systems operators should take appropriate actions if the regulatory guidelines of various water quality indicators are not met.

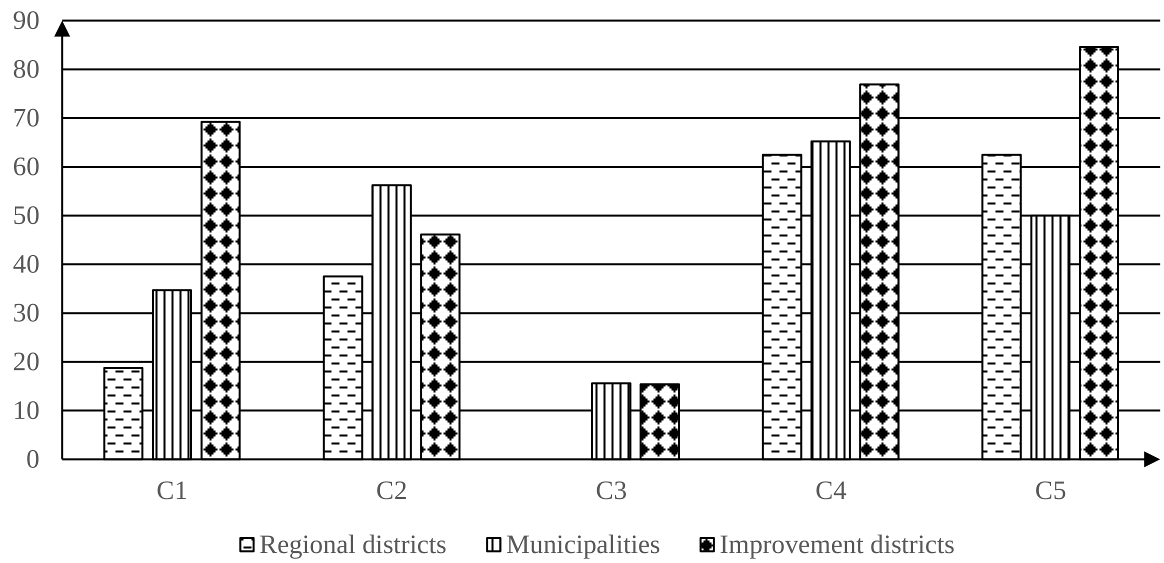


Figure 4-7: Proportion of local bodies under a “low” performance level

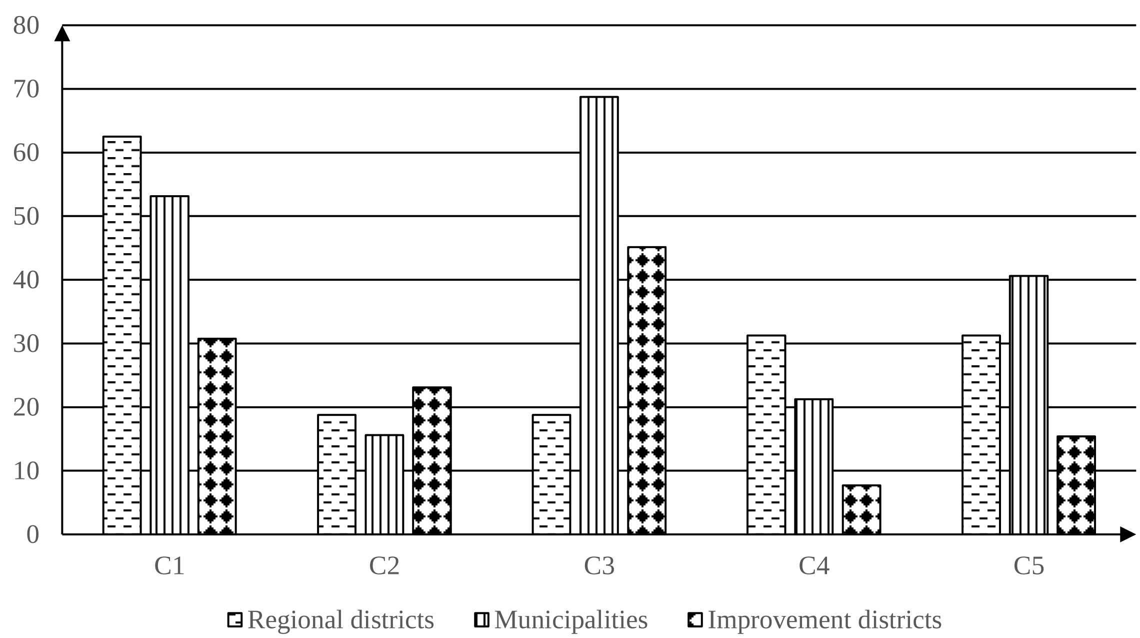


Figure 4-8: Proportion of local bodies under a “medium” performance level

The water quality related issues were observed more in municipality and improvement district compared to regional district water systems. This is evident, as 57% of municipality and 47% of improvement district water systems had a low performance level. The percentage dropped to 39 for regional district water systems (see Figure 4-7). One possible reason behind such a poor performance level can be related to the highest rate of water quality failures recorded for municipality water systems (50%) followed by the improvement districts (38%), and then regional districts (25%). The failure rate might have resulted in a larger number of customer complaints reported to the water systems. Approximately 69% of municipality, 62% of improvement district, and 25% regional district water systems received customers' complaints. Although, BC records the most BWAs across Canadian provinces (Chhipi-Shrestha et al. 2017), one common observation observed in all types of local bodies is that the majority of these water systems were not under BWAs (currently or in the past five years). The possible explanation behind this situation could be the exclusion of the First Nation Communities from the current study. The number of BWAs in the First Nation Communities are relatively high compared to the drinking water supplied to the majority of Canadian communities (Black and McBean 2017). The overall performance level of regional district operators was better compared to municipalities and improvement districts (Figure 4-6). This difference in the performance level might be attributed to the number of operators and experience of operators in all local bodies as shown in Figure 4-6. Operators' experience holds key to supply safe drinking water to consumers especially in small communities (Scheili et al. 2016b). The results indicated 75% of regional districts water system had an average of two or more operators, while the proportion of water systems with two or more operators dropped to 59% and 23% for municipalities and improvement district water systems, respectively. In addition, a majority of regional district operators (81%) had over 10 years of experience, while 56% and 23% of municipality and improvement district water systems had operators with over 10 years of experience.

A clear distinction in the performance level was observed among the three local bodies related to infrastructure and funding availabilities. One possible explanation behind this variability could be the difference in the financial resources of the local bodies. Improvement districts do not quality for provincial grants (Carter et al. 2008) and the grants distributed for small municipalities and regional districts operating water systems are not always sufficient. This statement is validated in the current study through C4 as a majority of improvement district water systems (77%), and municipality water systems (66%) had a “low” overall performance level compared to 62% of regional district water systems. Similarly, 56% of municipalities and 45% of improvement districts considered infrastructure replacement as an area of concern in their water systems. The percentage dropped to 39% for regional district water systems (see Figure4-7). The results clearly showed that there were more infrastructure and funding related issues in improvement districts, followed by municipalities, and then regional districts. In addition, some local bodies constitute multiple water systems in their region. However, the funds assigned for one water system cannot be transferred to another water system even if it represents the same local body.

The results strongly advocated the need of governmental attention in strengthening the financial and infrastructural needs for the respective local bodies. The availability of sufficient funds and better infrastructures would help operators increase the monitoring frequency of water quality indicators. On one hand, good infrastructure means more monitoring points in DWSs, while on the other hand, sufficient funding provides more training opportunities for operators, which can help operators to focus on the importance of monitoring water quality indicators.

The results suggested that when operators of the local bodies did not monitor the water quality indicators (C_5) periodically, the majority of all local bodies had a “low” overall performance level. Seventy-seven percent of improvement districts had a “low” performance level for C_5, while 65% of municipalities fell under the same low performance category, and the percentage drops slightly to 62% for regional districts. One explanation behind a “low” performance level in all types of local bodies could be the regulations established by a government body. For example, CDWG recommends only four samples of turbidity, three samples of residual chlorine per month for the water systems that serves population $\leq$ 5,000. These samples of turbidity, residual chlorine, and bacterial count be further reduced for water systems serving populations less than 500 (Health Canada 2013).

Statistically insignificant relationship established between the criteria pair in the majority of municipalities and improvement districts may be attributed to the similar rank order distribution of indicators in these local bodies. This is evident through Table 4-9, as the indicators of C_1, C_3, and C_4 had almost similar rank order distributions. The result emphasizes the need of further study to understand additional reasons behind similar performance level relationships between these two bodies.

The medium-strength correlation established between C_1 and C_3 for regional district water systems can be attributed to the increase in the performance level of treatment and disinfection with operators’ capabilities. This relationship was also observed among municipality water systems. The negative correlation between C_1 and C_2 for the improvement district water systems stresses the importance of reduction of water quality issues with improved performance of treatment and disinfection.

Table 4-10: Results of ANOVA and Kruskal Wallis testing in different weighting schemes

Scenarios	Test values	p-value	Post hoc tests
Equal weight	RD: M= 71.5 MU: M = 61.00 ID: M = 59.00	0.004 (Kruskal-Wallis)	Tukey test: RD and MU (p= 0.029), RD and ID (p=0.003) and MU and ID (p= 0.002).
Treatment technology-priority	RD: µ= 73.69 MU: µ = 63.00 ID: µ= 58.54	0.004 (ANOVA)	Tukey test: RD and MU (p= 0.019), RD and ID (p=0.006) and MU and ID (p= 0.529).
Water quality- priority	RD: M= 73.0 MU: M = 56.0 ID: M= 59.0	0.019 (Kruskal-Wallis)	H test: RD and MU (p=0.009), RD and ID (p= 0.087) and MU and ID (p= 0.214).
Operators' characteristics-priority	RD: µ= 84 MU: µ = 71 ID: µ= 67	0.000 (ANOVA)	Tukey test: RD and MU (p=0.000), RD and ID (p=0.000), and MU and ID (p=0.629).
Infrastructure and funding-priority	RD: µ= 65.38 MU: µ = 55.81 ID: µ= 49.85	0.009 (ANOVA)	Tukey test: RD and ID (p= 0.008), RD and MU (p=0.060), and MU and ID (p=0.374).
Monitoring frequency-priority	RD: µ= 69 MU: µ = 65 ID: µ= 50	0.000 (ANOVA)	Tukey test: RD and MU (p=0.000), RD and ID (p=0.999), and MU and ID (p=0.000).

Note: RD: Regional districts, MU: Municipalities, and ID: Improvement districts

Table 4-11: Spearman’s correlation coefficient between different performance criteria in local bodies

	Treatment and disinfection		Water quality issues		Operators’ capabilities		Infrastructure and funding		Operational characteristics	
Treatment and disinfection	RD	1	RD	0.465	RD	0.568*	RD	0.335	RD	0.328
	MU	1	MU	-0.122	MU	0.543**	MU	0.196	MU	0.237
	ID	1	ID	-0.575*	ID	0.054	ID	-0.426	ID	0.194
Water quality issues	RD	0.465	RD	1	RD	0.166	RD	0.126	RD	0.471
	MU	-0.122	MU	1	MU	-0.278	MU	0.5**	MU	-0.513**
	ID	-0.575*	ID	1	ID	-0.267	ID	0.256	ID	-0.309
Operators’ capabilities	RD	0.568*	RD	0.166	RD	1	RD	0.382	RD	0.034
	MU	0.543**	MU	-0.278	MU	1	MU	0.130	MU	0.432*
	ID	0.054	ID	-0.267	ID	1	ID	0.211	ID	0.365
Infrastructure and funding	RD	0.335	RD	0.126	RD	0.382	RD	1	RD	0.045
	MU	0.196	MU	0.5**	MU	-0.130	MU	1	MU	-0.221
	ID	-0.426	ID	0.256	ID	0.211	ID	1	ID	0.059
Operational characteristics	RD	0.328	RD	0.471	RD	0.034	RD	0.045	RD	1
	MU	0.237	MU	-0.513**	MU	0.432*	MU	0.045	MU	1
	ID	0.194	ID	-0.309	ID	0.365	ID	0.059	ID	1

*significant at p= 0.05
**significant at p = 0.01

4.4 Lessons learned

The implementation of performance assessment framework helps water system managers to improve the performance of their water utilities. Figure 4-9 presents a strategy for safe water supply based on the findings of this research and how research deliverables should be implemented

This strategy is designed based on the issues and challenges presented by the current study in the SWSs and recommends strategic actions that need to be taken by the government at all three levels. The strategy adopts a multi-barrier approach and can be used by the local bodies and water utility owners to assess the state of SWSs. This will assist decision makers to take necessary strategies for the overall improvement of drinking water quality.

The three level strategic methodology is explained as the following:

i) Federal and provincial government level

The first level shows that government at federal and provincial level play an important role to manage the SWSs. The federal government is responsible to supply water to various areas of federal jurisdiction, while provincial government oversees the operation of municipal and private water systems. Both these governments are responsible to set water quality guidelines and provide funds to local government.

ii) Local government level

The second level describes local bodies are more concerned in supplying water to consumers, collect revenues, and create awareness among people about the importance of safe water. In BC, the water systems are governed and regulated under the DWPA and DWPR (Provincial Government of British Columbia 2018a).

iii) Strategic actions

The third level represents the major part of the proposed strategy, which focuses on strategic actions to be taken for effective disinfection of drinking water. The strategic actions can be classified into five categories as described below:

The third level represents the major part of the proposed strategy, which focuses on strategic actions to be taken for effective disinfection of drinking water. The strategic actions can be classified into five categories as described below:

a) *Water quality management*. The physio-chemical and microbial water quality issues can be minimized to a large extent with a proper source water protection plan. The source water can be protected through land acquisition, watershed inspection programs, riparian buffers and reservoir-use restrictions (WHO 2004). Proper source water protection plan reduces the extra treatment cost and also further treatment can be carried out easily without any machinery complications. For instance, bad quality of source water can disrupt the working efficiency of filters. Similarly, an alternate source water is also an option to compensate the source water issues.

The identified water quality issues may be addressed with an adequate pre-treatment (e.g. use of roughing filters) followed by pre-sedimentation. Moreover, the usage of oxidants reduces the taste and odor issues followed by aeration. The treated water needs to undergo basic water treatment process of coagulation, flocculation, sedimentation and filtration. The adequate dosage of coagulants, appropriate mixing of particles, enough detention time to allow particles for the settlement, and selection of suitable method of filtration are significant to meet basic water treatment process. Finally, the water should be disinfected sufficiently (i.e., wise practice of primary and secondary disinfection of water) for safe drinking water supply.

b) *Residual chlorine management*. Water throughout the DNs should maintain an adequate concentration of residual chlorine in order to inhibit the bacterial growth. The growth of bacteria not only creates a pathway for the formation of biofilm but also develops corrosion in pipes. In case of an excess residual disinfectants, it leads to higher formation of DBPs, which are potentially detrimental to the human health. The issues associated with residual chlorine management can be minimized with some approaches such as reducing water age, periodic flushing, appropriate dosing, looping dead ends, increasing tank turnover, and plausible consideration of pipe design. As a majority of SWSs use sodium hypochlorite as their disinfectant, it is important to maintain an adequate solution concentration and store the solution in a safe space. Various regulatory agencies have set their own standards for the maintenance of residual concentration in their DN, however, SWSs are unable to follow these guidelines in the absence of funds, infrastructure, and manpower.

c) *Water quality failure:* The rate of water quality failure can be reduced through a proper asset management plan. This plan can be achieved through serious considerations, while designing water infrastructure such as storage tanks and reservoirs. The department of drinking water should closely work with road and electricity department such that the buried water infrastructure could not easily get contaminated during the maintenance.

d) *Sampling and monitoring of water quality indicators*: The monitoring of water quality indicators plays significant role in assessing the condition of source water, treated water, and distributed water to consumers. The monitoring of water quality indicators differs spatially and on the quality of source water. The monitoring program developed for one water system might vary with other. Therefore, it is important for water utilities to first gauge the quality of water in their respective water systems and initiate the monitoring programs accordingly. A regular monitoring of basic water quality indicators such as turbidity, coliforms, residual chlorine level, organic content, and DBPs is considered welcoming step to keep track on quality of water supplied.

e) *Water quality guidelines*: In Canada, each province has its own set of drinking water quality guidelines. However, government does not have any standardization in regards to the drinking water guidelines. Therefore, it is now high time for federal government to work with provincial government to build certain standards. A different set of standards are to be set for SWSs as most of SWSs are deprived of proper water infrastructure and facilities compared to medium and large water systems.

f) *Sustainable financing*: Sustainable finance is an important factor for the safe supply of water. Sufficient budget should be allocated to build and improve water infrastructure. The water price should be reasonable according to the size of population. All SWSs should be made eligible for the provincial grants. Financial transparency in collected revenues is necessary for the efficient management of resources such that consumers are acquainted with their money and tax have been utilized in a proper manner. In addition, accountability in water utilities increases the trust of consumers, which is important for the water infrastructure development in small communities.

g) *Technical capability*: The technical capability of water operators and engineers is necessary to ensure safe water supply to consumers. The contributing agents to generate sound technical capability is closely associated with operators' training and experience. The system understanding can be strengthened with adequate training of operators. Government should develop certain plans and policies to retain experienced operators in small communities. Operators must be facilitated with enough salary and their responsibilities must be divided properly. Operators and their profession should be looked with a great respect by the people of the community.

h) *Social aspects*: The accessibility to safe water supply is directly linked to consumers' health. Public participation in municipal water planning provides opportunities to consumers to share their views and in turn public awareness of consumers on water systems will be increased. Consumers' may have complaints on water quality, quantity, pressure, etc. In such scenarios, water utilities should address the complaints immediately. Moreover, the local body is recommended to play an active role in creating awareness among people regarding the benefits of treated water and threats associated with untreated water.

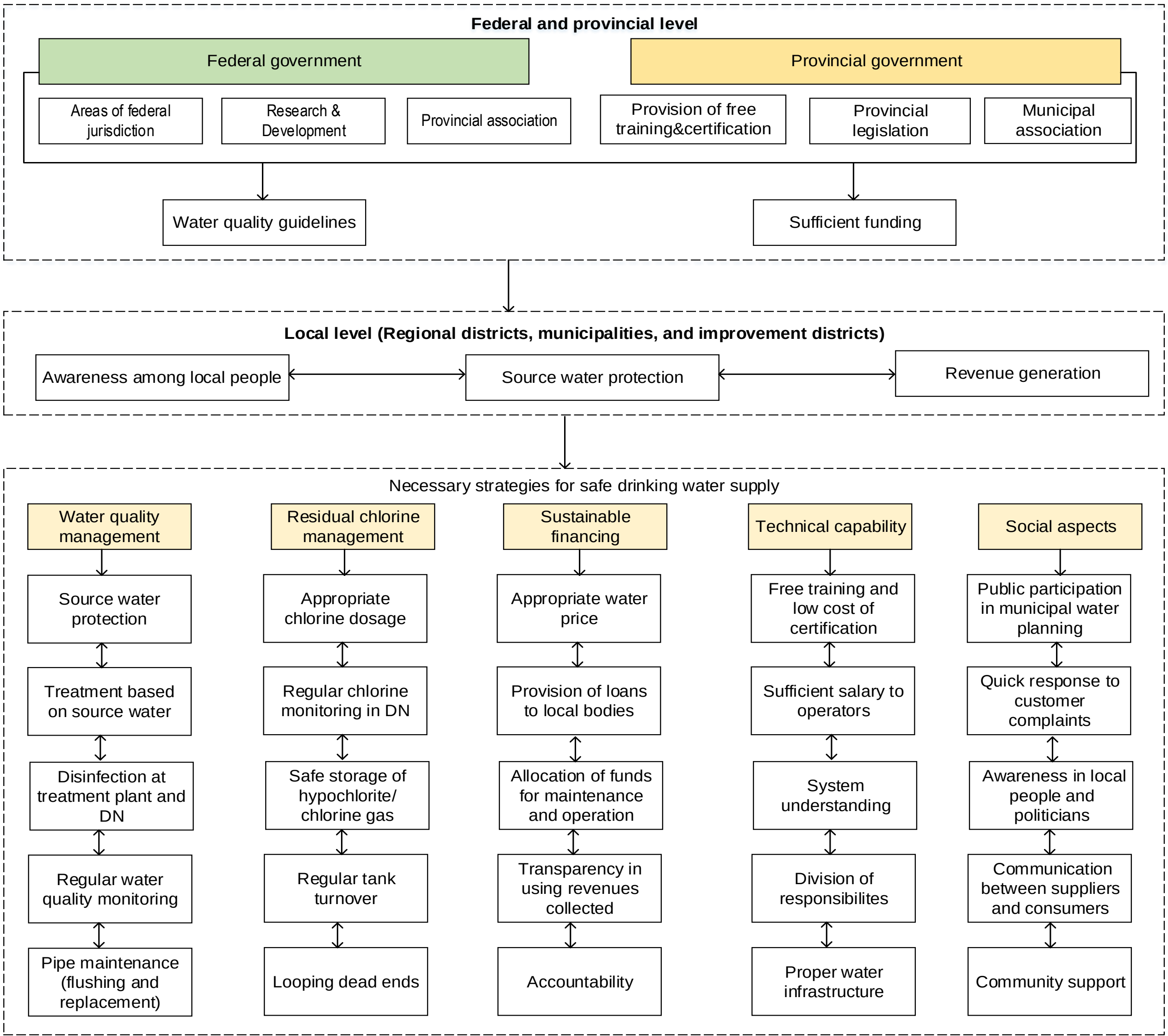


Figure 4-9: Strategy to supply safe water to consumers

Chapter 5: Conclusions and Recommendations

5.1 Summary and conclusions

The main objective of this research was to estimate the current state of SWSs in British Columbia. To achieve this objective, a questionnaire was distributed to 200 SWSs across the province. The response rate of the questionnaire was 33%, out of which, municipalities (MUs), regional districts (RDs), and improvement districts (IDs) represented 55%, 24%, and 21% of responses respectively. Based on the responses received, a performance assessment framework was developed, which provides a tool to evaluate the current state of SWSs in RDs, MUs, and IDs. The performance level of these SWSs was determined against on five performance criteria including, treatment and disinfection, water quality issues, operators' capability, infrastructure and funding, and operational characteristics, and 30 performance indicators.

Generally, SWSs in RDs had the "*best*" overall performance followed by MUs and IDs. The overall performance evaluation showed 69% of RDs fall within the "medium" performance level, while 60% and 69% of MUs and IDs were identified at the "low" performance level. A very small proportion of SWSs in RDs (19%) and MUs (3%) have a "high" performance level, while none of the IDs were identified in this category.

Followings are the main conclusions of this study:

5.1.1 Regional districts

In RDs, performance of SWSs are primarily concerned with issues related to unavailability of sophisticated/advanced water treatment facilities (44%), water quality issues in DNs (69%), and the lack of funding availability (82%). Although operators in this region sample physiochemical and microbiological indicators, the monitoring frequency of these indicators are much less compared to the medium and large sized water systems. Ninety-four percent of operators relied on the chlorination as a disinfectant. Most of the operators were well trained and educated (94%), while 82% of the operators had more than 10 years of experience.

5.1.2 Municipalities

In MUs, performance of SWSs are primarily concerned with issues related to lack of advanced water treatment facilities (56%), source (57%) and DN (69%) issues, water quality failure (50%) and complaints (69%), shortage of funds (69%), and infrastructure replacement (44%), which lead to the poor performance level of their water systems. Compared to the physical and microbiological indicators, chemical indicators particularly, THMs (50%) and HAAs (75%) were not monitored in the municipal water systems. Seventy-eight percent of operators relied on the chlorination as a disinfectant Ninety percent of the operators were trained, 79% certified, and 57% had an experience of over 10 years. However, sixty percent of operators performed more than one type of responsibility, which highlights the lack of human resources in the municipal water systems.

5.1.3 Improvement districts

In IDs, performance of SWSs are primarily concerned with issues related to unavailability of advanced treatment facilities (77%), DN issues (62%), customer complaints (62%), insufficient funds (77%), and infrastructure replacement (62%). Monitoring frequency of all the water quality indicators were observed in a low frequency, while only 38% of water systems used chlorine as a disinfectant. Compared to the RDs and MUs, the proportion of trained (82%) and certified (76%) operators were less in IDs, while only 38% of operators had more than 10 years of experience.

5.2 Contributions and originality

This BC specific study investigated key water quality issues and water governance challenges faced by SWS operators across the province. The proposed performance assessment framework will assist small utility managers to assess the performance of their systems by comparing performance of one system with similar systems. It is expected that this study will draw a greater attention for both federal and provincial governments to address the issues of SWSs with a higher priority; thereby developing strong plans and best management practices for the overall improvement of performance in SWSs.

5.3 Limitations and recommendations

The following challenges and limitations have been identified in the present study and necessary recommendations are made to overcome those challenges:

- The performance of SWSs was only determined through the lens of drinking water quality management. It did not consider climate change (e.g. emissions generated from pumps and vehicles), public safety (e.g. water supplied during a power failure, emergency water supplies), and water leakage (e.g. leakage in pipes, cross connections, meter readings). Future studies should focus on developing more comprehensive performance criteria and indicators, which includes environmental impacts (e.g. climate change), capacity of treatment plants and storage reservoirs, consumption of water per household per day, and water pricing.
- Performance scores were assigned based on the literatures and expert opinions. These performance scores assigned to a few indicators might reflect certain biasness. Therefore, a robust scoring technique should be established for assigning scores to the performance indicators. Moreover, water quality sampling and analysis can be conducted from water

systems to validate the actual severity of water quality issues and facilitate assigning performance scores.

- Questionnaire was not distributed among First Nation communities. These communities normally face many water quality issues and challenges to supply safe water to their residents. Future studies should be oriented to understand the status of all types of SWSs across BC. In addition, the questionnaire can also be distributed to medium and large-sized water systems. A comparative assessment between small and medium/large-sized water systems might be helpful in understanding the variation in the performance level of SWSs with respect to the bigger sized water systems.

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Appendices

Appendix A Rationale for the selection of performance indicators

A.1 Treatment and disinfection

This criterion includes indicators related to treatment and disinfection of drinking water. The main objective of this criteria is to understand the type of treatment and disinfectants used, temporal variation of chlorine decay, and the various methods of flushing used. The criteria that were selected based on this indicator are discussed as following;

A.1.1 Treatment prior to disinfection

The source water is contaminated with various contaminants and it is always suggested to remove maximum contaminants at the initial stages of water treatment which reduces treatment costs in later stages. Conventional treatment is considered as the best form of water treatment before disinfection of drinking water, hence the highest score of 5 is assigned to this category. This treatment includes the combination of coagulation, flocculation, sedimentation, and filtration that result in the heavy removal of contaminants from source water (EPA 2011). Some water systems are seen using only filtration as a method of treatment. Although, filtration removes contaminants from source water, it does not remove large amount of NOM and inorganic particles. In such condition, if filtration is used only as a method of treatment then there is a high possibility of filter media undergoing wear and tear which eventually could lead to the higher usage of disinfectants. This method gives an average performance, hence the score of 3 is assigned. There are also some water systems that do not use any treatment method prior to disinfection. The disinfectants used in untreated water get decayed quickly and it becomes difficult to maintain adequate concentration of residual throughout the treatment system and in DN. Such water utilities are assigned score of 1.

A.1.2 Use of disinfectants

Water should be adequately treated and disinfected before its distribution to consumers. Disinfection is achieved in two ways. The purpose of primary disinfection is to inactivate or kill the microorganisms in treatment plant where as secondary disinfection aims to maintain an adequate amount of disinfectant residual in finished drinking water ensuring no further growth of microorganism when water passes along the DN (EPA 2013) The water systems practicing both form of disinfection are assigned score of 5 where as if water systems perform only one type of disinfection then the score of 3 is assigned. Some water systems do not use any disinfectants in their drinking water supply which could be hazardous to human health. Such systems are rated as "poor" and are assigned score of 1.

A.1.3 Type of chlorination

Chlorine is the most popular disinfectant in water treatment and disinfection due to its simplicity, cost efficient and ability to fight against bacteria and viruses (Scheili et al. 2016b). Chlorination of drinking water can be done at multiple stages. Pre chlorination is the addition of chlorine to raw water. The chlorine dose at this stage should be of very little dosage. Basically, this method of chlorination reduces problems related to corrosion and algae formation. Inter chlorination is the addition of chlorine at the multiple points in the treatment plant before distribution. Post chlorination is the addition of chlorine at the end of treatment plant before distribution. This is the best practice of chlorination as it prevents the further microbial growth in DN. The water systems practicing post chlorination are assigned the score of 5 while water systems adopting inter-chlorination or pre chlorination is assigned score of 3. The water systems that do not practice any chlorination in their water systems were assigned the score of 1.

A.1.4 Seasonal variation in chlorine decay

The temporal variation plays a significant role in chlorine decay. Usually, the rate of decay is faster in the summer and fall season compared to winter season. The decay rate typically double its value for every 5^0C rise in temperature (Fisher et al. 2011). As a result, during the warmer temperature, there is higher formation of DBPs such as THMs and HAAs, higher number of heterotrophic plate count (HPC) and bad taste and odor. These problems are witnessed both in small and large water systems (Scheili et al. 2015). Undoubtedly, it is impossible to have zero seasonal variation in any water systems. However, if the variation is found in low amount, the water system is considered to have been performing better compared to high amount. The scores are assigned as 5 to “low” variation and 1 to “high” variation.

A.1.5 Flushing

Periodic flushing removes deposition of materials attached to the pipe surface. It further improves drinking water quality in regards to color, taste and odor and also combat the growth of biofilm, reduce bacterial counts and helps to maintain residual disinfectant (NRC 2006). Unidirectional flushing is the best method of flushing water mains as velocity of water is high and it uses 40% less water compared to conventional flushing (Newmarket 2018). The water systems adopting this flushing technique is assigned score of 5 while the systems using conventional flushing are assigned score of 3. Some water systems do not flush their water mains and these systems are assigned score of 1.

A.1.6 Compliance with water quality guidelines

The federal- provincial- territorial committee on drinking water developed guidelines for Canadian Drinking Water Quality and is published by Health Canada (Government of Canada 2016a). However, in Canada, these guidelines are not standardized and each province can have their own set of guidelines. For instance: In British Columbia, there are five health authorities that apply and enforce DWPA and DWPR to all the water systems across province. The water systems that follow water quality guidelines of any organization (Health Canada, WHO, US EPA and health authorities) are assigned score of 5 and those systems that do not follow the guidelines are assigned score of 1. Following water quality guidelines keep the water systems checked in, help monitor various water quality parameters, and also protect human health.

A.2 Water quality issues

This criterion includes indicators related to water quality issues and challenges.

A.2.1 Quality of source water

The type of water treatment that needs to be applied rely on the quality of source water. The water source with significant amount of contaminants needs to undergo pre-sedimentation before the application of any basic water treatment process. Pre- sedimentation removes readily settle able solids, heavily suspended particles and other contaminants present in source water(EPA 2011). The water systems that have "good" source water quality were assigned score of 5, "moderate" quality were scored 3 and water systems that have "poor" source water quality were assigned score of 1. The term "good" refers to water source that has no source water quality issues like high turbidity, taste, odor, color, suspended solids, algae blooms and hardness whereas "poor" refers to water source that has at least one or more issues listed above. The term “moderate” refers to occasional source water issues like spike in turbidity during spring freshet, seasonal change in color or occurrence of any water quality issues sporadically.

A.2.2 Water quality issues at source

Source water are often associated with various water quality issues. Some of common issues were listed in section 4.1.4. The identification of source water issues help water utilities better understand their source and take necessary strategies to overcome the challenges. Some source water might be heavily contaminated and timely identification of these issues might encourage water utilities to change their source for drinking water. Based on the survey results, the water systems that have any source water issues were assigned score of 1 and water source with zero issues were assigned score of 5.

A.2.3 Water quality issues at distribution network

Distribution network is one of the most important components of DWS as it is the final stage of water supply before its distribution to consumers. It is therefore essential for water of the highest quality to be continuously supplied throughout the DN. There might be various water quality issues that might be associated with DN. Some of common issues are high residence time, biofilm growth, inadequate residual disinfectant, old pipes and corrosion, formation of DBPs and increase in organic contents. Based on the survey results, the water systems that have any DN issues were assigned score of 1 and water source with zero issues were assigned score of 5.

A.2.4 Water quality failure

The failure in various components of DWS result in the outbreak of various incidents which can be catastrophic to human health. There are numerous incidents that have been recorded where failure in DWS lead to outbreak of various diseases (Gorchev and Ozolins 2011). Some of the factors responsible for water quality failure are main breaks, water leakages, power outages, system upgrade and malfunctioning and ignorance on the maintenance of water infrastructure. The frequency of water quality failure varies spatially and temporally. The score of 5 is assigned to water systems that have zero failure in their water systems, occasional (once in last five years) failures are assigned score of 3 and constant failures that occur every year due to spatial and temporal variation or any other reasons are assigned score of 1.

A.2.5 Instances of boil water advisories

In Canada, BC has maximum number of BWAs in small and medium water systems (Chhipi-Shrestha et al. 2017). BWA are generally issued when E.coli or total coliform are found in DWSs, any harmful contaminants degrade quality of distributed water or the DWSs fail to meet the treatment objectives set by the respective provinces (Ministry of Health 2013). Based on the survey result, scores are assigned to water systems depending on number of instances a water system had BWA. If a system had never undergone BWA, a score of 5 is assigned. Similarly, if the system had 1-2 BWA in last 5 years, the score of 3 is assigned. However, if the system had more than 2 BWA or is presently under BWA then, the score of 1 is assigned.

A.2.6 Customer complaints

Especially in small and rural communities, majority of customer complaints are associated to the taste and odor of chlorine, color in drinking water. Some of customers are often seen giving more priority to aesthetic side of water. The taste of chlorine in water persuade customers to drink bottled water compared to tap water (Kot et al. 2011;Minnes and Vodden 2017). Based on survey result, scores are assigned to water systems depending on number of customer complaints received by water utilities. If water system received no complaints over a period of 5 years, a score of 5 is assigned. Similarly, if there were 1-5 complaints in last 5 years, a score of 3 is assigned. Finally, if more than 5 complaints are registered in the last 5 years, a score of 1 is assigned.

A.3 Operator's capability

This criterion discusses about the various characteristics of operators in SWSs.

A.3.1 Training

The importance of trained operators in identifying water quality issues and monitoring exigencies in small communities is greater compared to large communities as SWSs lack advance water treatment installation in their plants (Scheili et al. 2016b). In some small communities, operators struggle to understand the issues related to source water protection and lack technical knowledge to reduce the formation of DBPs in DWSs (Minnes and Vodden 2017). As such, the importance of trained operators is pivotal especially in SWSs. Based on survey result, a score of 5 is assigned to operators who were trained and score of 1 is assigned to untrained operators.

A.3.2 Certification

In BC, SWSs operators are not required to be EOCP certified. However, Drinking water officer DWO can ask for a certificate if he/she feels that the operator should be certified depending on the complexity of small system (Provincial Governmnet of British Columbia 2018.). In addition, the health authorities in BC are encouraging the operators of SWS to be certified and trying to make it as a requirement for acquiring operating permits(Carter et al. 2008). Based on survey result, a score of 5 is assigned to the certified operators whereas score of 1 is assigned to uncertified operators.

A.3.3 Experience

Operators with sound technical knowledge and high experience in the field of drinking water treatment accounts for safe distribution of water to consumers (Minnes and Vodden 2017). Although, there is no specification in justifying the experience of an operator, it is obliviously better if an operator has maximum number of experience. In this study, a score of 5 is assigned if operators have an experience of 10 or more years. The score of 3 is assigned to operators with an experience between 5-9 years and score of 1 is assigned to operators with experience less than 5 years.

A.3.4 Number of operators

SWSs often find it challenging to find and retain trained and certified operators because of which the number of operators in these systems are fairly low (Minnes and Vodden 2017). Similar to experience criteria of operator, there is no any specification for ‘n’ number of operators to be assigned for a particular SWS. However, in this study, a score of 5 is assigned to water system that has 2 or more full time operators. The score of 3 is assigned to water system that has single full time operator and the score of 1 is assigned if water system does not have any operators.

A.3.5 Additional responsibilities

Often in small systems, an operator is shouldered multiple responsibilities and the work load doubles than the usual (Kot et al. 2011). In this study, a score of 5 is assigned to water system if operator has normal full time working hours. The score of 3 is assigned if an operator is sometimes assigned other duties and the score of 1 is assigned if an operator always has to perform multiple roles.

A.3.6 Experts' advice

SWSs are often surrounded with limited technical personnel and at times they seem to struggle to solve particular drinking water problem. In such scenario, the expert's opinion plays a significant role. In this study, experts are considered as water resource engineer, DW or utility managers who have vast knowledge and expertise in the field of drinking water management. The score of 5 is assigned if operators receive expert's advice monthly or whenever needed. The score of 3 is assigned if an advice is received annually and score of 1 is assigned if no advices are shared to operators.

A.4 Infrastructure and funding

This criterion includes indicators related to water infrastructure and funding options for SWSs.

A.4.1 Infrastructure replacement

Majority of SWSs have limited water infrastructure. In addition, many SWSs also have issues with aging infrastructure. In this study, respondents were asked to rank the technical problems associated with SWSs on a scale of 1-5 where 1 is major problem and 5 is minor. The technical problems listed are: inadequate source water supply, infrastructure replacement, lack of system knowledge, lack of regular maintenance, and lack of sufficient technical staff. Based on the survey results, the score of 5 was assigned, if respondents ranked problem of "infrastructure replacement" as 5. The score of 3 was assigned if problem was ranked either 3 or 4. The score of 1 was assigned if problem was ranked either 1 or 2.

A.4.2 Availability of funding

The problem with unavailability of adequate funds in SWSs is extremely common. In this study, respondents were asked to rank major problem of treatment plant and DN of SWSs on a scale of 1-5 where 1 is a major problem and 5 is minor. The problems listed are: financial, technical, managerial, political, and social. Based on the survey results, the score of 5 was assigned, if respondents ranked "financial" problem as 5. The score of 3 was assigned if problem was ranked either 3 or 4. The score of 1 was assigned if problem was ranked either 1 or 2.

A.4.3 Small population base

Due to small population base, SWSs struggle to collect tax and revenues from their consumers which adds additional financial burden in small systems. In this study, respondents were asked to rank financial problems on a scale of 1- 6where 1 is a major problem and 6 is minor. The problems listed are: revenue insufficiency, insufficient funds for operator training, small population base, low water price, lack of loan approval, and low per capita income of consumers. Based on survey results, the score of 5 was assigned, if respondents ranked "small population base" as 6. The score of 3 was assigned if problem was ranked between 3 &5. The score of 1 was assigned if problem was ranked either 1 or 2.

A.4.4 Use of GIS

The use of Geographic Information System (GIS) in water resource management bears significant importance. It helps to collect water quality data related to spatial variation, helps in monitoring water quality issues, identify the areas of leakage and low pressure areas, mapping land-use and population demographics in support of water and wastewater demand estimation procedures(Lynn E. Johnson n.d.). In this study, the water systems using GIS are assigned score of 5 and those systems that do not practice this technique is assigned score of 1.

A.4.5 Age of distribution network

Distribution network is an important component of drinking water supply. Although, there is no criteria separated for specific age of a DN in any of drinking water guidelines and standards, it is usually suggested to have low age of DN. In this study, the score of 5 is assigned to water systems with age less than 25 years, score of 3 is assigned to DN aged between 26-50 years while any DN with age above 50 years is assigned score of 1.

A.4.6 Age of treatment system

Similar to DN, the water treatment system is also an integral component of drinking water supply. No organization has set criteria for specific age of treatment system, however, low age is preferred over aging infrastructure. In this study, the score of 5 is assigned to water systems with age less than 15 years, score of 3 is assigned to treatment system aged between 16-40 years while TS with age above 40 years is assigned score of 1.

A.5 Operational characteristics

This criterion discusses the monitoring frequency various water quality indicators. Although, the sampling frequency of water varies with quality and location of source water, following parameters discussed below are the basic guidelines and standards set by various organizations.

A.5.1 Turbidity

Turbidity is an important physical parameter of water quality. The CDWQG suggests turbidity level of drinking water should be below 1 NTU. In addition, CDWQG recommends all the water systems serving population less than 5,000 to sample turbidity either continuously or daily in their water systems(Government of Canada 2013). In this study, water systems that follow CDWQG are assigned score of 5 while weekly – monthly monitoring programs are given score of 3. The systems with no monitoring programs are assigned score of 1. The same scoring scheme is assigned for both source water and distributed water.

A.5.2 Residual chlorine

An adequate amount of residual chlorine in a DN helps to inhibit microbial growth. In Canada, the usual range of chlorine in Canadian Drinking water systems range from 0.4 – 2 mg/l leaving treatment plant, 0.4 – 1.2 mg/l at intermediate points within DN and from 0.04 – 0.8 mg/l at extreme ends of DN (Government of Canada 2016b). The CDWQG recommends small systems (population less than 5,000) to sample residual chlorine level within their DN either continuously or daily (Government of Canada 2013). In this study, water systems that follow CDWQG are assigned score of 5 while weekly – monthly monitoring programs are given score of 3. The systems with no monitoring programs are assigned score of 1.

A.5.3 Disinfection by-products

When chlorine reacts with organic matters present in DN, the formation of DBPs takes place. THMs and HAAs are the regulated DBPs that are frequently found in drinking water. The CDWSG recommends the level of THMs and HAAs below 0.01 mg/l and 0.08 mg/l in their drinking water(Health Canada 2013). Basically, DBPs should be sampled and monitored quarterly. In this study, water systems that take samplings quarterly are assigned score of 5, semi-annually and annual monitoring samplings are assigned score of 3. The systems with no monitoring programs are assigned score of 1.

A.5.4 Organic content

The large quantity of organic matter in source water is not wanted. The organic matters usually found in water are leaves, lawn clippings, straw, sledges, and manures. Although, there is no any specification on monitoring frequency of organic content in drinking water source, it is usually recommended to take samplings regularly. In this study, the water systems that take samplings of organic content weekly-monthly are assigned score of 5, quarterly – annual samples are assigned score of 3 whereas no sampling is given score of 1.

Appendix B Detailed monitoring frequency of water quality indicators

Physical parameters						
Frequency	Tr (SW)%	Tr(TW) %	Tr (DW)%	T (SW)%	T (TW)%	T(DW)%
Daily	35	42	27	29	34	17
Weekly	23	13	25	23	15	22
Biweekly	0	0	0	2	0	0
Quarterly	0	0	0	0	2	0
Half yearly	5	2	3	3	3	2
Annually	9	4	5	10	7	17
Only on weekdays	2	2	2	0	0	0
No measurement	26	37	38	33	39	44

Chemical parameters										
	pH (SW)%	pH (TW)%	pH (DW)%	OC (SW)%	OC (TW)%	OC (DW)%	THMs (TW)%	THMs (DW)%	HAAs (TW)%	HAAs (DW)%
Daily	19	19	15	0	0	0	0	2	0	2
Weekly	13	13	18	3	0	3	0	0	0	0
Biweekly	3	2	2	2	2	0	0	0	0	0
Monthly	0	0	0	5	5	3	0	0	0	0
Quarterly	2	3	3	0	0	0	2	19	3	5
Half yearly	5	3	3	5	3	5	3	2	2	2
Bi annually	0	0	0	0	0	0	7	3	3	3
Annually	29	18	17	43	28	29	20	17	13	15
No measurement	29	42	42	40	60	62	70	57	79	73

Microbiological parameters		
	RC (DW)%	HPC (DW)%
Daily	3	31
Weekly	12	20
Biweekly	7	5
Monthly	0	3
Quarterly	2	0
Half yearly	0	0
Annually	8	0
On weekdays	0	3

Note: Tr: Turbidity, T: Temperature, OC: Organic content, THMs: Trihalomethanes, HAAs: Haloaceticacides RC: Residual chlorine, HPC: Heterotrophic plate count

Appendix C Probability plots for Kruskal Wallis analyses

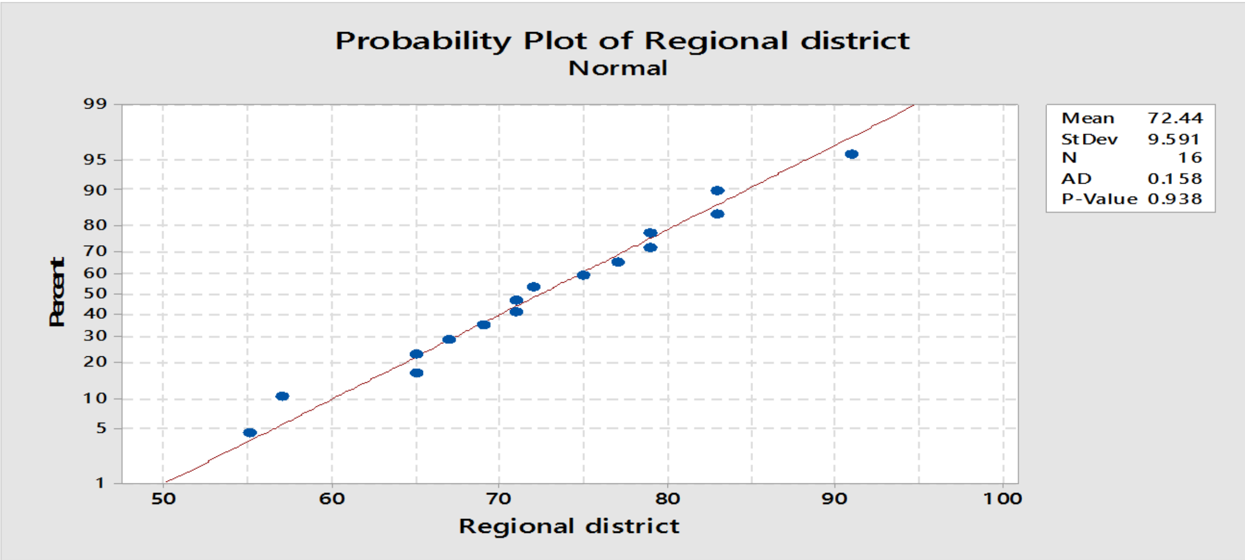

Figure C1: Normality plot for Regional districts (Overall performance)

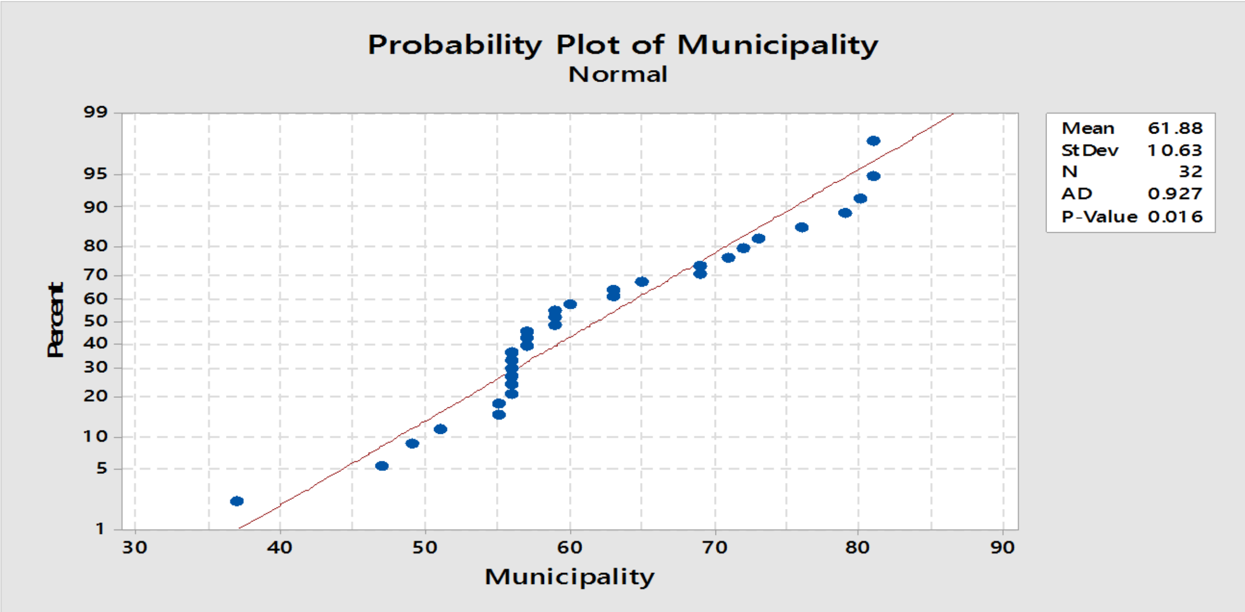

Figure C2: Non-normal plot for municipalities (Overall performance)

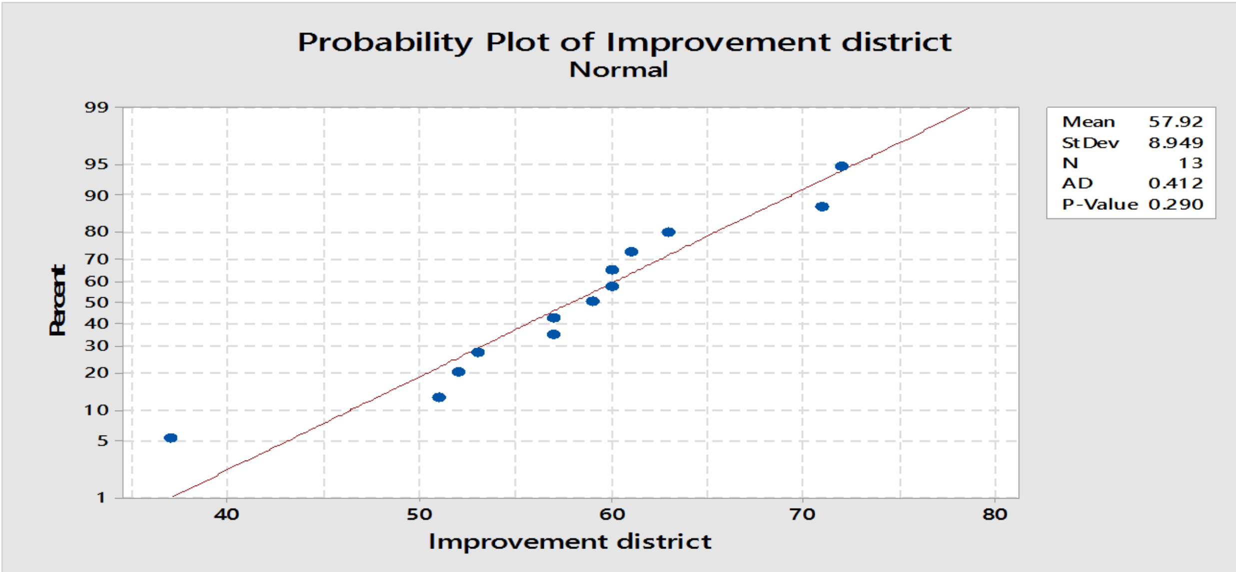

Figure C3: Normality plot for improvement districts (Overall performance)

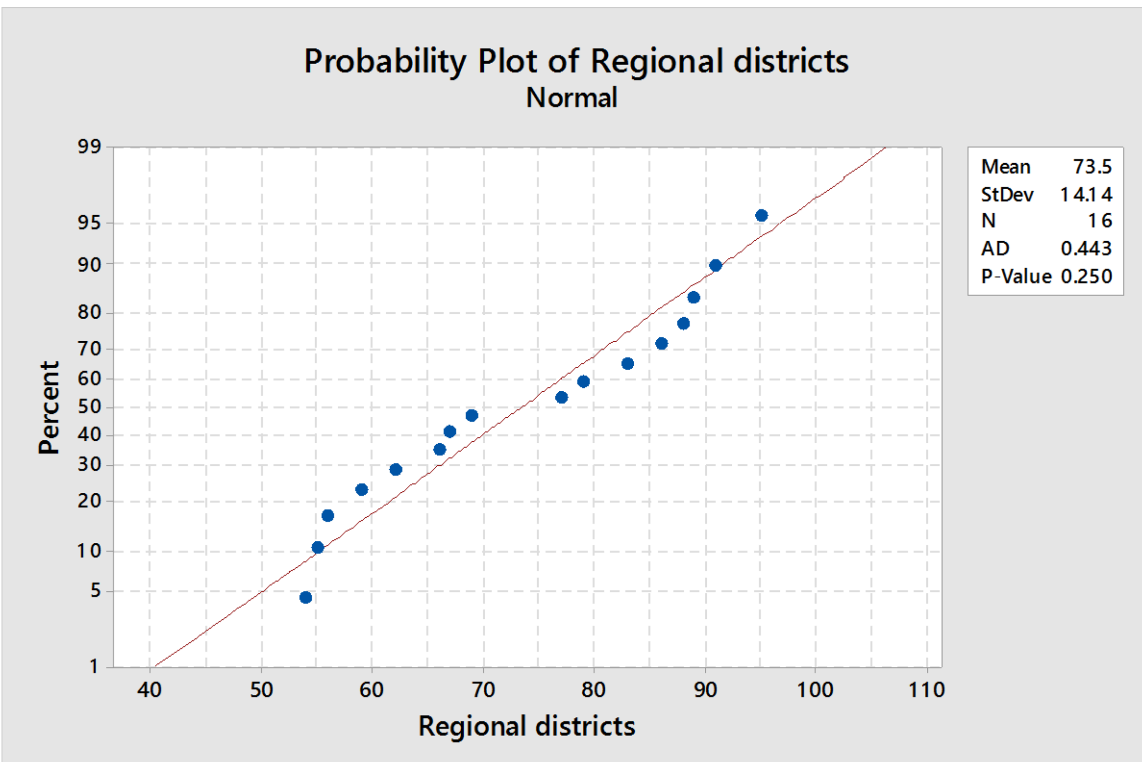

Figure C4: Normal plot for regional districts (water quality- priority)

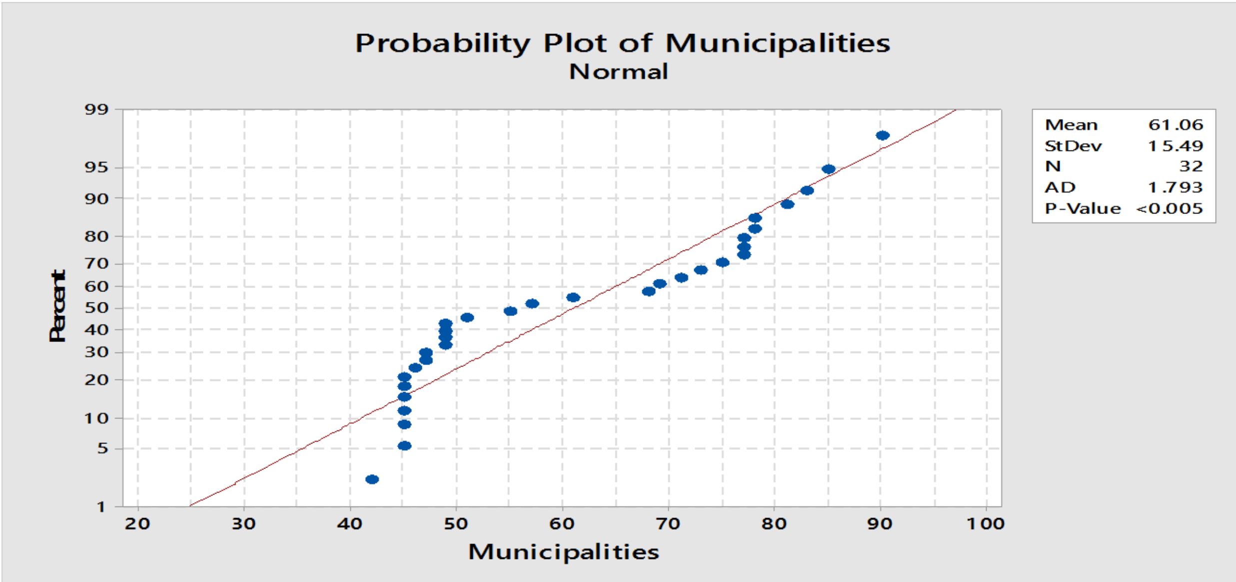

Figure C4: Non-normal plot for municipalities (water quality- priority)

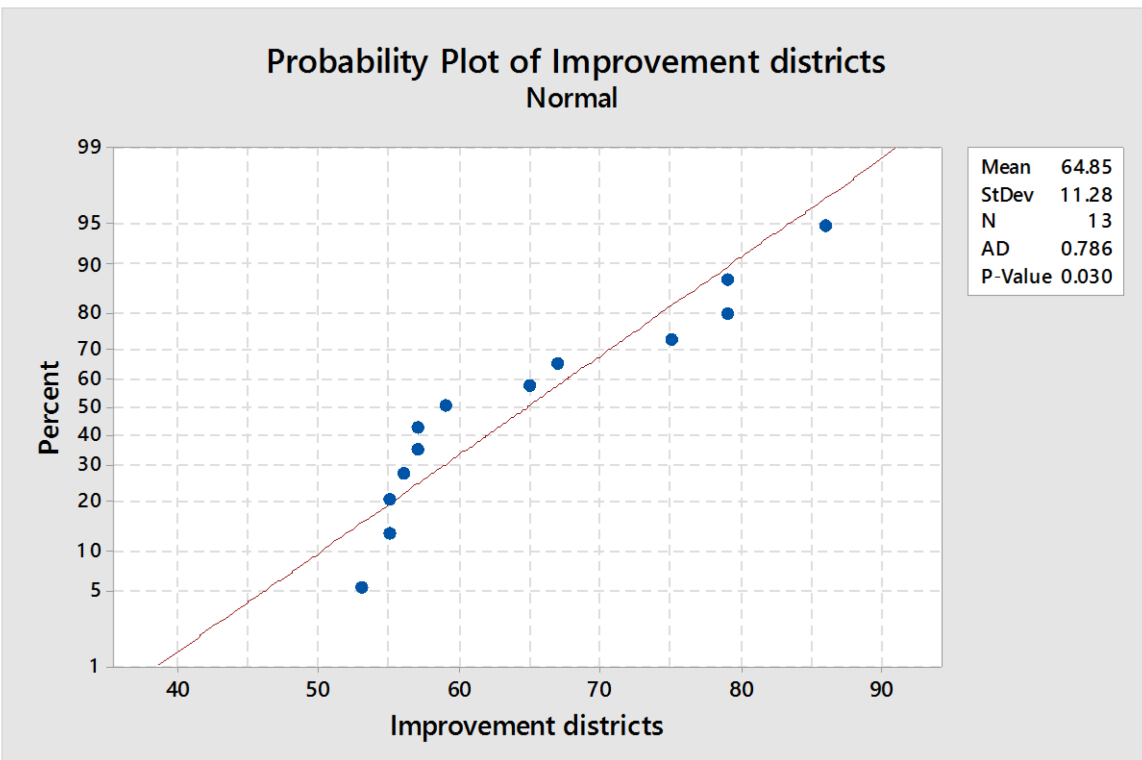

Figure C5: Non-normal plot for improvement districts (water quality- priority)

Appendix D Probability plots for ANOVA analyses

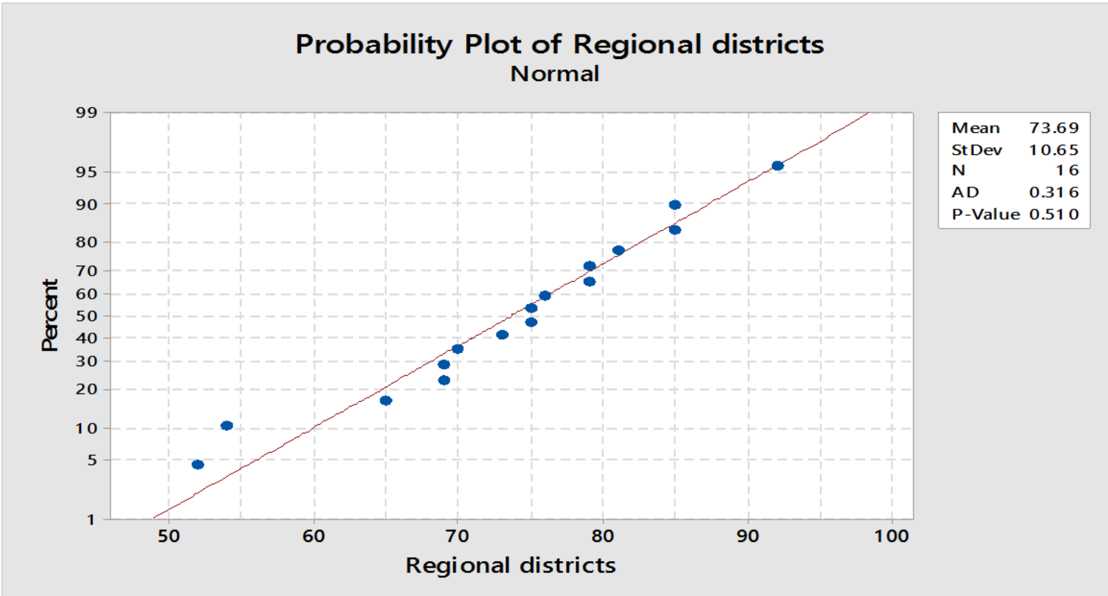

Figure D1: Normal plot for regional districts (treatment and disinfection- priority)

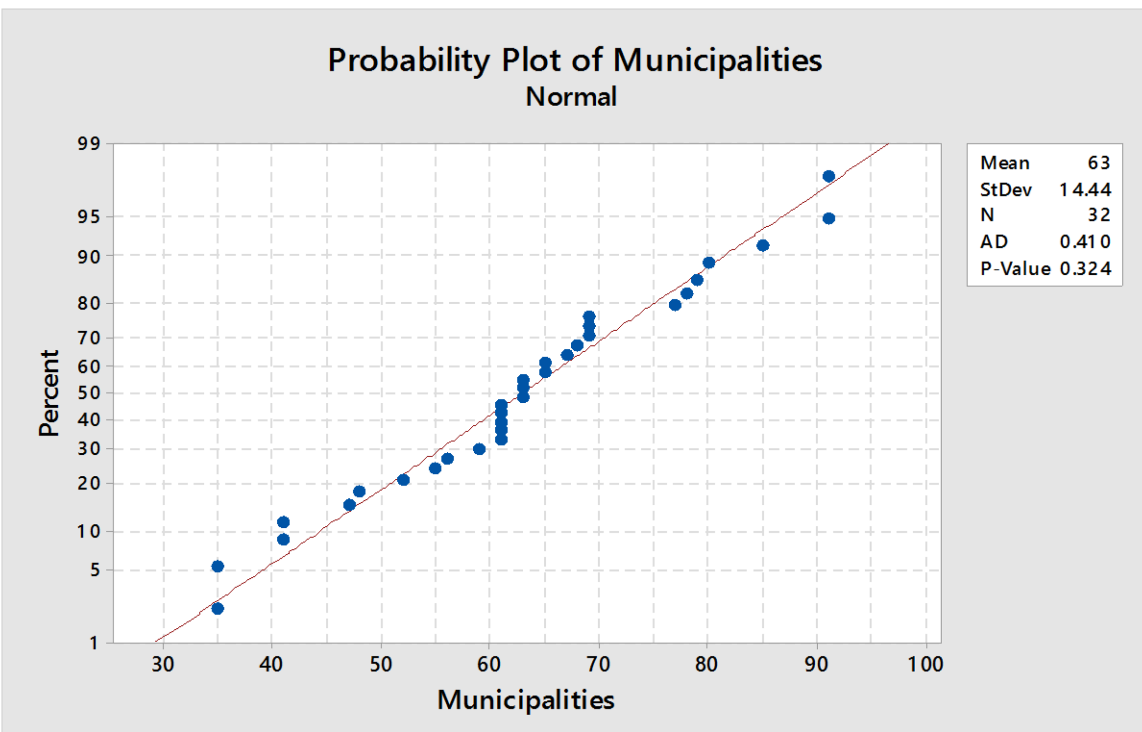

Figure D2: Normal plot for municipalities (treatment and disinfection- priority)

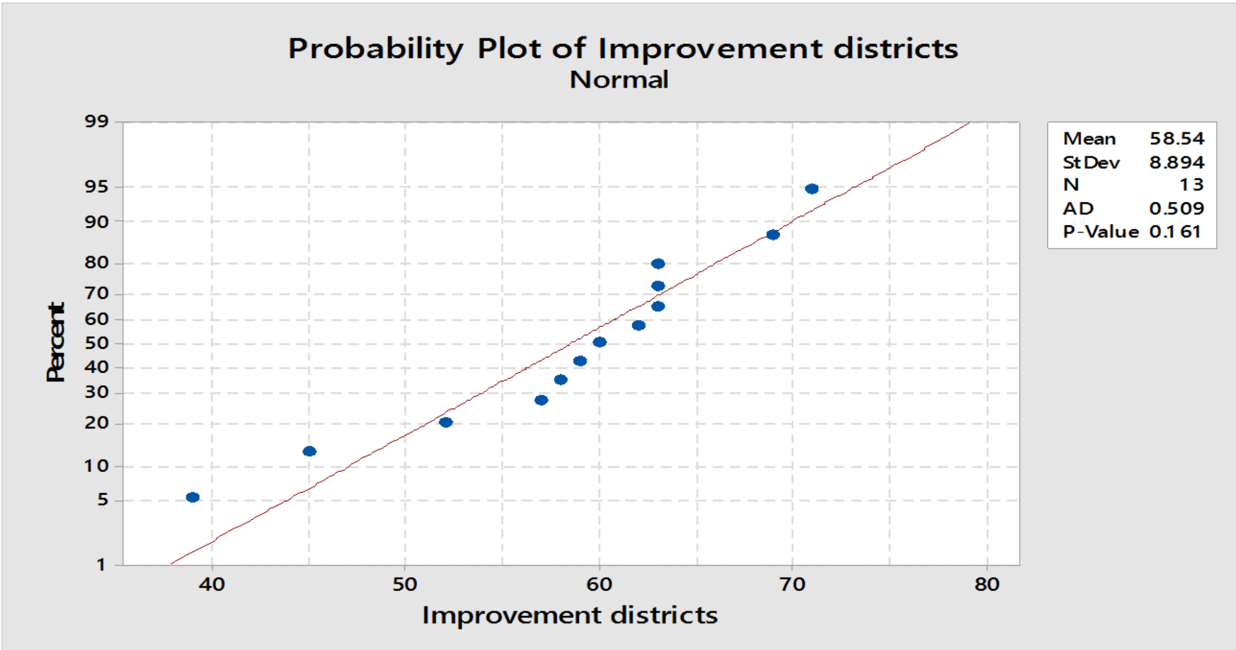

Figure D3: Normal plot for improvement districts (treatment and disinfection- priority)

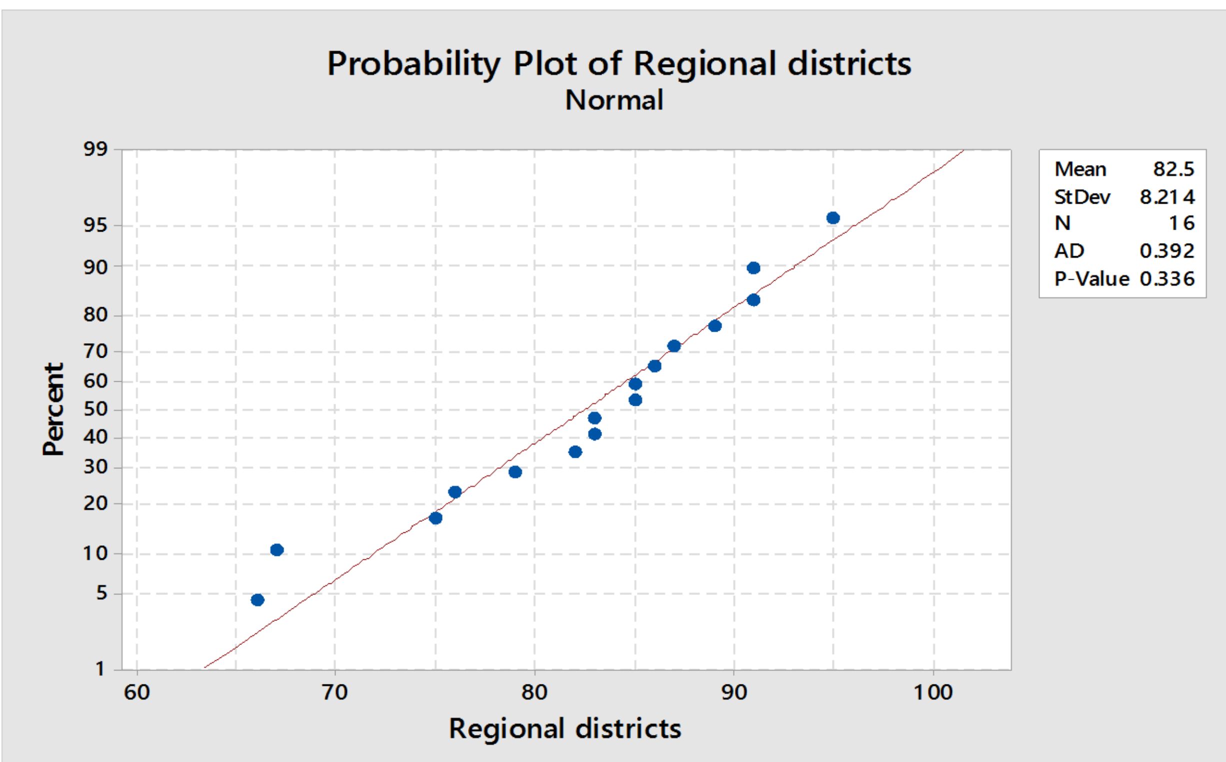

Figure D4: Normal plot for regional districts (operators' capability- priority)

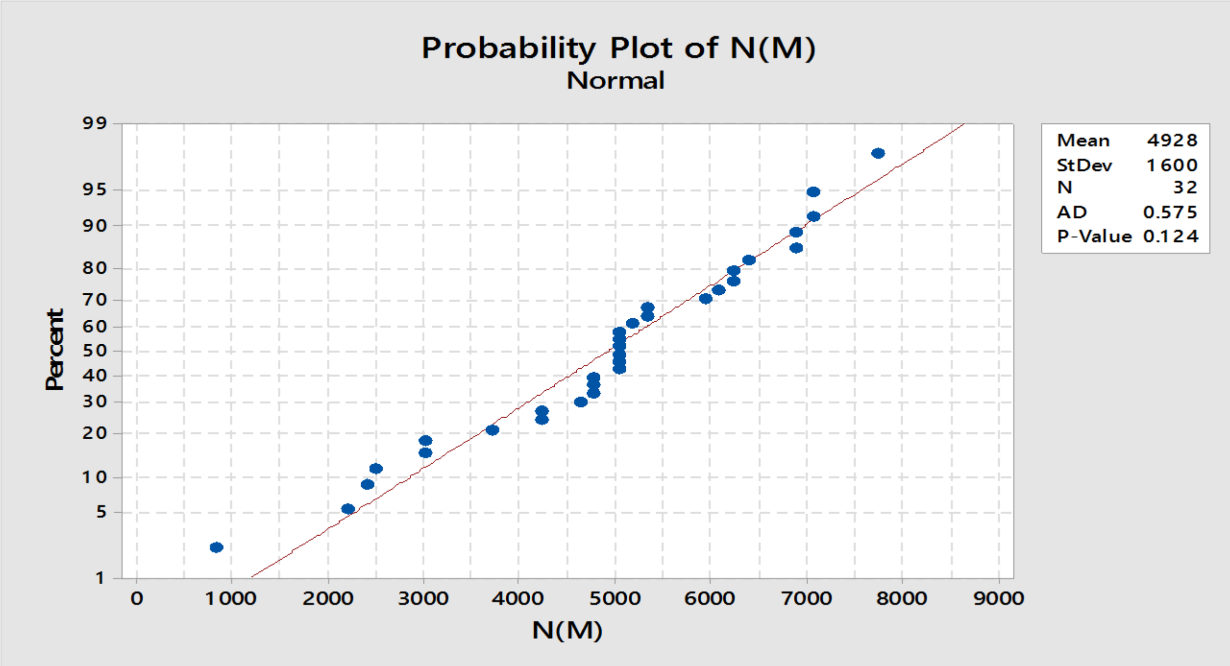

Figure D5: Normal plot for municipalities (operators' capability- priority)

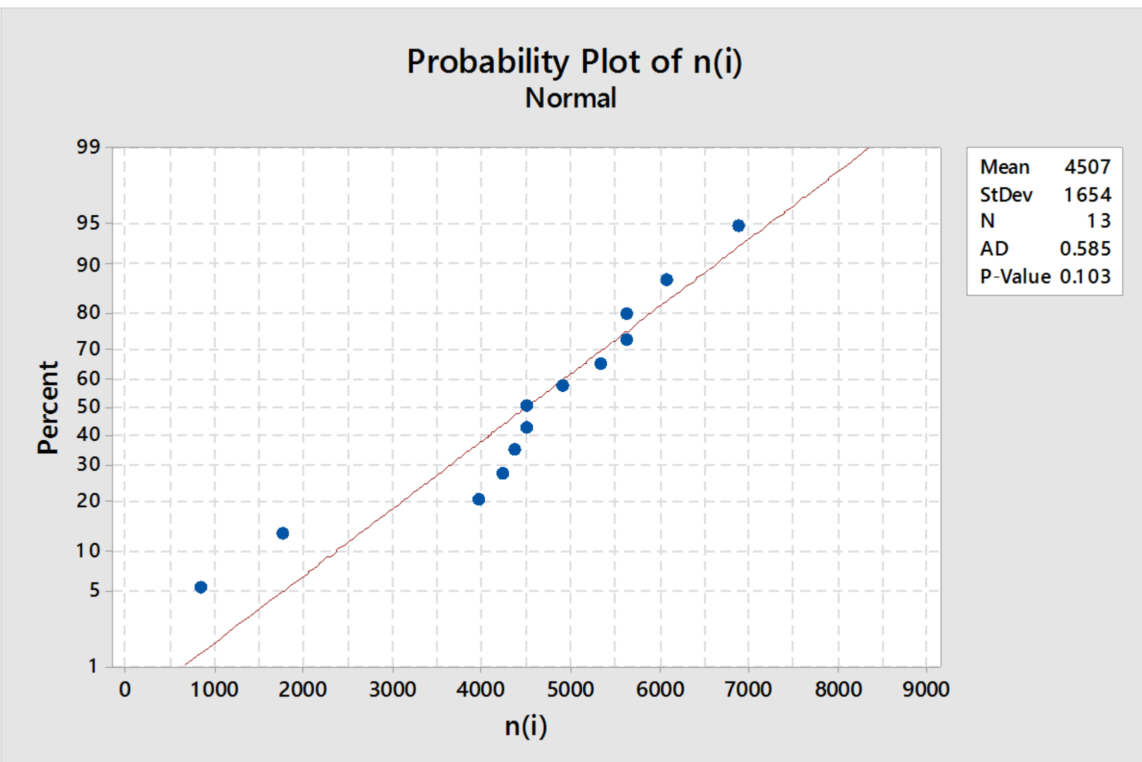

Figure D6: Normal plot for improvement districts (operators' capability- priority)

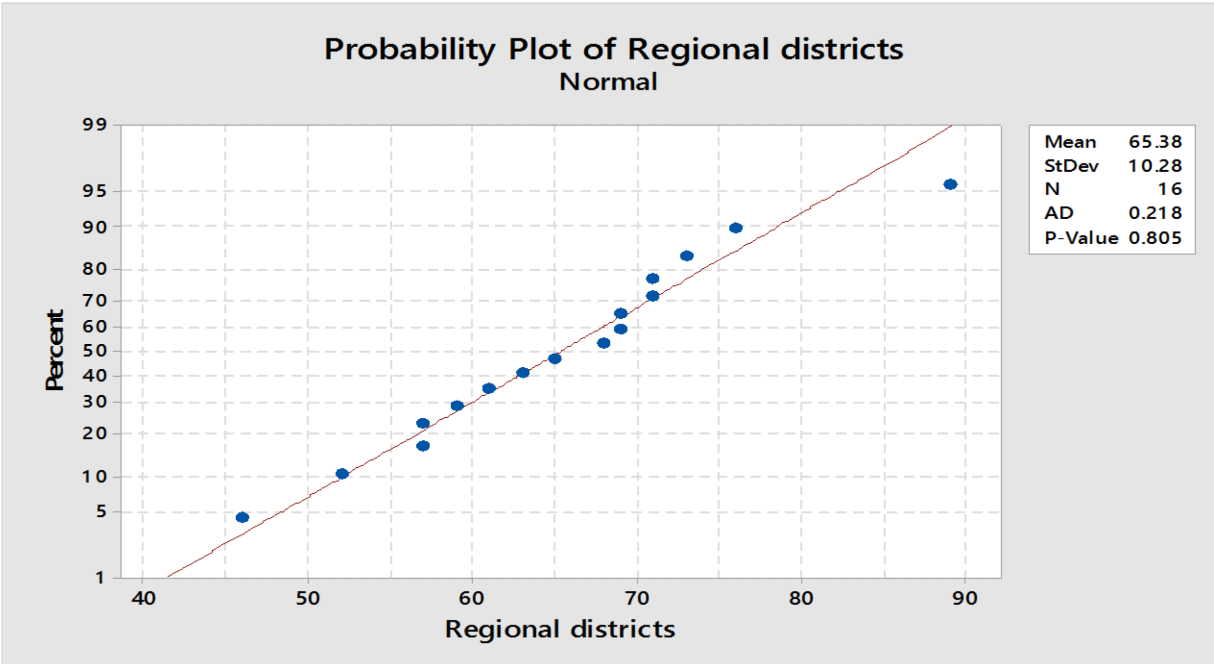

Figure D7: Normal plot for regional districts (infrastructure and funding - priority)

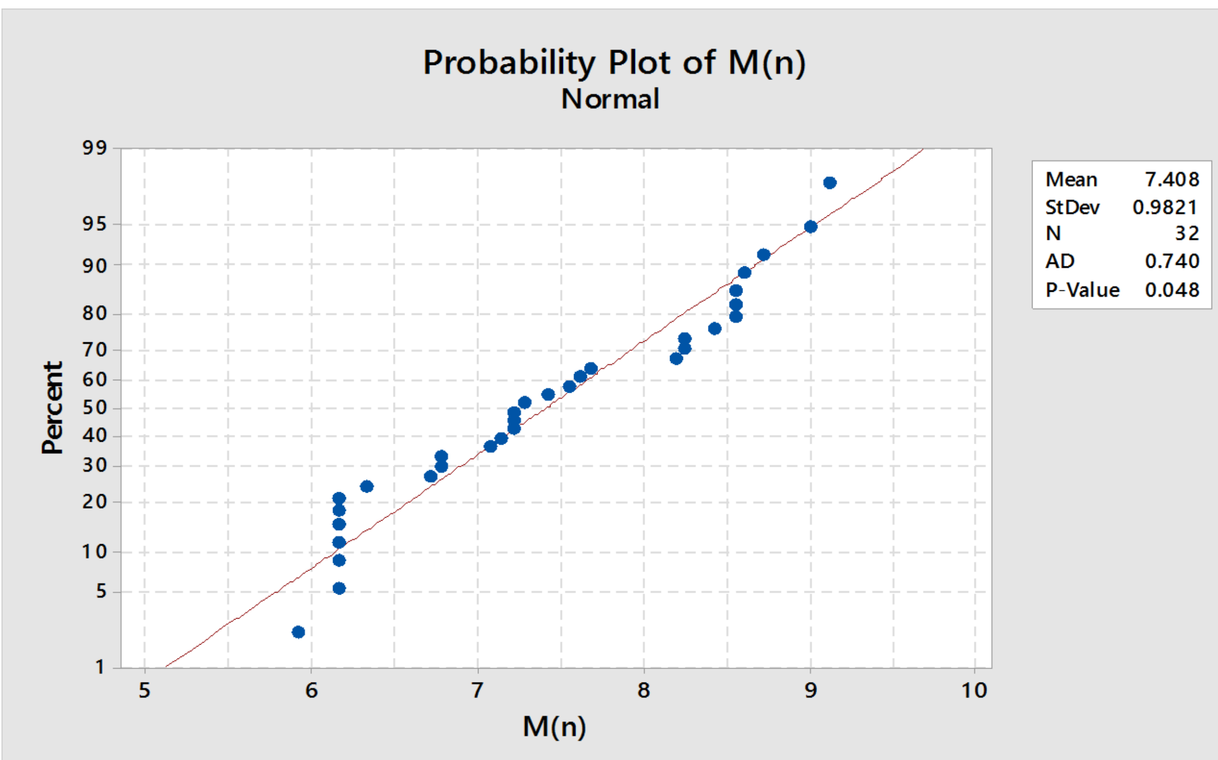

Figure D8: Normal plot for municipalities (infrastructure and funding - priority)

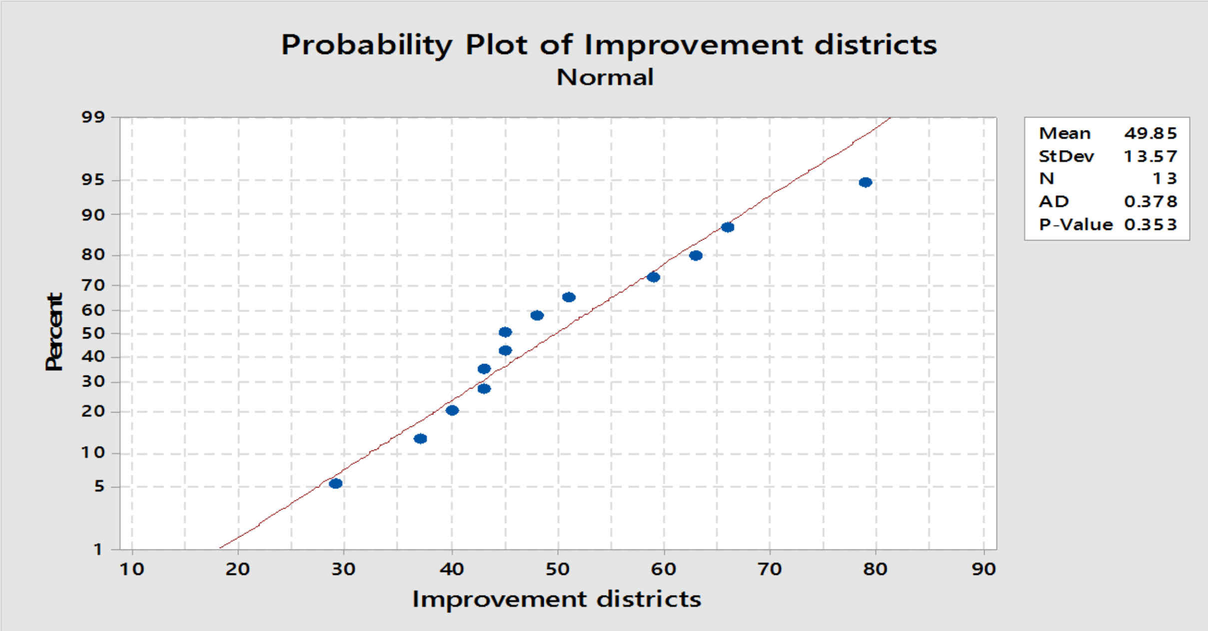

Figure D9: Normal plot for improvement districts (infrastructure and funding - priority)

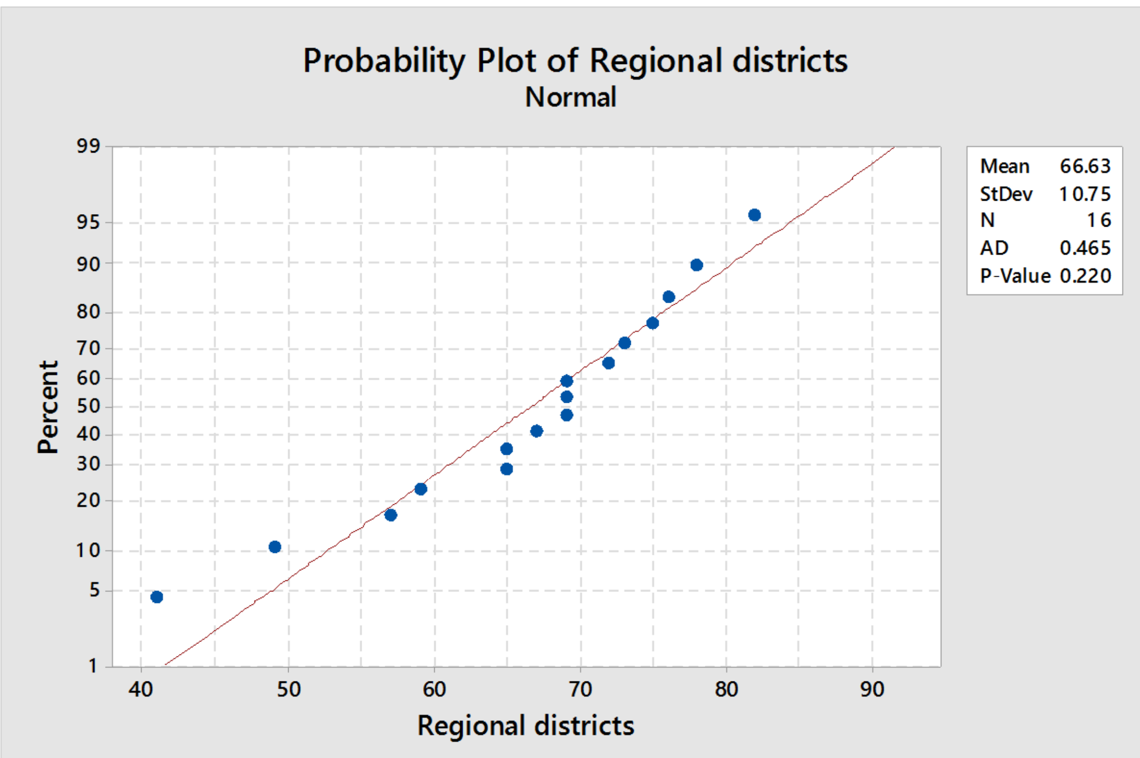

Figure D10: Normal plot for regional districts (monitoring frequency - priority)

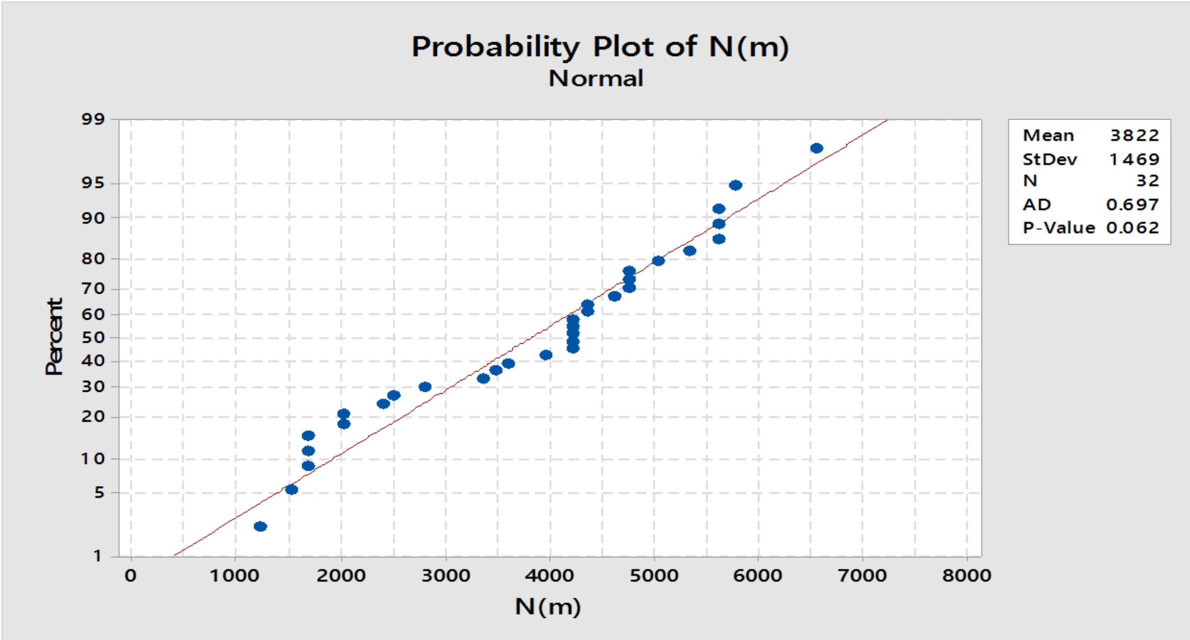

Figure D11: Normal plot for municipalities (monitoring frequency - priority)

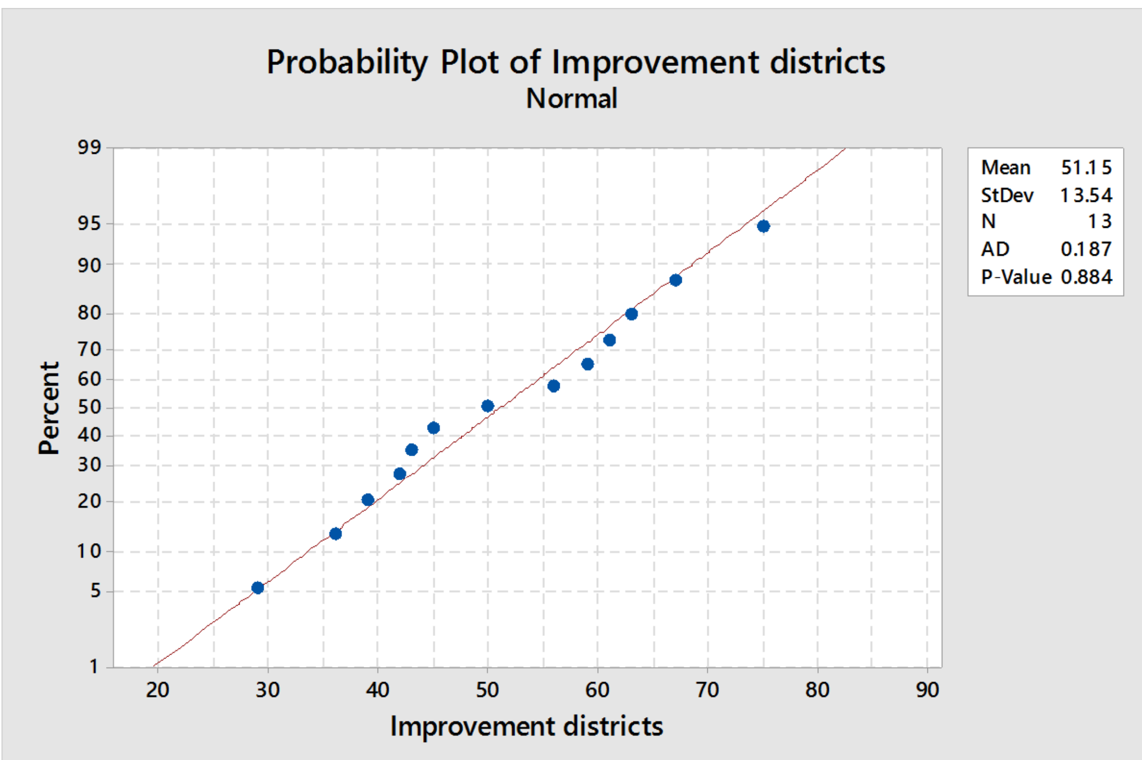

Figure D12: Normal plot for improvement districts (monitoring frequency - priority)

Appendix E TCPS 2 research ethics certificate

PANEL ON
RESEARCH ETHICS
Navigating the ethics of human research

TCPS 2: CORE

Certificate of Completion

This document certifies that

Sarin Raj Pokhrel

has completed the Tri-Council Policy Statement:
Ethical Conduct for Research Involving Humans
Course on Research Ethics (TCPS 2: CORE)

Date of Issue: **8 September, 2017**

Appendix F Consent document

Consent Form

Challenges and residual chlorine management practices in small water systems

Principal Investigator

Name: Dr. Rehan Sadiq, P.Eng

Position: Associate Dean, School of Engineering (SOE)

Phone: 250-807-9013

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Email: rehan.sadiq@ubc.ca

Co-Investigators

Name: Dr. Manuel Rodriguez

Position: Professor, Laval University

Phone: 418-656-2131

Email: manuel.rodriguez@esad.ulaval.ca

Name: Sarin Raj Pokhrel

Position: MASc student, SOE

Phone: 250-899-2134

Email: sarin.pokhrel@ubc.ca

Name: Dr. Kasun Hewage, P.Eng

Position: Professor, SOE

Phone: 250-907-9850

Email: kasun.hewage@ubc.ca

Data collected in this research will be used for the thesis of the student researcher, Sarin Raj Pokhrel. The thesis is considered to be a public document and will be available on the internet.

However, confidentiality and privacy of the research participants will be protected in any publications or presentations.

Sponsor

This research is funded by National Sciences and Engineering Research Council of Canada (NSERC).

Purpose:

The primary objective of the proposed research project is to identify the major challenges faced by small water systems (serving populations less than 5000) and their operators, understand the existing methods of disinfection, identify and comprehend water quality issues (particularly those issues related to residual chlorine management practices), and finally, put forward practical solutions to the existing problems. To achieve the research objectives, the student will perform an extensive literature review, collect the questionnaire forms filled by the operators, and, if needed, conduct telephone interviews with operators across Canada.

You are being invited to take part in this study to share your professional experiences related to various drinking water problems faced by small communities, including your experience with methods for residual chlorine management in distribution networks. Water experts, such as municipal engineers and water treatment plant operators, have been selected as research participants for this study.

Study Procedures

The data will be collected through questionnaire survey. Questionnaires will be sent to small municipalities and utility providers across Canada. Participants are suggested to complete the questionnaires and email them back to the co-investigator (student researcher).

<u>Questionnaire</u>: The questionnaire will take approximately 20 minutes to complete.

Questionnaire participants have the right to refuse to participate in this study. If questionnaire respondents decide to take part, he/she may choose not to answer any question in the questionnaire. He/ she may choose to withdraw from the study at any time without giving a reason and without any negative consequences to his/her employment, or relationship with the researcher, UBC Okanagan, or any other entity related to the study. Participants will have three options to fill the questionnaire form. First, participants may choose to fill the questionnaire using their personal computer and send it back to the student researcher. Second, participants may choose to print the questionnaire, fill the details, scan questionnaire and email it back to the student researcher. Third, if the participants express their interest to have a telephone conversation, he/she shall contact or email the co-investigator stating their desire to hold a one-to-one discussion. In case of telephone conversation, participants will not be responsible to bear any long distance charges. Questions asked during the interview will remain identical to those in the questionnaire form. Although, telephone conversation shall not be recorded, student researcher will be taking notes and these notes will be analyzed with the rest of the data. Data that have been collected will be combined with data from all the participants before any analysis is carried out.

Potential Risks

Risks involved in this project are no greater than one would experience in his/her daily life.

Potential Benefits

Water utilities, water treatment plant operators and small municipalities will be benefited from this research.

The proposed solution will create more awareness among the small municipalities to improve their disinfection practices and better understand the residual chlorine management practices in their communities and neighboring water utilities, which will eventually help the citizens to access safer drinking water.

Confidentiality

All documents will be identified only by code number and kept in a locked filing cabinet in the office of the principal investigator. Participants will not be identified by name in any reports of the completed study and their names shall not be used without their consent. The responses to the questionnaire survey will not be shared with managers, water utility board or any public news sites without the participants' consent. All computer files will be password protected and data will be stored and maintained in a UBC facility by the principal investigator for five years after publication. Data will be accessed only by the Principal investigator and co- investigators of this research. Electronic copies of data will be sent to Laval University using UBC workspace and will be kept secured on Laval's server or the co-investigator will be using his personal computer to store data using password protected device. After this time, the data will be deleted from the database.

Contact for information about the study

If you have any questions or desire further information with respect to this study, you may contact Dr. Rehan Sadiq or one of his associates at 1-250-807-8176.

Contact for concerns about the rights of research subjects:

You are strongly recommended to contact the Research Participant Complaint Line in the UBC Office of Research Services at 1-877-822-8598 or the UBC Okanagan Research Services Office at 250-807-8832 regarding any concern or complaints as a research participant. Further, you could also email your concern at RSIL@ors.ubc.ca. Please reference the study number (H17-02888) when contacting the Complaint Line so the staff can better assist you.

Copy of the findings of this research

If you like to receive a copy of the finding/results of the research, please provide your email address below.

____

Consent

Taking part in this study is voluntary. You have the right to refuse to participate in this study. If you decide to take part, you may choose not to answer any question in the interview. You may choose to withdraw from the study at any time without giving a reason and without any negative consequences to your employment or your relationship with the interviewer, UBC Okanagan, or any other entity related to the study. In case, you choose to withdraw from the study, data you provided shall not be used.

Your signature below indicates your consent to participate in this study and that you have received a copy of this consent form for your own records.

__________________________ _______________________

Participant’s Signature Date

____

Printed Name of the Participant

Appendix G Recruitment letter

THE UNIVERSITY OF BRITISH COLUMBIA

Faculty of Applied Science
Okanagan Campus
School of Engineering
1137 Alumni Avenue
Kelowna, BC Canada V1V 1V7

Phone 250 807 8723
Fax 250 807 9850
www.ubc.ca/okanagan/engineering

December 5, 2017

RECRUITMENT LETTER

Challenges of small water systems and residual chlorine management practices

Dear Sir / Madam:

The University of British Columbia – Okanagan (UBCO) is conducting an educational research project on identifying the various challenges faced by the small water system in Canada.

The primary objective of the proposed research project is to identify the major challenges faced by the small water systems (population serving less than 5000) and their operators, understand the existing methods of disinfection, identify and comprehend the water quality issues particularly to the residual chlorine management practices, and finally, put forward practical solutions to the existing problems. To achieve the research objectives, the student will perform an extensive literature review; collect the questionnaire forms filled by the operators and interview the small water operators across Canada. The purpose of the questionnaire is to understand the residual chlorine management practices in small communities and analyze the current scenario of their distribution network. Each questionnaire will take about 20 minutes to complete.

The research student, Sarin Raj Pokhrel (co-investigator), from UBCO will email you the questionnaire upon obtaining your consent to participate in the survey. The data gathered by the researcher from the questionnaire survey will remain with UBCO and electronic copies will be sent to Laval University using UBC workspace. One of the co-investigators at Laval University will store electronic files on Laval's server or his personal computer using password protected device. Data will not be disclosed to a third party without your permission. The data collection is a part of student researcher's thesis.

We appreciate your sincere cooperation and willingness to share your experience and help the researchers to conduct this study. If you would like to participate in this study, please contact Sarin Raj Pokhrel, co-investigator at 250-899-2134 or email at sarin.pokhrel@ubc.ca to find out more information in regards to participation for this study. If you have any further questions, please contact Dr. Rehan Sadiq (Principal Investigator) in the School of Engineering, University of British Columbia - Okanagan.

Sincerely,

Rehan Sadiq, Ph.D., P.Eng.
Associate Dean, School of Engineering
rehan.sadiq@ubc.ca
Phone: 250-869-9517

Co-investigator

Sarin Raj Pokhrel
M.A.Sc student
sarin.pokhrel@ubc.ca
Phone: 250-899-2134

Appendix H Questionnaire sample

Challenges of Small Water Systems

Questionnaire

The main purpose of this study is to identify various challenges faced by small water systems and their operators, understand the existing methods of disinfection, identify and comprehend the water quality issues in particular those related to disinfectant residuals, and finally, propose practical solutions to the existing problems. We highly appreciate your valuable time and efforts, and would like to thank you for taking an active role in this research.

Pseudonym (For official use only): ________________________________

1. **Name of water system**

   ____

2. **Population served by your system (in number)**

   ____

3. **Type of source water you use and its quality**

Source water	Source water quality
☐River/ Creek	☐Good ☐ Moderate ☐ Bad
☐Lake	☐Good ☐Moderate ☐Bad
☐Ground water	☐Good ☐Moderate ☐Bad

If water quality is bad or moderate, please specify water quality issues and their occurrence in different months/seasons if applicable.

____

4. **Method of treatment**

4.1 Treatment applied prior to primary and secondary disinfection

☐Conventional (includes coagulation, flocculation, sedimentation & filtration)

☐Only filtration

☐No treatment

☐Others (Please specify) ____

4.2 Primary Disinfection

☐Chlorine Gas	☐Sodium hypochlorite	☐Calcium hypochlorite
☐Chlorine dioxide	☐Ozone	☐UV
☐Others (please specify)		

4.3 Secondary disinfection, if different than primary disinfection (for disinfecting distribution network)

☐Chlorine gas	☐Sodium hypochlorite	☐Calcium hypochlorite
☐Chloramines	☐Chlorine dioxide	☐No secondary disinfection
☐Others (please specify)		

4.4 Do you use booster station within your distribution system?

☐Yes ☐No

4.5 If yes, please give the following details:

Number of booster station ___________________________

Type of disinfection ____________________________

4.6 How old is your treatment system (from the date of construction approximately)?

_______________ Years

4.7 How old is your distribution system (from the date of construction approximately)?

________________ Years

5.**Please answer the following section if you use hypochlorite solution as disinfectant (primary or secondary)**

5.1 Which of the following hypochlorite solution do you use?

☐Sodium hypochlorite ☐Calcium hypochlorite

5.2 Challenges of hypochlorite solution in your system (On a scale of 1-6, rate the following challenges) Note: (1 being the most important and 6 as the least important)

☐Controlling pH ☐Storage time ☐Ionic strength
☐Maintaining temperature ☐Health effects ☐Maintaining solution concentration

5.3 Storage of hypochlorite solution

Location __________________________

Temperature (summer/&winter) __________________________

Duration (replacing &refilling) __________________________

Light exposure (Yes/No) __________________________

5.4 Frequency (approx.) of purchasing hypochlorite solution

☐Quarterly ☐Monthly ☐Bimonthly
☐Every three months ☐Half yearly ☐Annually

5.5 Do you clean your hypochlorite solution tank before adding hypochlorite solution? Please state reason behind your justification.

____

____

5.6 Do you dilute the previously used hypochlorite solution for its new use?

☐Yes ☐No

5.7 Do you verify (receipt of purchase, check quantity of solution purchased) hypochlorite solution purchased? If yes, how often (e.g., once, twice)?

____,

6. Residual Chlorine Management Practices

6.1Range of chlorine dosage applied for

Primary disinfection: winter __________ summer________________

Secondary disinfection: winter _________ summer___________________

6.2 What are the types of chlorination stages in your system? (Please tick all the applicable options)

☐Pre-chlorination (before treatment)
☐Inter-chlorination (multiple points at water treatment plant)
☐Post-chlorination (If chlorination is only method of treatment)

6.3Water quality is poor at extremities due to: (On a scale of 1-8, rate the following problems)

Note: (1 being the most important and 8 as the least important)

☐High residence time ☐Low flow rates ☐High DBP formation (eg. THMs)

☐Low concentration of residual chlorine ☐ Contamination in network

☐Taste and odors ☐Microbiological contamination

☐ Others (please specify) ____

6.4 Challenges to maintain residual chlorine in your water distribution network (On a scale of 1-6, rate the following challenges.)

Note: (1 being the most important and 5 as the least important)

☐Dead end sections ☐Remoteness of area ☐High residence time

☐Lack of infrastructure ☐Lack of monitoring ☐ Others (please specify)____________

6.5Location of monitoring residual chlorine in the distribution system (Please check more than one boxes if monitored)

☐Point of entry ☐Reservoir ☐Extremities

☐Low flow area ☐High flow area ☐End of treatment plant

6.6How often do you sample for monitoring residual chlorine in your distribution network?

____

6.7 Do you have residual chlorine online analyzer?

____

6.8 How do you maintain chlorine residuals in regards to operational decision making? (You can check more than one box)

☐Adjust dose according to residual changes

☐Adjust dose according to water quality changes upstream of dosing point

☐Adjust dose according to water temperature changes

☐Others(Please specify) ____

6.9 Do you have information about water age within your distribution system?

____

6.10 Residual chlorine testing

Method	Manual	Sensor based
☐DPD: Diethyl paraphenylene diamine (Indicator test)	☐	☐
☐Potentiometric	☐	☐
☐Membrane covered polarographic sensor	☐	☐

6.11 Do you observe any seasonal variation in residual chlorine decay? If yes, please specify with observed data (Can be separate data file).

____

6.12Adopted strategies to maintain sufficient levels of residual chlorine concentration in Distribution network (DN) (You can check more than one box)

☐Reduce water age ☐Mains cleaning ☐Change in pipes

☐use of booster station ☐Others (please specify)___________________________________

6.13 Do you know what are the water ages (residence times) within your distribution system?

☐Yes ☐No

6.14 Do you control water age?

☐Yes ☐No

6.15 If yes, what are the major method/s applied?(You can check more than one box)

☐Reduce amount of water storage ☐Increase in water velocity

☐Others (please specify)____

6.16 Do you clean water mains?

☐Yes ☐No

6.17 Adopted strategy to clean water mains

☐Continuous blow off ☐Conventional flushing ☐Unidirectional flushing

6.18 Do you follow any standard guidelines (Health Canada, US EPA, WHO) to maintain chlorine concentration in your distribution network? (If yes, please specify)

____

6.19 Do you use GIS in your distribution network?

☐Yes ☐No

7. Water Quality

7.1 Testing raw water and plant treated water quality parameters (frequency)

Parameter	Frequency (Source)	Frequency (Treated water)
pH	________	________
Turbidity	________	________
Temperature	________	________
Heterotropic plate count	________	________
Trihalomethane	________	________
Haloacetic acid	________	________
Organic content	________	________

7.2 Testing distributed water quality parameters (Location and frequency)

Parameter	Frequency	Point of entry	Distribution system	Extremity
pH	________	☐	☐	☐
Turbidity	________	☐	☐	☐
Temperature	________	☐	☐	☐
HPC	________	☐	☐	☐
Trihalomethane	________	☐	☐	☐
Haloacetic acid	________	☐	☐	☐
Organic content	________	☐	☐	☐

7.3 Method of sampling (You can check more than one box)

Parameter	Online instruments	Automatic sample	Manual sample
pH	☐	☐	☐
Turbidity	☐	☐	☐
Temperature	☐	☐	☐
HPC	☐	☐	☐
Trihalomethane	☐	☐	☐
Haloacetic acid	☐	☐	☐

7.4Have water quality problems occurred in your distribution system during last five years? If yes, please mention the parameters from the above list.

____

____

7.5 Causes of deterioration of water quality in your distribution network (If more than one, please rank them. 1 being the major cause)

☐Water age ☐Internal corrosion ☐Biofilm growth

☐Disinfection by-product ☐pH stability ☐Negative pressure

☐Faulty gasket and appurtenance ☐Pipe cracks

☐Others (please specify)___________

7.6 How often water quality failure occurs in your system and how many days it affects to consumer from each failure?

☐Monthly ☐Annually

☐Others (please specify)

____

Effect:

_____________days/event

7.7 Method of water quality control? (You can check more than one box)

☐Adjusting pH ☐Maintaining optimum chlorine residual ☐Proper water sampling in DN

☐Interaction with consumers ☐Comparing data with standard guidelines

☐Others (please specify)___________

7.8 Any complaints on water quality from consumers and how often?

☐Yes and ….. complaints/month ☐No

7.9 Complaints were on (On a scale of 1-6, rank the following problems. 1 being the most important and 6 as the least important)

☐Taste and odor other than chlorine ☐Chlorine related taste and odor ☐Aesthetic ☐Color

☐Water quality guidelines ☐Others (please specify)___________________________________

7.10 Are you under any Boil Water Advisory at present or in the past five years?

____

8. **Major problems of treatment plant and distribution network (On a scale of 1-5, rate the following problems)**

Note: (1 being the most important and 5 as the least important)

☐Financial ☐Technical ☐Managerial

☐Political ☐Social

8.1 Causes of financial problems (On a scale of 1-7, rate the following problems)

Note: (1 being the most important and 7 as the least important)

☐ Revenue insufficiency ☐Insufficiency funds for operator training ☐Low water price

☐Lack of approval of loans ☐Small population base ☐Low per capita income of people

☐Others (please specify)____

8.2 Causes of technical problems (On a scale of 1-6, rate the following problems.)

Note: (1 being the most important and 6 as the least important)

☐Inadequate source water supply ☐Infrastructure replacement (pipe, pumps, réservoirs) ☐Lack of system knowledge

☐Lack of regular maintenance ☐Others (please specify)__________________________

☐ Lack of sufficient technical staff

8.3 Causes of managerial problems (On a scale of 1-7, rate the following problems)

Note : (1 being the most important and 7 as the least important)

☐ Lack of ownership or accountability

☐Insufficient operators

☐Insufficient staffing and organization

☐Lack of external linkage

☐Lack of experience among managers

☐Others (please specify)____________________

☐ Lack of community support

9. Basic information of operators:

9.1 What according to you is/are the best possible solution(s) to above challenges?

____

9.2 Did you receive any training prior to being appointed as an operator and how many years?

____

9.3 What type of training did you receive?

____

9.4 How long have you been working as an operator?

____

9.5 How often do you get advice from water quality experts/ engineers?

☐Daily ☐Weekly ☐Monthly

☐Quarterly ☐Annually ☐Never

☐Others (please specify)____

9.6 What is the most challenging part of your work?

☐Customer satisfaction ☐Meeting water quality guidelines ☐Managing limited resources

☐Others (please specify)____

9.7 Number of operators working for water treatment

____

9.8 Do you have certificate to serve as an operator for the drinking water facility?

☐Yes (Please mention the type of certificate) ____________________________

☐No

9.9 What are your responsibilities as an operator? You may check more than one boxes

☐Take measurement of water quality parameters and entry in register

☐Maintenance and repairmen of equipment in treatment plant and distribution network

☐Order/ purchase of chemicals (hypochlorite, permanganate) /purchase of equipment

☐Sampling of water in treatment plant and distribution network

☐Interpret and assess water quality result

9.10Any additional responsibilities other than mentioned in 9.9?

____

Appendix I Sample email sent to the prospective participants

Hi Mr. XYZ,

Hope this email finds you at a good time.

My name is Sarin and I am a Master of Applied Science (M.A.Sc, Civil Engineering) student under the supervision of Dr. Rehan Sadiq at University of British Columbia (UBC), Okanagan campus.

Currently, I am doing research on identifying the challenges faced by small water systems across BC. For this particular research, any water system that serves population less than 5000 is considered to be small. The result of this research is based on a questionnaire survey responded by the water system operators. The survey is made up of a number of questions related to the size of population served by your system, residual chlorine management practices, disinfection practices and existing water quality issues in your system. Along with this email, I have attached my research proposal and questionnaire for your reference. If you are interested to participate in this research, please find attached consent form and recruitment letter declaring your interest to participate in this survey. This research is funded by the Natural Sciences and Engineering Research Council (NSERC) of Canada.

The survey can be responded using any of the following three ways;

i) I choose to fill the questionnaire using my personal computer and email it back to you.

ii) I will print the questionnaire, scan the completed questionnaire, and email it back to you.

iii) I prefer to participate in a telephone call to answer the questionnaire items. In this case, if you wish to have a telephone conversation, please do not hesitate to contact me at 250-899-2134.

I look forward to hearing from you. Your contributions will make a meaningful impact to my research..

Thank you for your time and attention.

Have a good day ahead.

Kind regards,

Sarin