



CORE

Public Health Functions for BC

Evidence Review:
Water Quality
(Drinking Water)

Population Health and Wellness
BC Ministry of Health

April 2007

This paper is a review of the scientific evidence for this core program. Core program evidence reviews may draw from a number of sources, including scientific studies circulated in the academic literature, and observational or anecdotal reports recorded in community-based publications. By bringing together multiple forms of evidence, these reviews aim to provide a proven context through which public health workers can focus their local and provincial objectives. This document should be seen as a guide to understanding the scientific and community-based research, rather than as a formula for achieving success. The evidence presented for a core program will inform the health authorities in developing their priorities, but these priorities will be tailored by local context.

This Evidence Review should be read in conjunction with the accompanying Model Core Program Paper.

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TABLE OF CONTENTS

Executive Summary	i
1.1 Part I.....	i
1.2 Part II	ii
1.0 Overview/ Setting the Context.....	1
1.1 An Introduction to This Paper.....	1
2.0 Methodology	4
3.0 Background.....	6
3.1 Microbiological.....	6
3.2 Chemical	7
3.3 British Columbia Water Quality and Outbreaks.....	9
3.4 Outbreaks in Other Areas.....	10
PART I.....	12
4.0 Results.....	12
4.1 Summary of Results.....	12
4.2 Source Protection	12
4.3 Water Treatment	13
4.4 Distribution System	14
4.5 Monitoring	15
4.6 At-Home Intervention Studies	15
4.7 Public Education	16
PART II.....	18
5.0 An Overview of Practices in Other Jurisdictions.....	18
5.1 Canada.....	18
5.2 World Health Organization.....	19
5.3 European Union	20
5.4 United Kingdom.....	21
5.5 United States	21
5.6 Australia.....	21
5.7 New Zealand	22
6.0 Drinking Water Quality Management	23
6.1 Principles.....	23
6.2 Management Framework	24
6.3 Risk Assessment	25
6.4 Incident and Emergency Response Plans	27
7.0 Preventive Measures – The Multi-Barrier System.....	29
8.0 Source Water Protection	30
9.0 Treatment	33
9.1 Microbial Quality.....	35
9.2 Physical and Chemical Quality.....	37
10.0 Distribution System	40
11.0 Operational Monitoring and Control Systems	41
11.1 Operational Procedures.....	41
11.2 Operational Monitoring	41

Core Public Health Functions for BC: Evidence Review

Water Quality (Drinking Water)

11.3	Corrective Action.....	43
12.0	Regulatory Oversight.....	44
13.0	Operator Awareness and Training.....	47
14.0	Communications.....	49
14.1	Community Involvement.....	49
14.2	Public Education.....	50
14.3	Public Reporting.....	51
15.0	Management of Small Drinking Water Systems.....	53
16.0	Research and Development.....	54
17.0	Conclusion.....	55
17.1	Part I.....	55
17.2	Part II.....	55
	References.....	57
	Appendix 1: British Columbia Drinking Water Roles and Responsibilities.....	62
	Appendix 2: Studies on Turbidity.....	64

List of Tables

Table 1.	Water-borne Disease Outbreaks in BC 1995-1996.....	13
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EXECUTIVE SUMMARY

This evidence review is split into two parts: Part I discusses the effectiveness of interventions to reduce illness from drinking water. Part II looks at best practices in the management of drinking water quality.

1.1 Part I

Providing clean drinking water is a top priority for public health officials. Water system managers and public health officials are trusted by the public to ensure that drinking water provided is free of disease-causing contaminants. Maximizing health protection in a cost-effective manner requires that public health decisions concerning drinking water management are based upon sound scientific data. This review was conducted to assess the evidence behind drinking water-related interventions.

A literature search on drinking water interventions was conducted using several online databases. To be included in the review, the studies had to focus on interventions and their effects on health. Several exclusion criteria were identified. Due to the small number of intervention studies identified in the database searches, the grey literature was also searched for drinking water interventions.

Using the multi-barrier approach to safe drinking water, six potential stages of interventions were identified, including source water protection, water treatment, distribution system, monitoring, at-home strategies and public education. A total of five intervention studies were retrieved and reviewed for this report. All intervention studies retrieved involved at-home treatment of tap water. The lack of data for the other intervention stages is discussed.

No published studies were identified that examined the effectiveness of interventions at the source water or distribution system stages. Although there are several mentions of interventions used to increase source water quality in the grey literature, pre- and post-intervention rates of enteric disease are not reported. Without this data, it is not possible to evaluate the effectiveness of these interventions for health protection.

Approximately three-quarters of British Columbians receive their supply of drinking water from surface sources such as creeks, rivers, lakes, streams and reservoirs. Due to the high vulnerability of surface water to contamination from wildlife and human activity, source water protection is an essential step in the provision of clean drinking water.

The outbreaks of *Cryptosporidium* in multiple cities in BC in 1996 resulted in the implementation of various water treatment interventions. For those cities that employed routine disinfection prior to the outbreaks, added measures succeeded in reducing rates of intestinal disease. The additional actions taken included added filtration, issuance of turbidity advisories and increased disinfection.

Boil water advisories are often issued as part of the multi-barrier approach to safe drinking water when tap water has been shown to be unfit for consumption. However, the data indicates that

public health officials should not rely on boil water advisories as a means of protecting the population against drinking water-related disease, as compliance with advisories can be low.

With the exception of at-home devices, there were no scientific studies found that examined the effectiveness of interventions on reducing enteric illness. There is some evidence from reviews of experience in BC communities that shows improvements to drinking water treatment is associated with a reduction in enteric illness. Despite the lack of formal studies identified in a search of recent literature, disinfection of drinking water is well accepted as an effective means of reducing water borne illness. Although the grey literature may contain information that could assist public health officials in making drinking water-related decisions, this information is not easily obtainable. A coordinated effort is needed to ensure that further research on drinking water is available to interested individuals and agencies.

1.2 Part II

While much progress has been made in the quality of drinking water through water disinfection and other measures in developed countries, the risk of water-borne diseases remains a potentially serious problem that can only be kept a bay by a high degree of vigilance. Between 1980 and 2004, BC had one of the highest reported number of water-borne disease outbreaks in Canada: 29 confirmed outbreaks that affected tens of thousand of British Columbians.

This evidence review discusses the contaminants in BC water supplies that present health concerns. For example, the bacteria *Campylobacter* was responsible for at least four disease outbreaks since 1990; a number of other bacteria, such as *E. coli*, cyanobacteria and *Salmonella* are of concern because of their potential for serious impact on human health. The parasite *Giardia* was responsible for thirteen outbreaks since 1980, and the parasite *Cryptosporidium* for three outbreaks since 1995.

An overview of the status of drinking water legislation, standards and guidelines in leading international jurisdictions is provided to provide a context and comparison for safe drinking water practices in BC. The regulatory approaches adopted by the federal government as well the European Union, United Kingdom, United States, Australia and New Zealand, are discussed. Recently released recommendations and guidance from the World Health Organization and International Water Association highlight the importance of a management framework and comprehensive water safety planning, in particular risk assessment and risk management. The emphasis on these measures in reflected strongly in mandated legislation in New Zealand (currently in draft form), and guidelines recently established by Australia.

A multi-barrier approach is a fundamental “best practice”, which is repeatedly recommended in the literature by experts in the field, and reflected in recent years in the statutes and guidelines of many jurisdictions considered to be leaders in the field. A multi-barrier system is an integrated approach to reducing the risk of contamination at key points in the water supply system, including: source water protection, treatment measures and the distribution system.

Source water protection involves: developing and implementing a watershed management plan that delineates controls to protect surface water and groundwater sources from contaminants; planning regulations to ensure the enforcement of protection from potentially polluting activities; and promoting awareness in the community about the importance of water quality.

Treatment measures include an adequate level of disinfection as an essential element for most water systems to achieve the necessary level of microbial risk reduction. In addition, depending on the quality of local supplies, filtration processes may also be required, particularly in areas that experience frequent turbidity in source waters. A range of treatment options and technologies are available to effectively reduce contaminants based on local requirements (although different technologies are noted, this review does not examine their relative effectiveness). A “best practice” for treatment has been developed by the Interior Health Region, as an expansion of recommendations in the *Guidelines for Canadian Drinking Water Quality*. Interior Health Region requires water suppliers to provide details on how they plan to achieve the “4-3-2-1-0” objectives as part of a continuing performance improvement plan. The “4-3-2-1-0” objectives are:

- 4 log (99.99 per cent) inactivation of viruses.
- 3 log (99.9 per cent) removal or inactivation of *Giardia* and *Cryptosporidium*.
- 2 treatment processes for surface water (e.g., filtration and disinfection).
- 1 NTU¹ of turbidity, or less, with a target of 0.1 NTU.
- 0 total and fecal coliforms and *E. coli*.

Water transmission and distribution mains are a vital component of a safe water supply system. Good engineering practices are required with respect to pipe sizing, material, layout and burial. Cross-connection control and disinfection is also important to protect against contamination.

Operational monitoring is a key protective function for each stage of the multi-barrier system. As well, operator awareness and training is an important best practice in ensuring safe drinking water. As noted in the *Report of the Walkerton Inquiry* (O’Connor 2002), “ultimately the safety of drinking water is protected by effective management systems and operating practices, run by skilled and well-trained staff.”

Additional preventive measures are highlighted in the literature and practices of other jurisdictions. These include the importance of public education and consultation, as well as strengthened research and evaluation strategies. A major challenge for many jurisdictions is safeguarding water supplies for small communities and rural populations. Approaches taken in other jurisdictions are noted for information and consideration.

¹ nephelometric turbidity unit.

1.0 OVERVIEW/ SETTING THE CONTEXT

In 2005, the British Columbia Ministry of Health released a policy framework to support the delivery of effective public health services. The *Framework for Core Functions in Public Health* identifies water quality as one of the 21 core programs that a health authority provides in a renewed and comprehensive public health system.

The process for developing performance improvement plans for each core program involves completion of an evidence review used to inform the development of a model core program paper. These resources are then utilized by the health authority in their performance improvement planning processes.

This evidence review was developed to identify the current state of the evidence based on the research literature and accepted standards that have proven to be effective, especially at the health authority level. In addition, the evidence review identifies best practices and benchmarks where this information is available.

1.1 An Introduction to This Paper

This evidence review is split into two parts: Part I discusses the effectiveness of interventions to reduce illness from drinking water. Part II looks at best practices in the management of drinking water quality.

1.1.1 Part I

Major outbreaks of disease still occur in countries with highly developed water treatment systems (Westrell, Bergstedt, Stenstrom, & Ashbolt, 2003). BC has the highest rate of intestinal illness of all Canadian provinces and the second oldest water system infrastructure (Drinking Water Review Panel, 2002). Although community drinking water disease outbreaks are not common occurrences, when they do occur, a large population may be affected. Several different kinds of water-borne bacterial and parasitic diseases have been reported over the past several decades in BC, including *Campylobacter*, *Giardia* and *Cryptosporidium*. Exposure to these entities may cause enteric illnesses, with symptoms such as diarrhea, abdominal cramps, gas, malaise and weight loss. Vomiting, chills, headache and fever may also occur (Rowe, 1998).

All water systems should provide high quality water under normal conditions, and deviate little in quality during periods of upset or challenge (Huck & Coffey, 2004). While it is certain that disease outbreaks can result from mistakes in the management of drinking water systems, illness may also be attributed to drinking water from systems that operate properly (Colford et al., 2005). Measurement of the magnitude of endemic illness derived from the ingestion of contaminated drinking water is difficult, due to underreporting and the challenge in establishing a causal link between water consumption and illness.

Due to the potential unreliability of a single barrier for protection against water-borne illness, the multi-barrier approach has been developed. The multi-barrier approach involves source water protection, water treatment, safe distribution, effective monitoring and appropriate response to any adverse event within the water system (Huck & Coffey, 2004). A failure at any one of these

stages could result in negative health outcomes from water-borne disease. Effective interventions at any one of the stages could, in turn, be valuable in preventing outbreaks within the community.

Water treatment interventions can be very expensive. Due to the lack of scientific data on the effectiveness of drinking water system interventions, government risks committing large sums of money on changes within the water system that may be unnecessary and produce no benefit to public health. This review assessed published studies and systematic reviews in the scientific literature that involved intervention strategies used to reduce drinking water-related illness. The goal of Part I of this report is to present a review of the scientific literature that provides evidence for the human health benefits of drinking water interventions. The scientific literature was evaluated in order to present recommendations to the Ministry of Health on effective interventions for reducing drinking water-related illness.

1.1.2 Part II

Part II of the water quality evidence review presents:

- Information from the literature reflecting progressive drinking water quality practices from other jurisdictions that are considered to be leaders in the field. This includes a wide range of initiatives in key jurisdictions internationally and nationally, with a particular focus on recent developments such as recommendations from the World Health Organization and the International Water Association, and revised guidelines newly implemented in Australia and New Zealand.
- Exemplary Canadian practices developed by the federal government, and by federal/provincial/territorial consensus. Also included are effective practices adopted in British Columbia based on the views and experiences of experts in the field, and on evidence where this is available.

This document has been prepared to support representatives of the Ministry of Health and the health authorities in developing a model core program for the management of quality drinking water throughout the province. Although BC practices are considered to be well-developed, a focus on practices in other jurisdictions is intended to provide a basis for assessing the strengths and possible gaps in BC practices.

As noted in Part I, there are few scientific studies that examine the effectiveness of drinking water interventions on the health of the population. Well-established drinking water programs have been in effect in developed countries for over one hundred years, and as a result, there is little comparative data on the effects of poor quality drinking water in these countries. However, there is considerable scientific and technical information on protecting the quality of drinking water, particularly source water protection, water treatment and water distribution systems. This paper provides general information but does not attempt to provide in-depth technical details to assess different technologies, as these are well covered in published guidelines and supporting research documentation for the *Guidelines for Canadian Drinking Water Quality*, the World Health Organization (WHO) *Guidelines for Drinking-Water Quality*, as well as WHO background papers and documents from the International Water Association and American Water Works Association.

Core Public Health Functions for BC: Evidence Review
Water Quality (Drinking Water)

Water quality management practices that appear to be effective in quality control and continuous performance improvement are highlighted as “best practices”. An overview of the approaches taken by major jurisdictions is provided as context. This is followed by a description of the components that are fundamental to effective drinking water quality management. These include: drinking water quality management, preventive measures (multi-barrier system: source water protection, treatment, distribution system), operational monitoring and control systems, regulatory oversight, operator awareness and education, communication, management of small drinking water systems and research and development. Although little evidence is available on “best practices” in the regulation of safe drinking water, some references on the advisory and regulatory role of public health inspectors are identified to suggest effective regulatory oversight practices.

The term “best practices” is used to encompass initiatives considered to be “good practices”, “generally accepted practices” or “better practices” that have yielded positive results in some settings. The term is used to reflect the range of practices that are supported and/or recommended by leading jurisdictions, by experts in the field and/or by research studies. For simplicity, they are referred to as best practices in this document.

2.0 METHODOLOGY

2.1.1 Part I

A literature search was conducted to identify all published studies and systematic reviews involving drinking water interventions. The literature search was conducted using EBSCOhost² and PubMed. EbscoHost includes the following databases: Academic Search Premier, Biomedical Reference Collection and the Cochrane Database of Systematic Reviews. The published studies were limited to intervention studies and evidence-based medicine databases. The systematic reviews were limited to reviews of intervention studies.

EBSCOhost and PubMed were searched using a combination of the following keywords: drinking water OR potable water AND interventions OR source protection OR source water OR distribution system OR treatment OR at-home interventions OR monitoring OR hazard control OR public health OR public education. EBSCOhost and PubMed were also searched for papers dealing with the human health effects of nitrate, arsenic and disinfection by-products. The following keywords were used in this search: drinking water OR potable water AND health AND nitrate OR arsenic OR disinfection products OR trihalomethanes OR chlorination by-products.

Exclusion criteria included:

- 1) Intervention studies that examined the efficacy of interventions solely on water quality rather than health outcomes.
- 2) Studies with a specific focus on interventions in developing countries.
- 3) Studies that examined interventions based upon computer modeling

To be included in the review, the studies had to focus on the effects of interventions on health. Since the relationship between water-borne disease and health risks is well-established (Rowe, 1998; Huck & Coffey, 2004), health was defined in terms of enteric illness. Searches were first performed in EBSCOhost, followed by PubMed. Any studies previously identified in EBSCOhost were discarded in PubMed. The grey literature available on the Internet was also searched for drinking water interventions.

Due to the wide acceptance of the multi-barrier approach towards providing safe drinking water, intervention studies were classified according to the stage in the water system at which the intervention took place. Six potential stages of interventions were identified, including source protection, water treatment, distribution system, monitoring, at-home and public education. All studies related to drinking water intervention strategies were compiled into tables outlining methodology, intervention type and results.

A total of five intervention studies were retrieved. All the retrieved studies involved at-home interventions. Due to the small number of retrieved studies, the grey literature was also searched. A search of the grey literature revealed that, although interventions may have been set in place, pre- and post-rates of enteric illness were not available in the published literature.

² EBSCOhost a journal index service providing full text for nearly 4,500 magazines and journals, including many health periodicals, pamphlets, and reference books.

2.1.2 Part II

A literature review was conducted using the following sources and databases:

- EBSCOhost.
- Internet sources.
- The University of Victoria library and online databases.
- Ministry of Health library and online databases.
- Discussion with representatives of the Ministry of Health and the BC health authorities who are responsible for drinking water safety.

Some of the major reference documents considered in this review include:

- *Draft Guidelines for Drinking-water Quality Management for New Zealand* [2nd Edition] (2005), by the Government of New Zealand.
- *National Water Quality Management Strategy: Australian Drinking Water Guidelines 6* (2004), by the Australian Government, National Health and Medical Research Council and National Resource Management Ministerial Council.
- *Guidelines for Drinking-water Quality* [3rd Edition] (2004), by the World Health Organization.
- *The Bonn Charter for Safe Drinking Water* (2004), by the International Water Association.
- A variety of documents from the United States Environmental Protection Agency (US EPA) in relation to the *Safe Drinking Water Act* (1996).
- Documents of the Federal-Provincial-Territorial Committee on Drinking Water, including:
 - *Guidelines for Canadian Drinking Water Quality* [6th Edition] (1996).
 - *Guidance for Safe Drinking Water in Canada: From Intake to Tap* (2001).
 - *From Source to Tap: the Multi-Barrier Approach to Safe Drinking Water* (2002)
 - *From Source to Tap: Guidance on the Multi-Barrier Approach to Safe Drinking Water* (2004) (companion document).
- *Report of the Walkerton Inquiry, Part 2. A Strategy for Safe Drinking Water* (2002b), by D.R. O'Connor.
- *Safe Drinking Water: Lessons from Recent Outbreaks in Affluent Nations* (2004), by S.E. Hrudey and E.J. Hrudey. (2004).

3.0 BACKGROUND

Contaminants in drinking water that pose a health risk can be divided into two categories: microbiological and chemical. From a public health standpoint, microbiological pathogens are of greater concern due to their ability to cause acute illness in exposed populations at levels commonly present in source waters. While chemical contamination of drinking water is of lower significance than microbiological contamination in British Columbia, the burden of illness from chronic exposure to chemical contaminants, such as disinfection by-products, has not been assessed.

3.1 Microbiological

Microbiological pathogens in drinking water can be divided up into three types: bacteria, viruses and parasitic protozoa. Pathogens identified as potential threats to Canadian drinking water supplies include the bacteria *Campylobacter* and *Escherichia coli* (*E. coli*) as well as the protozoa *Cryptosporidium parvum* and *Giardia lamblia* (Federal-Provincial-Territorial [FPT] Committee on Drinking Water, 2004). Surface water is at the highest risk of microbiological contamination by protozoa due to potential contamination from wildlife and human activity.

3.1.1 Bacteria

The *Campylobacter* organism is the most common cause of bacterial diarrhea in British Columbia. The percentage contribution of *Campylobacter* from drinking water as opposed to food is unknown. The most common clinical symptoms of *Campylobacter* infections include diarrhea (frequently with blood in the feces), abdominal pain, fever, headache, nausea and/or vomiting. The symptoms typically last three to six days (Ministry of Health, 2006).

Coliform bacteria live in soil or vegetation and in the gastrointestinal tract of animals. Coliforms enter water supplies from the direct disposal of waste into streams or lakes, or from runoff from wooded areas, pastures, feedlots, septic tanks and sewage plants into streams or groundwater. Coliforms are not a single type of bacteria, but a grouping of bacteria that includes many strains, such as *E. coli*. *E. coli* is a coliform bacterium that exists exclusively in the intestines of humans and warm-blooded animals. It is often used as an indicator of fecal contamination in water supplies, and the possible presence of intestinal pathogens. Certain strains of *E. coli* can cause severe illness in humans.

The largest multi-bacterial water-borne outbreak in Canada's history occurred in 2000 due to a treated municipal water supply. The infamous Walkerton, Ontario outbreak was estimated to have affected over 2,000 residents. Stool analysis implicated both *E. coli* O157:H7 and *Campylobacter* as causative agents. Sixty-five persons were hospitalized and seven died. Heavy rains and flooding contributed to the transport of these pathogens into the groundwater, while increased turbidity from the runoff overwhelmed the water treatment (Reynolds, 2003).

3.1.2 Protozoa

Protozoa pose the greatest risk to human health from water-borne contamination in BC. They are very difficult to measure or monitor in water, making tap-water standards ineffective as a shield

against these parasites (Drinking Water Review Panel, 2002) and leading to periodic outbreaks of gastrointestinal illness (Casman, Fischhoff, Palmgren, Small, & Wu, 2000).

Cryptosporidium parvum, the causal agent of cryptosporidiosis, and *Giardia lamblia*, the causal agent of giardiasis, are two widespread protozoan parasites. Both are human pathogens and have been responsible for both epidemics and well as endemic levels of intestinal diseases (Redlinger, Corella-Barud, Graham, Galindo, Avitia, & Cardenas, 2002). Cattle feces are the main source of *Cryptosporidium*, while beaver, human, dog and other animal feces are the main source of *Giardia*. Source water contamination by *Cryptosporidium* and *Giardia* is a great concern because these protozoa are more resistant to disinfection than bacterial pathogens (FPT Committee on Drinking Water, 2004).

Giardia are flagellated protozoa that are parasitic in the intestines of humans and animals. Once in the body, *Giardia* causes giardiasis, a disease characterized by symptoms such as diarrhea, abdominal cramps, nausea, weight loss and general gastrointestinal distress. Disinfection of water by chlorination often does not provide adequate protection for *Giardia*, due to low free chlorous residuals and limited contact time (Redlinger et al., 2002).

Cryptosporidiosis is an acute gastrointestinal disease, caused in humans by the single-celled intracellular protozoan parasite. The illness is self-limiting in immunocompetent individuals, with symptoms of fulminating, watery diarrhea, cramping, vomiting and fever. In immunocompromised individuals, however, cryptosporidiosis may become chronic and sometimes even fatal (Casman et al., 2000).

3.1.3 Viruses

Viruses are extremely small microbes (<0.3 microns) that pose a risk to human health in untreated drinking water sources. Viral agents in source waters could include hepatitis A and E, rotaviruses and Norwalk-like viruses. As there are a number of viruses that could be present in drinking water, the symptoms of virus exposures ranges widely.

3.2 **Chemical**

Of all the advancements made possible through science and technology, the treatment and distribution of water for safe use is truly one of the greatest accomplishments for public health. Despite the obvious health benefits of chlorine disinfection, there remains concern about the health effects of chronic exposure to disinfection by-products (Do, Birkett, Johnson, Krewski, Villeneuve, & the Canadian Cancer Registries Epidemiology Research Group, 2005). Other chemical parameters of concern in specific regions of BC include arsenic and nitrates. Additionally, there are periodic events when chemicals are accidentally introduced into source waters and distribution systems at concentrations that can either cause loss of the source, or significant adverse health consequences (Boettger, n.d.).

3.2.1 Arsenic

Arsenic is a natural element widely found in the earth's crust. There are trace amounts of it in all living matter. Arsenic may enter lakes, rivers or underground water naturally, when mineral deposits or rocks containing arsenic dissolve.

Arsenic may also get into water through the discharge of industrial wastes and by the deposition of arsenic particles in dust or dissolved in rain or snow. These arsenic particles can get into the environment through the burning of fossil fuels, metal production, agricultural use or by waste burning. The International Agency for Research on Cancer considers arsenic a human carcinogen. Consuming drinking water that contains arsenic at levels close to or higher than the guideline value over a period of years has been found to increase the risk of skin cancer and tumours of the bladder, kidney, liver and lung (Health Canada, 2003).

Arsenic in groundwater has become recognized as a problem in BC during the last couple of decades. In common with the Western United States, naturally high levels of arsenic occur in groundwater in several parts of BC, including the Sunshine Coast, Bowen Island, Gulf Islands and central interior (Copes, 2005). Naturally occurring arsenic in drinking water is occasionally detected at levels that pose acute health risks and more commonly at levels that increase lifetime cancer risk (Boettger, n.d.).

3.2.2 Nitrates

Increasing human production of nitrogen since the 1950s has led to steadily accumulating levels of nitrate in source water (Ward et al., 2005). The major adult human intake of nitrate is from food rather than from water. Drinking water normally contributes only a small percentage of the total nitrate intake. Nitrate levels in well water tend to be highest in heavily-farmed areas. Fertilizer applications and animal manure are the principal sources of nitrates, which sink down into the water table from which well water is taken.

Although low levels of nitrates may occur naturally in water, sometimes higher levels, which are potentially dangerous, are found. High levels (more than 10 mg/L) of nitrate-nitrogen have been found in well-water samples from a number of wells in Langley/Brookwood, Hopington, Abbotsford/Sumas, Osoyoos, Spallumcheen and Grand Forks (Ministry of Health, 2000).

Infants under six months are particularly at risk from drinking well water that bears excessive nitrates (Ministry of Health, 2000). Infants are particularly susceptible to developing methemoglobinemia. Ingested nitrate is reduced to nitrite, which binds to hemoglobin to form methemoglobin (MetHb). Methemoglobinemia occurs when elevated levels of MetHb interfere with the oxygen-carrying capacity of the blood. The role of nitrate exposure ingestion of drinking water alone in causing methemoglobinemia is not clearly understood (Ward et al., 2005). The results of studies designed to investigate the link between cancer and drinking water nitrate levels have been mixed. Several studies have suggested that drinking water nitrate may be linked to stomach cancer (Cantor, 1997), colon cancer (Gulis, Czompolyova, & Cerhan, 2002) and bladder cancer (Weyer, Cerhan, Kross, Hallberg, Kantamneni, & Brauer, 2001). The role of nitrate as a risk factor for cancer needs to be more thoroughly researched.

3.2.3 Disinfection By-products

Drinking water disinfection has been a major contributor to the reduction in world mortality and morbidity figures during the last century (Van Leewen, 2000). It has been responsible for almost eliminating life-threatening disease such as cholera and typhoid in developing countries (Kerwick, Reddy, Chamberlain, & Holt, 2005). More recently, concern has arisen over the effects of long-term exposure to disinfection by-products.

Researchers in Canada recently conducted a population-based case-control study of 1,068 incidents of leukemia cases and 5,039 controls, to examine the association between exposure to drinking water chlorination disinfection by-products and adult leukemia risk in Canada (Kasim, Levallois, Johnson, Abdous, Auger, & the Canadian Cancer Registries Epidemiology Research Group, 2005). The authors reported an increased risk of chronic myeloid leukemia, which was associated with increasing years of exposure to different chlorination disinfection by-products, including trihalomethanes of more than 40 µg/litre. In contrast, the risk of the other studied leukemia subtypes was found to decrease with increasing years of exposure to chlorination disinfection by-products.

Several studies completed in Ontario demonstrated an association between exposure to chlorination by-products and the risk of cancer. The first study examined the relationship between bladder cancer and exposure to chlorination by-products in public water supplies. Exposures were estimated for the 40 years prior to the interview using 696 cases diagnosed with bladder cancer and 1,545 controls. Odds ratios adjusted for potential confounders were used to estimate the relative risk. The results of the study indicated that the risk of bladder cancer increases with both duration and concentration of exposure to chlorination by-products (King & Marrett, 1996). A more recent study conducted a pooled analysis of studies looking at bladder cancer and disinfection by-products. The authors of the study also concluded that the risk of bladder cancer increases with long-term exposure to disinfection by-products at levels currently observed in many industrialized countries (Villanueva et al., 2004).

A second population-based control study was conducted in Ontario to assess the relationship between chlorination by-products in public water supplies and cancers of the colon and rectum. Individual exposures to water sources, chlorination status and by-products levels as represented by trihalomethanes (THMs) were estimated for the 40-year period before the interview. Among males, colon cancer risk was associated with cumulative exposure to THMs, duration of exposure to chlorinated surface water and duration of exposure to a THM level ≥ 50 µg/litre. In contrast, these relationships were not observed among females. No relationship was observed between rectal cancer risk and any of the measures of exposure to chlorination by-products (King, Marrett & Woolcott, 2000).

3.3 British Columbia Water Quality and Outbreaks

In 2001, the Provincial Health Officer (PHO) reported that British Columbia had 3,016 water systems under provincial jurisdiction; two-thirds of these were small systems serving 2 to 14 connections each. More than half of BC's population receives water from the 2 largest water systems: the Greater Vancouver Regional District system, which services 18 municipalities, and the Capital Regional District on southern Vancouver Island. Many small and medium-sized

water systems are found in less-populated areas of the province. The PHO has noted that approximately three-quarters of BC's water supply comes from surface water.

The BC *Framework for Core Functions in Public Health* (Ministry of Health, 2005) notes that "On a global scale, water-borne infectious diseases remain one of the great scourges of humanity. While much less common in Canada, water-borne disease remains a potentially serious problem that can only be kept at bay by a high degree of vigilance over the quality of drinking water..." Water-borne illness has been, and continues to be, a serious public health threat in BC. There were 29 confirmed water-borne disease outbreaks in BC between 1980 and 2004, which affected tens of thousands of people (PHO, 2005). There are more than 5,500 cases of intestinal infections reported to BC public health authorities each year.

Part I of this evidence review discusses the contaminants in BC water supplies that present health concerns. For example, the bacteria *Campylobacter* was responsible for at least 4 water-borne outbreaks in BC since 1990, and a number of other bacteria such as *E. coli*, *Cyanobacteria* (blue-green algae), and *Salmonella*, are of concern because of their potential for serious impact on human health. The parasite *Giardia* was responsible for 13 outbreaks since 1980, and the *Cryptosporidium* parasite was responsible for at least 3 outbreaks since 1995. The largest outbreak was in Kelowna in 1996, when 177 cases of cryptosporidiosis were confirmed by laboratory tests, and an estimated 10,000 residents were infected. The *Toxoplasma gondii* parasite was responsible for an outbreak in Victoria in 1995. As well, Part I points out that chemical contaminants such as arsenic, nitrates and disinfection by-products are a health concern particularly with long-term exposures.

As well, there is a concern expressed in the 2000 PHO Annual Report that the quality of drinking water quality in some Aboriginal communities, is "inadequate" although there are examples where water treatment on-reserve is "state-of-the-art."

3.4 Outbreaks in Other Areas

3.4.1 Walkerton

The 2000 outbreak of *E. coli* and *Campylobacter* in Walkerton, Ontario illustrates the danger that can occur from contaminated water. The causes included a combination of factors: runoff from a farmer's field contaminated one of the town's wells; the well was shallow and vulnerable to contamination; the staff of the public utilities commission were not adequately trained nor even cognizant of their duty of care; test results were ignored; chlorination was haphazard; communication with the local public health official was neither systematic nor honest; and prompt communication with the public did not occur. Seven people died as a result. *The Report of the Walkerton Inquiry* (O'Connor, 2002) made 93 recommendations to avoid such a situation happening in the future. Major recommendations were to implement a multiple-barrier approach across Ontario, with particular attention to source protection, and to improve standards-setting with greater transparency, and improved provincial oversight, including regulatory obligations under comprehensive legislation to manage quality from source to tap, with special considerations for small systems (O'Connor, 2002).

“Perhaps the most significant recommendation in this report addresses the need for quality management through mandatory accreditation and operational planning. Sound management and operational systems help prevent, not simply react to, the contamination of drinking water” (O’Connor, 2002). The proposed quality management system includes the following: the adoption of best practices and continuous improvement; “real time” process control (e.g., continuous monitoring of turbidity, chlorine residual and disinfectant contact time) wherever feasible; the effective operation of robust multiple barriers to protect public health; preventive rather than strictly reactive strategies to identify and manage risks to public health; and effective leadership (O’Connor, 2002).

3.4.2 Summary of Outbreaks

Safe Drinking Water: Lessons from Recent Outbreak in Affluent Nations (Hrudey & Hrudey, 2004) examined water-borne disease outbreaks over the past 30 years in 15 affluent nations, and notes that these outbreaks occur on a relatively regular basis and are usually the cumulative impact of small individual events, each of which on their own may be relatively inconsequential. The importance of the cumulative impact of events is emphasized, along with the importance of taking a preventive approach to providing high-quality drinking water. The authors note that many of the outbreaks could have been prevented without the need for additional treatment infrastructure—all that would have been needed was better awareness and communication between the different groups responsible for providing the drinking water to consumers (Hrudey & Hrudey, 2004).

PART I

4.0 RESULTS

4.1 Summary of Results

The literature search performed for this review identified a limited number of intervention strategies. The only intervention strategies found in the published literature involved at-home interventions. Among these studies, there was little consensus on the effectiveness of at home interventions. The varying results are likely due to differences in the source water quality, as well as the different at-home water treatment devices used.

No scientific studies were recovered that dealt with intervention strategies for water source or distribution systems. It is probable that interventions have been set in place in several water treatment facilities; however, a review of the grey literature did not identify any rates of pre- and post-intervention enteric disease rates. Without this data, the effectiveness of these interventions in protecting health cannot be evaluated.

Many of the drinking water-related disease outbreaks in BC have been associated with surface water from watersheds undergoing development. None of the communities that experienced water-borne disease outbreaks had protected watershed lands. Rather than focusing on upgrading water treatment systems, it is possible that in the long-term it may be more cost-effective to initiate source water protection policies.

Several water treatment interventions were used in BC following the drinking water-related outbreaks in 1996. For those cities that employed routine disinfection prior to the outbreaks, added measures succeeded in reducing rates of intestinal disease. The additional actions taken included added filtration, issuance of turbidity advisories and increased disinfection for *Giardia* control. In Princeton, where well water was susceptible to cross-contamination by leaking sewer lines, warning sensors were added to signal future breaks in the sewer lines. This intervention, along with added chlorine disinfection, proved effective in reducing rates of gastrointestinal illness.

Boil water advisories may be issued as part of the multi-barrier approach to safe drinking water. The data indicates, however, that public health officials should not rely on boil water advisories as a means of protecting the population against drinking water-related disease, as compliance with advisories can be low.

4.2 Source Protection

The first step in the multi-barrier approach to providing safe drinking water is ensuring a clean source of water. Source water protection should be a standard part of providing safe drinking water to the public (United States Environmental Protection Agency [US EPA], 1997). British Columbians receive their supply of drinking water primarily from surface sources (75 per cent), including reservoirs, lakes, rivers, streams and creeks. An estimated 750,000 people in British Columbia rely on groundwater as their drinking water source. Protection of groundwater as a

drinking water source has become a major issue in rural areas such as the Fraser Valley and Osoyoos, where the aquifers have elevated levels of nitrates from agricultural activities and septic systems (Drinking Water Review Panel, 2002).

Surface water is extremely vulnerable to contamination by pathogens carried by wildlife and transported through sediment movement. Twenty-five of the twenty-eight incidents of disease outbreaks between 1980 and 2002 in BC involved communities supplied by surface waters. In just over 60 per cent of the cases, the community water supplies were threatened by development activities in the watershed. In only 6 of the 28 outbreaks were the watershed lands undeveloped or minimally developed.

No published studies were found that involved the use of interventions at the water source as a means of decreasing enteric disease outbreaks. A search of the grey literature did reveal that following the Milwaukee outbreak in 1993, the treatment plant did extend one water intake 4,200 feet farther into the lake out of the path of contamination. This measure was reported to have substantially improved raw water quality (Wisconsin Department of Natural Resources, 2003). No information was available, however, on rates of enteric illness pre- and post-intake location change, and so the effectiveness of this measure on human health could not be evaluated.

4.3 Water Treatment

There were no studies found in scientific papers on the effectiveness of changes in water treatment on rates of enteric disease pre- and post-interventions. This data likely exists in the grey literature for cases such as Walkerton, Ontario; however, it is beyond the scope of this review to contact water system managers and public health officials in the various municipalities to obtain this data. The water treatment interventions discussed in this review are those that were used following the disease outbreaks in BC in 1996. This data was obtained through communication with public health officials in BC, as well as from the report on water-borne disease outbreaks in BC from 1980 to 2002, written by the Sierra Legal Defence Fund (2003).

Table 1. Water-borne Disease Outbreaks in BC 1995-1996

Community	Organism	Water Treatment Prior to Outbreak	Action Taken	Statistically Significant*
Penticton	Cryptosporidiosis	Regular disinfection	Filtration added	Yes
Kamloops	Cryptosporidiosis	Routine disinfection	Turbidity advisory added	Yes
Kelowna	Cryptosporidiosis	Routine disinfection	No change	No
Vernon	Cryptosporidiosis	Routine disinfection	Increased disinfection for giardia control	Yes
Revelstoke	Giardia/Campylobacter	No disinfection	Routine disinfection	No
Princeton	Unidentified	No disinfection	Periodic disinfection	Yes

Note:

* Statically significant change in weekly rates of Medical Services Plan services for intestinal infectious diseases.

Although chlorine is effective in killing potentially harmful bacteria and some protozoa, it does not kill all pathogens. *Cryptosporidium* is housed in a protective shell and can survive immersion

in chlorine. Chlorine disinfection is therefore not an effective treatment against protozoa such as *Cryptosporidium*. Filtration may also be necessary to ensure water is not contaminated. Filtration acts as a barrier against contamination through filtering out soil and organic matter that transports pathogens into water bodies (Sierra Legal Defence Fund, 2003).

Due to the ineffectiveness of chlorine disinfection in guarding against cryptosporidiosis-related enteric illness, the action taken in Penticton and Kamloops following the outbreaks was a sound public health decision. Filtration was added in Penticton and a turbidity advisory was added to routine disinfection in Kamloops. Both of these interventions decreased rates of Medical Services Plan services for intestinal infectious diseases, compared to rates recorded prior to the intervention. In Kelowna, where no action was taken immediately following the outbreak, no change in rates of enteric disease was evident.

Following the outbreak in Vernon, increased disinfection for *Giardia* control was put into place. Routine chlorine disinfection is not effective against *Giardia*; however, chlorine treatment can kill *Giardia* if the contact time between disinfectant and water is extended. The increase in disinfection for *Giardia* control resulted in statistically significant reduced rates of intestinal illness in Vernon.

Revelstoke suffered from a multi-organism-caused outbreak in 1995. At the time of the outbreak, the city was not employing chlorine disinfection. Following the outbreak, Revelstoke installed full chlorine treatment. In 2000, the city later installed a membrane filtration system. No difference was evident in rates of intestinal illness pre- and post-installation of routine disinfection.

Princeton was the only city that experienced an outbreak whose main water source was groundwater. Due to wells generally not experiencing contamination levels as high as surface water, the well water was not treated with chlorine or filtered prior to the outbreak. Following the outbreak, which was caused by cross-contamination by a sewage leakage, Princeton installed sensors to warn of future breaks in sewer lines. The community now also employs chlorine disinfection. The interventions used in Princeton succeeded in reducing rates of enteric disease.

4.4 Distribution System

No studies that examined rates of enteric disease before and after an intervention in the distribution system were recovered. The distribution system is somewhat overlooked in the management of safe drinking water. The Drinking Water Review Panel (2002) recognized this in their statement “The best quality treated water is still not safe at the tap if it passes through a faulty distribution system where contamination can occur. The multi-barrier approach to drinking water management recognizes all three stages of drinking water: the source, treatment and distribution. So far, distribution is not adequately safeguarded in the legislation.” BC has the second oldest water treatment system in Canada and the average age of many of the water systems is beyond their life expectancy.

The United States Centers for Disease Control and Prevention reported that among the seven outbreaks associated with community water systems in 2000–2001, one (14.3 per cent) was

caused by contaminated, untreated groundwater; one (14.3 per cent) was related to a treatment deficiency; and four (57.1 per cent) were related to problems in the water distribution system (Blackburn et al. 2004). A review of outbreaks in the United States between 1991 and 1998 also reported a high percentage of outbreaks in community water systems were associated with distribution system deficiencies (36 per cent) compared to inadequately treated water (19 per cent), inadequately treated surface water (17 per cent), undetermined causes (17 per cent) and inadequate control of chemical feed (11 per cent) (Craun, Nwachuku, Calderon, & Craun, 2002).

4.5 Monitoring

Monitoring of water quality is necessary to keep drinking water safe. The testing of treated drinking water for the presence of protozoa such as *Cryptosporidium* and *Giardia* continues to be plagued with problems. To date, many municipalities use fecal coliform, *E. coli* and total coliform as indicators of contamination. Since the interpretation of testing results for parasites and viruses is difficult to interpret in terms of health risk, this data is not used in public health decisions. The lack of adequate testing procedures for *Cryptosporidium* and *Giardia* has resulted in numerous outbreaks in BC.

The problems involved in testing for parasites include setting the volume of water tested. If the volume filtered is much larger than the laboratory can actually process and examine, much of this material may be discarded in the analysis. On the other hand, if too small a volume is filtered, there is a risk that no cysts will be detected even though clumps of infectious micro-organisms may be present (Angulo et al., 1997). Even if cysts or oocytes are detected in water, there is no easy way of knowing if they are alive or infective to humans. Closely related species of both parasites that are not human infective are nearly identical in appearance and a recently deceased cyst looks very similar to a live one (Angulo et al., 1997).

Due to the length of time required for analysis and the ambiguity of the results, testing for *Giardia* and *Cryptosporidium* may not be useful in the protection of health. Instead, continuous, real-time monitoring through the measurement of turbidity has been employed in cities such as Kamloops. After the cryptosporidiosis outbreak in Kamloops in 1996, the city added turbidity advisories. This action resulted in a reduced rate of enteric illness within the exposed population.

4.6 At-Home Intervention Studies

Several studies have examined the effectiveness of in-home drinking water intervention to reduce gastrointestinal illness. All of the studies have used tap water that met current water quality microbiological standards. The studies assessed whether gastrointestinal illness could be attributable to consumption of tap water that meets current water quality guidelines.

The most recent study that utilized an in-home drinking water intervention to reduce gastrointestinal illness was completed in an Iowa community with a well-run water utility with microbiologically challenged source water (Colford et al., 2005). The principal objective of the study was to measure the change in the incidence of gastrointestinal illness from use of supplemental in-home drinking water treatment by a healthy population consuming tap water. The tap water was supplied by a municipal system using conventional treatment methods to purify microbiologically contaminated river water, while maintaining the system to meet all

current American regulatory standards. The authors of the study randomly assigned volunteers to use either a sham or active device. The active device consisted of a 1 µm ceramic prefilter and ultraviolet treatment. The sham device was externally identical to the active device. The treatment groups were assigned for 6 months, at which point the groups switched to the opposite device for 6 months. The episodes of highly credible gastrointestinal illness (HCGI) and water usage were recorded throughout the study period. No reduction in gastrointestinal illness was detected after in-home use of a device designed to be highly effective in removing micro-organisms from water. The study suggests that less than 11 percent of the gastrointestinal illnesses observed in a community with such standards can be attributed to the consumption of tap water among those who use tap water as their primary source of drinking water (Colford et al., 2005). It should be noted that the results of this study cannot be generalized to other communities with different water treatment efficiencies.

The results of two major epidemiological studies conducted in Canada suggest that a high percentage of gastrointestinal illness are attributable to tap water that meets current standards. The first study completed in Montreal measured the level of gastrointestinal illness related to the consumption of tap water prepared from sewage-contaminated surface water that was currently meeting water quality criteria (Payment, Richardson, Siemiatycki, Dewar, Edwardes, & Franco, 1991). A randomized intervention trial was carried out with 299 households supplied with reverse-osmosis water filters and 309 households left with their usual tap water. Gastrointestinal symptoms were recorded in a family health diary maintained prospectively over a 15-month period. The results of the study show the annual incidence of gastrointestinal illness was significantly higher among tap water drinkers compared to filtered water drinkers ($p < 0.01$). It was estimated that 35 per cent of the reported gastrointestinal illnesses among the tap water drinkers were water-related (Payment et al., 1991).

The objective of the second study completed by the same group of authors also included the attempt to identify the sources of gastrointestinal illnesses (Payment, Siemiatycki, Richardson, Renaud, Franco, & Prevost, 1997). The randomized prospective study was conducted over a period of 16 months in a middle class suburban community served by a single water filtration plant. The families selected were randomly allocated to 1 of 4 regimens: (a) tap water; (b) tap water from a continuously purged tap (tap-valve group); (c) bottled plant water; (d) purified bottled water. Using the purified water group as baseline, the excess of gastrointestinal illnesses associated with tap water was found to be 14 per cent in the tap water group and 19 per cent in the tap-valve group. The results suggest that 14 to 40 per cent of the gastrointestinal illnesses are attributable to tap water that meets current standards, and that the tap water distribution system appears to be partly responsible for these illnesses.

4.7 Public Education

Ideally, the multi-barrier approach to providing safe drinking water would negate the necessity of issuing boil water advisories. Effective source water protection, appropriate water treatment and a well-maintained distribution system should ensure that tap water is safe to drink.

Unfortunately, many water systems fall short in one of these three areas. In this case, public education may be the most important part of the multi-barrier approach to risk minimization for drinking water safety. High consumer compliance with boil water alerts can, to some extent,

compensate for a utility's inability to repair a drinking water treatment problem quickly (Casman et al., 2000). Public education is considered to be a virtual barrier to water-borne epidemics, reducing exposure to contaminated water by encouraging consumers to adopt averting behaviours during water quality emergencies (Casman et al., 2000).

Studies have determined that boil water advisories may not be highly effective. Consumers drink tap water until notified of the emergency situation, whereupon some adopt proper averting behaviours and others do not. It is assumed that about half of the consumers continue to drink contaminated water after receiving a boil water notice (Casman et al., 2000).

Researchers used a drinking water outbreak of salmonellosis in Missouri to examine the effectiveness of a boil water order (Angulo et al., 1997). They found that 10 per cent of residents never heard the boil water order broadcasted on a local radio station. Thirty one percent of households had someone in the house that drank unboiled water after being informed about the order. The most common reasons for non-compliance were forgetting (44 per cent), not believing the initial notice (25 per cent) and not understanding that ice should be made with boiled water (17 per cent) (Angulo et al., 1997).

Many residents continued to drink unboiled water after the order to boil water had been issued. Many of the people did not appreciate the severity of the situation. The initial boil order gave no reason for its issuance and did not mention the associated illness. Only when the information sheets appeared, which clearly explained the rationale and boiling procedure, did compliance with the order improve. When boil orders are issued, water supply operators, local governments and public health officials should ensure that all residents are adequately informed about the health risks associated with drinking contaminated water and the consequences of not boiling their water. Boil orders should be issued with easy-to-understand instructions. In small towns with limited media outlets, door-to-door delivery of information sheets should begin as early as possible (Angulo et al., 1997).

The lack of effective monitoring and water testing for common pathogens makes the timing of issuing a boil water advisory a difficult decision for public health officials. Under current conditions, a water authority's best chance to avoid an outbreak is to issue prophylactic boil water notices on the basis of trigger events, rather than on confirmed treatment failure. Since many of these will turn out to be false alarms, it may be difficult to secure the high compliance needed (Casman et al., 2000).

PART II

5.0 AN OVERVIEW OF PRACTICES IN OTHER JURISDICTIONS

A brief overview of the status of practices in leading international jurisdictions, including Canada, is provided as an introduction to current practices in the field of drinking water quality. More substantive information on these practices is covered in the discussion of major strategies used to ensure drinking water quality.

5.1 Canada

Health Canada is responsible for developing the *Guidelines for Canadian Drinking Water Quality* in collaboration with representatives from provincial and territorial drinking water authorities, and Environment Canada. Health Canada's Water Quality and Health Bureau is responsible for: research on guidelines for Canadian drinking water quality; emergency health advisories and guidance values for drinking water contaminants; support for international health-based standards for drinking water materials; and development of source water quality indicators, and guidelines for grey-water re-use.

The federal government also provides financial assistance to drinking water system owners through various cost-sharing arrangements such as infrastructure development programs. The federal government is responsible for water quality on First Nations lands, and for decisions related to water transportation, water use conflicts, inter-basin transfers and related issues.

Strong federal-provincial-territorial (FPT) collaboration, via the FPT Committee on Drinking Water (CDW), is an essential component in the development process for the Guidelines. For each guideline developed, Health Canada prepares a document outlining the latest research on the health effects associated with the contaminant, the level of Canadian exposure and treatment and analytical considerations. Committee members provide input on the feasibility of implementing the guidelines, discuss any concerns and reach consensus on the guideline.

In addition to the Canadian Guidelines, which focus on the scientific and technical parameters of safe drinking water, the FPT Committee on Drinking Water has also prepared a number of documents to provide guidance to drinking water system owners and operators and to emphasize the importance of a multi-barrier approach, such as *From Source on Tap: Guidance on the Multi-Barrier Approach to Safe Drinking Water* (CDW & Canadian Council of Ministers of the Environment [CCME], 2004).

5.1.1 Provinces and Territories

Regulatory oversight of drinking water quality is the responsibility of provinces and territories (except for federal areas of jurisdiction). All jurisdictions in Canada use the *Guidelines for Canadian Drinking Water Quality* (CDW, 2007) as a basis for establishing and enforcing their own drinking water quality requirements.

Most provinces and territories have established legislation and regulations to:

- Protect water resources.
- Approve the design, construction, operation and maintenance of water treatment and distribution systems.
- Establish drinking water quality criteria.
- Set monitoring, remediation and enforcement activities (CDW & CCME, 2004).

In many provinces and territories, the responsibilities related to source water protection rest with departments of natural resources, environment, municipal affairs and agriculture. Drinking water regulation or policies may involve the departments of public health and/or environment. Monitoring is often undertaken by regionalized operations staff, while centralized specialists conduct specialized assessments. Compliance and performance monitoring requirements are a key component of provincial and territorial drinking water programs. Compliance monitoring requirements deal with the quality of drinking water that reaches consumers, while performance monitoring ensures treatment and distributions systems are functioning as designed and, ideally, at optimal levels (CDW & CCME, 2004).

Requirements for very small water systems may be different than those for municipal systems—monitoring requirements may be less stringent or may not be included in regulations.

The roles and responsibilities of provincial ministries, health authorities, and local water suppliers in British Columbia, as defined by the BC *Drinking Water Protection Act* and Regulation, are summarized in Appendix 1.

5.1.2 Municipalities and Non-Municipal System Owners

Municipalities are the primary providers of water services across Canada, although there are a variety of arrangements related to the type of ownership for waterworks systems. Municipal water purveyors are generally vested with the responsibility to ensure drinking water provided to consumers is safe for consumption. The utility organization has a legal and moral responsibility to its users to provide potable water that does not pose a threat to public health and is satisfactory in its physical, chemical and aesthetic characteristics.

5.2 **World Health Organization**

The World Health Organization released the 3rd Edition of *Guidelines for Drinking-water Quality* in 2004. The WHO Guidelines are addressed primarily to water and health regulators, policy-makers and their advisors, to assist in the development of national standards and practices. Included are: a preventive management “framework” for safe drinking water including health-based targets, risk-based water safety plans, operational monitoring, and independent surveillance. Extensive information is provided on microbial, chemical, and radiological hazards (including risks, detection, assessment, and treatment). The WHO Guidelines are accompanied by a series of fact sheets and publications providing information on the assessment and management of risks associated with microbial hazards and by internationally peer-reviewed risk assessments for specific chemicals.

The new Guidelines expand on important concepts and approaches presented in previous editions, noting:

- Experience has shown that microbial hazards continue to be the primary concern in developing and developed countries, and that a systematic approach is necessary to secure microbial safety. It builds on the multiple-barrier approach and the importance of source protection.
- An emphasis is necessary on the important participation of many different stakeholders in ensuring drinking water safety.
- The need for different tools and approaches in supporting safe management of large piped supplies versus small community supplies. Descriptions of the principal characteristics of the different approaches are provided.
- An increased recognition that only a few key chemicals cause large-scale health effects through drinking water exposure—these include fluoride and arsenic. Other chemicals such as lead, selenium and uranium may also be significant under certain conditions.

5.2.1 International Water Association

The *Bonn Charter for Safe Drinking Water* was developed by the International Water Association (2004) through the efforts of a large group of experts across many disciplines and from many different countries. It provides a generic framework for the effective management of water quality. It was developed because of recognition among water professionals of the need for a consistent framework, following the increased emphasis placed on proactive risk-based management of drinking water supplies recommended in the 2004 edition of the WHO Guidelines. It provides a high-level framework, describing the operational and institutional arrangements that are basic requirements for managing water supplies from catchment to consumer (International Water Association, 2004).

The Bonn Charter emphasizes the importance of: clear roles and responsibilities for government, regulatory authorities, water suppliers and consumers; drinking water safety plans including assessment of risks, effective management control systems, monitoring and third-party verification (International Water Association, 2004).

5.3 European Union

The European Union issued a Drinking Water Directive (Council Directive 98/83/EC) to protect the health of the consumers in the European Union and to ensure that drinking water is wholesome, clear and has a pleasant appearance. The Directive focuses on establishing standards for the most common substances that can be found in drinking water, rather than a management process. It requires that a total of 48 microbiological and chemical parameters be monitored and tested regularly. In principle, the WHO Guidelines for drinking water are used as a basis for the standards selected in the Drinking Water Directive.

While translating the Drinking Water Directive into their own national legislation, Member States can include additional requirements (e.g., regulate additional substances that are relevant

within their territory or set higher standards). Member States are not allowed to set lower standards, as the level of protection of human health must be the same within the European Union. Member States are required to monitor the quality of the drinking water (this must be done mainly at the tap, inside public and private premises), and report monitoring results at three yearly intervals to the European Commission. The Commission assesses the results of water quality and produces a synthesis report summarizing the results. The reports are available to the public.³

5.4 United Kingdom

The United Kingdom Government has set legal standards for drinking water, based on standards from European law and the WHO Guidelines, as well as additional standards to safeguard a high quality of water in the country. The standards are strict and include wide safety margins. They are regulated through the Drinking Water Inspectorate, which was set up in 1990 after the water industry was privatized, to operate as an independent body. The Directorate monitors the quality of drinking water, and enforces the legislation. While advice is also provided to water suppliers, there are no specific practices or measures that are recommended or required.⁴

5.5 United States

The United States has strong federal drinking water regulations. *The Safe Drinking Water Act* (SWDA) regulates the country's public drinking water supply and applies to every public water system in the United States. It stipulates actions required to protect drinking water and its sources: rivers, lakes, reservoirs, springs and groundwater wells (it does not regulate private wells that serve fewer than 25 individuals) (US EPA, n.d.).

Originally, the SWDA focused primarily on treatment as the means of providing safe drinking water at the tap. The 1996 amendments enhanced the law by recognizing source water protection, operator training, funding for water system improvements and public information as important components of safe drinking water. This approach was adopted to ensure the quality of drinking water by protecting it from source to tap.

The SWDA authorizes the US EPA to set national health-based standards for drinking water to protect against both naturally-occurring and man-made contaminants that may be found in drinking water. The US EPA, the States and water systems work together to ensure the standards are met (US EPA, n.d.).

5.6 Australia

The *Australian Drinking Water Guidelines* (ADWG) were released in 2004 to provide a framework for effective management of drinking water supplies. The recommended framework, if implemented by regional and local districts, would assure safety at point-of-use. The ADWG was developed after an extensive process, including public consultation and consideration of available scientific evidence. It was designed as an authoritative reference on what defines safe,

³ More information on the reports can be found at http://ec.europa.eu/environment/water/water-drink/index_en.html.

⁴ More information on the Drinking Water Inspectorate can be found at <http://www.dwi.gov.uk>.

good quality water, how it can be achieved and how it can be assured in all parts of Australia. The ADWG are not mandatory standards. They acknowledge that some diversity is needed to consider the wide array of regional and local factors, as well as economic, political and cultural issues (Australian Government, 2004).

The ADWG provide thorough descriptions of policies and practices, incorporating: a management framework; risk assessment and hazard identification; multi-barrier approaches; operational monitoring; management of incidents and emergencies; employee training; community involvement/awareness; research and development; and evaluation.

5.7 New Zealand

The New Zealand Ministry of Health issued new Drinking Water Standards effective December 31, 2005. The Standards apply to public and private water supplies, and detail how to assess the quality and safety of drinking water. The Standards are mandatory and draw heavily on the WHO Guidelines and the US EPA Surface and Groundwater Rules. Included are: new sections dealing with small water suppliers (servicing populations under 500 people), 'blue-green algae', and ultra-violet light disinfection, and cautious approaches to the potential risk from heavy metals that are dissolved out of metal plumbing fittings (most New Zealand waters are plumbosolvent) (New Zealand Ministry of Health, 2005).

In addition, new legislation, the *Health (Drinking Water) Amendment Bill*, is currently being drafted (based upon *Draft Guidelines for Drinking-water Quality Management for New Zealand*, 2005), to require suppliers to take all practicable steps to comply with the Standards. It will require that the Standards be applied in conjunction with Public Health Risk Management Plans for each water supply. The plans will identify: public health risks to water supplies; relative importance of these risks; how risks could be managed; the water supplier's plans to manage the risk (including a multi-barrier system); and cases where risks cannot be managed within existing resources and further assistance may be necessary. A number of specific guides have been prepared to assist water suppliers in developing each step of the Public Health Risk Management Plan (New Zealand Ministry of Health, 2005).

6.0 DRINKING WATER QUALITY MANAGEMENT

6.1 Principles

Guidelines from a number of countries address principles for managing water quality. The Australian Guidelines (ADWG) describe fundamental principles for safe drinking water quality, reflecting a similar approaches by the WHO and the FPT Committee on Drinking Water. These include:

- “The greatest risk to consumers of drinking water is pathogenic micro-organisms. Protection of water sources and treatment are of paramount importance and must never be compromised.
- The drinking water system must have, and continuously maintain, robust multiple barriers appropriate to the level of potential contamination facing the raw water supply.
- Any sudden or extreme change in water quality, flow or environmental conditions (e.g., extreme rainfall or flooding) should arouse suspicion that drinking water might become contaminated.
- System operators must be able to respond quickly and effectively to adverse monitoring signals.
- System operators must maintain a personal sense of responsibility and dedication to providing consumers with safe water, and should never ignore a consumer complaint about water quality.
- Ensuring drinking water safety and quality required the application of a considered risk management approach” (Australian Government, 2004).

In addition, the Bonn Charter stresses:

- The importance of “management of the whole water supply chain, with management control systems to assess risks at all points throughout the water supply system.”
- “...close cooperation and partnership between all stakeholders including governments, independent regulatory authorities, water suppliers, local public authorities, health agencies, environmental agencies, land users, contractors, plumbers and manufacturers of relevant materials and products, and consumers. Open communication between all stakeholders is essential to developing trust” (International Water Association, 2004).

6.2 Management Framework

The WHO Guidelines, the ADWG, and the New Zealand Draft Guidelines all outline a preventive management framework for safe drinking water, which includes an extensive risk assessment process. For example, the WHO Guidelines and Bonn Charter propose that water suppliers develop drinking water safety plans—documented plans that identify credible risks and planning controls to mitigate them. The stages proposed are:

- “Management plans documenting the system assessment and monitoring plans and describing actions to be taken in normal operation and incident conditions, including upgrade and improvement, documentation and communication.
- A system-wide assessment of risk from catchment to consumer, and prioritization of the risks.
- Identification and monitoring of the most effective control points to reduce identified risks.
- A system of independent surveillance that verifies that the above are operating properly” (WHO, 2004).

The ADWG echo this approach. “In the Australian water industry, risk management and quality management are increasingly being used as a means of assuring drinking water quality by strengthening the focus on more preventive approaches” (Australian Government, 2004). The ADWG present a framework that includes risk assessment, including elements of the Hazard Analysis and Critical Control Point (HACCP) system adapted to drinking water quality, as well as management systems based on principles of quality management. The framework consists of four general areas, and twelve required elements:

- Commitment to drinking water quality management:
 - Drinking water quality policy, regulatory and formal requirements and engagement with stakeholders.
- System analysis and management:
 - Assessment of the drinking water system—water supply system analysis, assessment of water quality data, hazards and risk assessment.
 - Preventive measures for drinking water quality management—multiple barriers and critical control points.
 - Operational procedures and process control—procedures, monitoring, corrective action, equipment capacity and maintenance, materials and chemicals.
 - Verification of drinking water quality—monitoring, consumer satisfaction, evaluation of results and corrective action.
 - Management of incidents and emergencies—communication, and incident and emergency response protocols.

- Supporting requirements:
 - Employee awareness and training—employee awareness and involvement, and employee training.
 - Community involvement—community consultation and communication.
 - Research and development—investigative studies and research monitoring, validation of processes, design of equipment.
 - Documentation and reporting—management of documentation and records, and reporting.
- Review:
 - Evaluation and audit—long-term evaluation of results, and audit of drinking water quality management.
 - Review and continual improvement—review by senior executive, and a drinking water quality management improvement plan (Australian Government, 2004).

It should be noted that Canadian guidelines and British Columbia legislation do not require that water suppliers develop an overall management framework for drinking water quality, although BC legislation does allow for drinking water protection plans to be required on the authority of the Minister, on recommendation from the Provincial Health Officer. Such plans are considered appropriate when monitoring or assessment results indicate a potential threat to drinking water that may result in a drinking water health hazard, and no other practicable measures are available under the legislation to address or prevent the drinking water health hazard (BC Drinking Water Leadership Council, 2006). Generally, source protection plans, emergency response plans and long-term business plans are encouraged in BC as best practices (Interior Health Authority, n.d.).

In addition, the Canadian document *Source to Tap: Guidance on the Multi-Barrier Approach to Safe Drinking Water*, (CDW & CCME, 2004) discusses many aspects of an integrated approach to safe drinking water. The emphasis is on a multi-barrier approach being fundamental to an effective management system (discussed in Section 6.0). A risk management process is also discussed, noting the need to identify hazards, assess risks, manage risks and communicate risks. A section on total quality management, although in the concluding section of the document, emphasizes the importance of monitoring, record-keeping, reporting, operating procedures, training, emergency response plans, program evaluation and enforcement programs.

6.3 Risk Assessment

The management frameworks recommended by the WHO, the Australian Guidelines (ADWG) and the New Zealand Draft Guidelines incorporate principles and procedures for the assessment of water quality risks. The ADWG provide considerable detail in conducting risk assessments. They suggest that a review of historical water quality data can assist in understanding source water characteristics and system performance both over time and following specific events such as heavy rainfall. This can aid the identification of hazards and aspects of the drinking water

system that require improvement. Also, where available, water quality data should be assessed from monitoring of source waters, the operation of treatment processes, and drinking water supplied to consumers. Trend analysis and control charts can be valuable tools for recognizing potential problems or hazards and the accumulation of any gradual changes or cumulative effects (Australian Government, 2004).

The ADWG summarize recommended hazard identification and risk assessment actions as follows:

- Define the approach and methodology to be used for hazard identification and risk assessment.
- Identify and document hazards, sources and hazardous events for each component of the water supply system.
- Estimate the level of risk for each identified hazard or hazardous event.
- Evaluate the major sources of uncertainty associated with each hazard and hazardous event and consider actions to reduce uncertainty.
- Determine significant risks and document priorities for risk management.
- Periodically review and update the hazard identification and risk assessment to incorporate any changes (Australian Government, 2004).

The use of established risk assessment systems is also examined, including the Australia/New Zealand Standard (AS/NZS) 4360 on Risk Management, the HACCP system, the International Standards Organization (ISO) 9001 on Quality Management, and ISO 14001 on Environmental Management. In particular, the Guidelines note that the application of the HACCP system to drinking water supplies has “received increasing recognition due to the many parallel issues in food and drinking water supply” (Australian Government, 2004). It comprises seven principles, many of which are equivalent to elements in the Guidelines.

HACCP offers a systematic approach to the identification of hazards and their prevention, with a particular focus on process control to ensure that preventive measures are operating effectively. HACCP was not designed to be a fully comprehensive management system but was intended to be added on to existing good management practices. Thus, its scope and application are limited in several important areas of the Framework such as commitment, stakeholder involvement, emergency response, employee training, community consultation and research and development. Furthermore, while HACCP is aligned quite readily to the treatment component of drinking water supply, its application may not transfer as easily to the important areas of catchment and distribution systems (Australian Government, 2004).

New Zealand’s Draft Guidelines require the development of Public Health Risk Management Plans for drinking water supplies, noting that

While monitoring the quality of the water produced by water suppliers is always important, Public Health Risk Management Plans for drinking water supplies provide the additional benefit of reducing the likelihood of contaminants entering supplies in the first place... By the time monitoring shows that contaminants are present, a hazard is already present in the water... The Plans encourage the use of risk-management principles (covering source water, treatment and distribution) so that monitoring is not the only water quality management technique in place (New Zealand Ministry of Health, 2005).

A risk management process is emphasized including: risk analysis, risk reduction, readiness, response (based on contingency planning) and recovery (return to normal with planning to reduce a recurrence). The Draft Guidelines also support the Australian approach to the use of AS/NZS standards on risk management, the ISO standards on quality management, and a strong focus on management responsibility, risk analysis and continual performance improvement.

To assist water suppliers in preparing the Public Health Risk Management Plans, the New Zealand Ministry of Health has produced 39 guides covering the system elements that are most important in protecting drinking water supplies. Events with various levels of risk have been included in each guide. While HACCP is discussed, the use of critical control points is not advocated as it is thought that better water quality protection could be achieved by implementing as many preventive measures as necessary, rather than highlighting a few regarded as critical.

6.4 Incident and Emergency Response Plans

Guidance for Safe Drinking Water in Canada (FPT Subcommittee on Drinking Water ,2001) notes that

Every system must have a set of procedures to follow in the event of incidents and emergencies. These procedures should be in place well in advance of any event. Plans should cover off any number of incidents, such as loss of source water, major main breaks, vandalisms, power failures and deliberate chemical or biological contamination of the distribution system or reservoirs. Emergency plans should include clear procedures for the remediation of the situation and communication with appropriate authorities.

In BC, the *Drinking Water Protection Act* and Regulation require that water suppliers prepare emergency response and contingency plans. A variety of resources are available to assist water suppliers in this process (such as BC Ministry of Health emergency management documents available on the ministry website, as well as best management practices included on the BC Water & Waste Association website (<http://www/bcwwa.org/BMP>)).

The importance of contingency planning is noted in many major guidelines including those issued by the WHO, and the governments of Australia, New Zealand, the United States and Canada. For example, New Zealand's Draft Guidelines (New Zealand Ministry of Health, 2005) require that contingency planning be developed in the event that an emergency arises.

These plans should consider:

- Potential natural disasters (such as earthquakes, volcanic eruptions, algal blooms, droughts and floods).
- Accidents (spills in the catchment or recharge areas).
- Areas with potential backflow problems (including ones with fluctuating or low pressures).
- Damage to the electrical supply, damage to intakes, treatment plant and distribution systems.
- Human actions (strikes, vandalism and sabotage).

The WHO (2004) notes that incident response plans typically comprise: accountability and contact details for key personnel, a scale of alert levels, and clear descriptions of the actions required in response to alerts; location and identity of standard operation procedures, and required equipment; location of backup equipment; relevant logistical and technical information, and checklists and quick reference guides. Plans should be developed in consultation with relevant regulatory authorities and other key agencies, and they should be consistent with national and local emergency response arrangements.

7.0 PREVENTIVE MEASURES – THE MULTI-BARRIER SYSTEM

Traditionally, drinking water suppliers have relied heavily on compliance monitoring, based on regular testing of small samples, to ensure water is safe to drink. However, if the water is contaminated, people may become ill before the problem is identified and resolved.

In recent years, the drinking water industry has shifted its focus to using a more preventive, integrated approach to water quality management. The multi-barrier approach aims to reduce the risk of drinking water contamination in three key elements: source water (watershed/aquifer), the drinking water treatment plant and the distribution system. These elements are managed in an integrated manner, using procedures and tools such as: water quality monitoring and management of water supplies from source to tap; legislative and policy frameworks; public involvement and awareness; guidelines, standards and objectives; research and the development of science and technology solutions (CDW & CCME, 2004).

The strength of this approach is that a failure of one barrier may be compensated by effective operation of the remaining barriers, minimizing the likelihood of contaminants passing through the entire treatment system and being present in sufficient amounts to cause harm to consumers (Australian Government, 2004).⁵

⁵ Other measures such as monitoring, public education/communication and at-home strategies are also protective and can be considered as additional barriers—these are addressed in later sections of this review.

8.0 SOURCE WATER PROTECTION

Source water protection is emphasized in the practices of leading jurisdictions, including the WHO, the United States, Australia and New Zealand, as a critical element in assuring safe drinking water. It is accepted as a key “best practice”.

In BC, legislation does not specifically require source water protection, although a water supplier can be required to conduct an assessment of their drinking water source, and a drinking water officer can order the preparation of an assessment response plan. The 1999 Auditor General of British Columbia’s report *Protecting Drinking Water Sources* discussed at length the stresses and strains that are now facing our drinking water sources. In particular, it discussed the impact of logging, cattle grazing, mining, outdoor recreation, transportation, agriculture and human settlement on source water quality. It made a number of recommendations to improve source water protection including water quality objectives for all community watersheds as a matter of priority.

Development of water safety plans, which include source water protection, are an integral component to the WHO Guidelines, the Australian Guidelines and the New Zealand Draft Guidelines. These guidelines all specify the importance of a comprehensive source water risk assessment and effective source protection control measures as a first step in developing a water safety plan. For example, the WHO (2004) proposes that information be gathered on factors including geology and hydrology, meteorology and weather patterns, wildlife, agriculture, competing water uses, the nature and intensity of development and land use, other activities that potentially release contaminants, planned future activity and wellhead protection for groundwater. Following assessment, several steps are recommended in developing effective source protection control measures, including:

- Developing and implementing a catchment management plan, which includes control measures to protect surface water and groundwater sources.
- Ensuring that planning regulations include the protection of water resources (land use planning and watershed management) from potentially polluting activities, and that they are enforced.
- Promoting awareness in the community of the impact of human activity on water quality.

The major types of preventive measures described in the Australian Guidelines (Australian Government, 2004) (and reflected in the WHO and New Zealand Guidelines) include:

- Exclusion or limitations of uses (e.g., restriction on human access and agriculture).
- Protection of waterways (e.g., fencing out livestock, management of riparian zones).
- Use of planning and environmental regulations to regulate potential water-polluting development (e.g., urban, agricultural, industrial, mining and forestry).
- Use of industrial codes of practice and best practice management.
- Regulation of community and onsite wastewater treatment and disposal systems.

- Storm water interception.

In the United States, the *Safe Drinking Water Act* (1996) requires that American States submit a program for delineating source water areas of public water systems, and for assessing the susceptibility of such source waters to contamination. States may use funding from federal sources to pay for source water assessment and for coordination among the varied programs to gather and analyze water resource-oriented data. Results of completed source water assessments must be made available to the public. The assessment results are a statutory prerequisite for a State-tailored monitoring program, as they provide a scientific basis for such monitoring. They also provide the information necessary for water suppliers to seek help from States in protecting source water, initiating local government efforts or other source water protection activities.

Similarly, the Canadian document *From Source to Tap: Guidance on the Multi-Barrier Approach to Safe Drinking Water* (CDW & CCME, 2004) notes that source water protection is “key to maintaining the quality of drinking water over time.” It is recommended that source water protection be based on watershed/aquifer management, involving a coordinated approach among stakeholders to develop short- and long-term plans to prevent, minimize or control potential sources of pollution or to enhance water quality where necessary. The steps that are proposed are:

- Delineating source water protection areas.
- Identifying contaminants of concern through various inventories (such as contaminant or land use inventories).
- Assessing the risk vulnerability and ranking the risk levels.
- Developing a watershed/aquifer management plan.

Specific guidelines are also provided in *From Source to Tap* on the factors that affect source water quality, including natural, human and agricultural factors. It is suggested that “assessment proceed in stages with each successive stage providing more layers of detail, until an adequate amount of watershed/aquifer data is collected to decide how best to minimize risks.” Surface water, groundwater and groundwater under the direct influence of surface water (GWUDI) should be managed together.

Although viewed as separate, they are interconnected since they are part of the water cycle and can exert their influence on one another. For this reason, each water source should be developed and managed with careful attention to the hydrologic and ecologic systems of which the particular source is a part. Surface and ground water sources should be managed conjunctively (CDW & CCME, 2004).

A number of analytical and numerical models are identified to assist in predicting water flow, contaminants and other factors important to the effective management of the watershed/aquifer.

On completion of the watershed/aquifer assessment, *From Source to Tap* recommends the plan development process involve four stages:

Core Public Health Functions for BC: Evidence Review
Water Quality (Drinking Water)

- Evaluation of management options from source water assessment results.
- Development of the protection plan.
- Implementation of the plan.
- Performance evaluation and plan adjustment.

There are a number of technical documents readily available that provide guidance in assessing source water and developing protection plans. For example, a number of tools and resources are available from the American Water Works Association (www.awwa.org), the US EPA (<http://cfpub.epa.gov/safewater/source/sourcewater.cfm?action=tools>) and other technical associations.

9.0 TREATMENT

In BC, the Drinking Water Protection Regulation requires that “drinking water from a water supply system must be disinfected by a water supplier if the water originates from a) surface water, or b) ground water that, in the opinion of a drinking water officer, is at risk of containing pathogens.” The legislation does not refer to other forms of treatment.

Generally, treatment measures may include pre-treatment, coagulation/flocculation/sedimentation, filtration and disinfection. Pre-treatment includes processes such as roughing filters, microstrainers, off-stream storage and bankside filtration. Pre-treatment options may be compatible with a variety of treatment processes ranging in complexity from simple disinfection to membrane processes. Pre-treatment can reduce and/or stabilize the microbial, natural organic matter and particulate load. Coagulation, flocculation, sedimentation (or flotation) and filtration remove particles, including micro-organisms (bacteria, viruses and protozoa). It is important that processes are optimized and controlled to achieve consistent and reliable performance (WHO, 2004).

Various filtration processes are used in drinking water treatment, including granular, slow sand, precoat and membrane filtration (microfiltration, ultrafiltration, nanofiltration and reverse osmosis). With proper design and operation, filtration can act as a consistent and effective barrier for microbial pathogens and may in some cases be the only treatment barrier (e.g., for removing *Cryptosporidium* oocysts by direct filtration when chlorine is used as the sole disinfectant) (WHO, 2004).

The WHO (2004) notes that the application of an adequate level of disinfection is an essential element for most treatment systems to achieve the necessary level of microbial risk reduction. Taking account of the level of microbial inactivation required for the more resistant microbial pathogens through the application of the Ct concept⁶ for a particular pH and temperature, ensure that other more sensitive microbes are also effectively controlled. Where disinfection is used, measures to minimize disinfection by-products should be taken into consideration.

The most commonly used disinfection process is chlorination. Ozonation, UV irradiation, chloramination and application of chlorine dioxide are also used. WHO notes that these methods are very effective in killing bacteria and can be reasonably effective in inactivating viruses (depending on type) and many protozoa, including *Giardia* and *Cryptosporidium*. For effective removal or inactivation of protozoal cysts and oocysts, filtration with the aid of coagulation/flocculation (to reduce particles and turbidity) followed by disinfection (by one or a combination of disinfectants) is the most practical method. Storage of water after disinfection and before supply to consumers can improve disinfection by increasing disinfectant contact time. This can be particularly important for more resistant micro-organisms, such as *Giardia*, and some viruses (WHO, 2004).

The *Guidelines for Canadian Drinking Water Quality* set out the basic parameters that every Canadian water system (public, semi-public and private) should strive to achieve in order to

⁶ Product of disinfectant concentration and contact time.

provide the cleanest, safest and most reliable drinking water supply possible. These guidelines are based on extensive scientific analysis and research conducted by Health Canada (with consideration of guidelines and standards recommended by WHO, the US EPA and other countries that have conducted extensive analysis), and collaborative decisions by the FPT Committee on Drinking Water. The Canadian guidelines establish maximum acceptable concentrations of disease-causing micro-organisms, chemical substances, and radiological contamination.

The document *Source to Tap: Guidance on the Multi-Barrier Approach to Safe Drinking Water* (CDW & CCME, 2004) recommends that, “at a minimum, treatment requirements for surface water or GWUDI is filtration and disinfection to ensure greater than:

- 99.9 per cent (3-log) reduction of *Cryptosporidium*.
- 99.9 per cent (3-log) reduction of *Giardia*.
- 99.99 per cent (4-log) reduction of viruses.”

The Interior Health Region established “4-3-2-1-0” objectives (see below) as part of its Drinking Water Quality Improvement Program for water suppliers, based on the Canadian Guidelines and US EPA standards. This approach is considered a best practice by BC experts, and an important priority in a continuing performance improvement plan. Water suppliers are required to provide an outline of how they plan to reach the objectives of:

- 4 log (99.99 per cent) inactivation of viruses.
- 3 log (99.9 per cent) removal or inactivation of *Giardia* and *Cryptosporidium*.
- 2 treatment processes for surface water (e.g., filtration and disinfection).
- 1 NTU of turbidity, or less, with a target of 0.1 NTU.
- 0 total and fecal coliforms and *E. coli*.

The selection of appropriate filtration and disinfection technologies is dependent on a variety of factors including: reasonable financial costs; the availability of skilled personnel; and the objectives of the utility and its customers. The source water quality is the single most important factor in determining the type and the extent of treatment required for a particular source of water (CDW & CCME, 2004).

Major contaminants that are a particular concern in BC are addressed in the following sections. Additional technical information on these and many other water-borne contaminants is available in the WHO guidelines, from the US EPA, and the Australian and New Zealand guidelines, as well as publications of the American Water Works Association and International Water Association. These documents generally provide detailed information on each contaminant, the health effects, other effects, analytical methods, treatment technologies and extensive bibliographies.

9.1 Microbial Quality

As noted in Part I of this paper, microbiological pathogens pose the greatest and most tangible risk to drinking water safety. Microbiological pathogens in drinking water fall into three types: bacteria, viruses and parasitic protozoa. Pathogens identified as potential threats to Canadian drinking water supplies include the bacteria *Campylobacter* and *Escherichia coli* (*E. coli*), as well as the protozoa *Cryptosporidium* and *Giardia*.

In comparison to groundwater, surface water is at a higher risk of microbiological contamination by pathogens due to wildlife and human activity.

In general, it is recognized by Health Canada, the WHO, the US EPA, Australia, New Zealand, the European Union and others, that chlorine disinfection is the major treatment strategy for microbiological safety. Also, “in general, treatment facilities for a surface water source or groundwater source directly affected by surface water, should include screening, coagulation/flocculation, sedimentation, filtration, taste and colour control...” (CDW & CCME, 2004).

9.1.1 Bacteria

The *Guidelines for Canadian Drinking Water Quality* state that no maximum acceptable concentration has been established for current or emerging bacterial water-borne pathogens (CDW, 2006b). Current bacterial pathogens of concern include *E. coli*, *Salmonella* and *Shigella*, and *Campylobacter* and *Yersinia*. Emerging bacterial pathogens of concern include *Legionella*, *Mycobacterium* and *Aeromonas*.

The multi-barrier approach is an effective way to reduce the risk of illness from pathogens in drinking water. If possible, water supply protection programs should be the first line of defense. *E. coli* is used as an indicator organism in the assessment of the possible presence of other bacteria (as well as viruses, and protozoa). However, there are also naturally occurring water-borne bacteria (such as *Legionella* and *Aeromonas hydrophila*), so the absence of *E. coli* does not necessarily indicate the absence of these organisms; for many of these pathogens, no suitable microbiological indicators are currently known. The detection of *E. coli* should lead to the immediate issue of a boil water advisory and to corrective action being taken (CDW, 2006b).

As well as source water protection, treatment technologies should include effective filtration and disinfection and an adequate disinfection residual. Filtration systems should be designed and operated to reduce turbidity levels as low as reasonably achievable without major fluctuations. Combined with a well-maintained distribution system, these measures can reduce these bacterial pathogens to non-detectable levels or to levels that have never been associated with human illness (CDW, 2006b).

9.1.2 Enteric Viruses

Health Canada recently completed a review of the health risks associated with viruses in drinking water. Based on this review, no maximum acceptable concentration is proposed for enteric viruses in drinking water. Instead, the

supporting document recommends the use of a multi-barrier approach, including source protection and water treatment, to reduce exposures to enteric viruses in drinking water. Routine water quality monitoring for *E. coli* is also important as the presence of *E. coli* is an indication that enteric viruses could also be present. However, because enteric viruses are more resistant to disinfection, the absence of *E. coli* does not necessarily mean that enteric viruses are also absent” (CDW, 2004a).

In the United States, the US EPA has promulgated the Surface Water Treatment Rule to control the presence of viruses...in public drinking water systems using surface water and groundwater under the influence of surface water. Under the rule, a public water system...must use filtration unless it meets certain water quality, operational and public health standards. It is assumed that filtration removes at least 90 per cent (1 log) of viruses and that disinfection provides a further 99.9 per cent (3 log) inactivation. Similar regulations are in place in Alberta (1997), Quebec (2001) and Saskatchewan (2002) (CDW, 2004a).

9.1.3 Protozoa

The removal and inactivation of *Giardia* cysts and *Cyptosporidium* oocysts from raw water are complicated by their small size and resistance to commonly used oxidants such as chlorine. The *Guidelines for Canadian Drinking Water Quality, Supporting Documentation: Protozoa* (CDW, 2004b) notes that for these contaminants

the multiple-barrier approach to treatment, including watershed or wellhead protection, optimized filtration and disinfection, a well-maintained distribution system, and monitoring treatment effectiveness (e.g., turbidity, disinfection residuals, etc.) is by far the best approach to reduce the risk of infection to acceptable or non-detectable levels. In communities where filtration is not economically feasible, an effective watershed protection plan, adequate disinfection, an intact distribution system, and possibly recognized point-of-entry or point-of-use treatment must be relied upon to reduce these risks (CDW, 2004b).

The *Supporting Documentation: Protozoa* explains that filtration with the aid of coagulation/flocculation, followed by disinfection, is the most practical method to achieve high removal/inactivation rates of cysts and oocysts. One study showed that 99.998 per cent of *Giardia* cysts and *Cyptosporidium* oocysts were removed from heavily polluted water by full conventional treatment (flocculation, settling, pre- and post-disinfection with chlorine dioxide and chlorine, and filtration). Chlorination alone does not appear practical for the inactivation of *Cryptosporidium*. Work carried out by Finch, Gryurek, Lyanage, and Belosevic (1997) has shown that ozonation may be effective when used properly. These authors also demonstrated that the use of two disinfectants sequentially gave better results than previously believed and can inactivate *Cryptosporidium* oocysts by up to 1.6 log. Chlorine following ozone or chlorine dioxide was particularly effective. Also, “UV light disinfection is an emerging (alternative) treatment approach that appears to be highly effective...” (CDW, 2004b)

The *Supporting Documentation: Protozoa* (CDW, 2004b) includes an extensive bibliography with 273 citations on these contaminants, their health effects, prevalence, control measures used in other countries and studies on the effectiveness of a range of treatment approaches.

9.2 Physical and Chemical Quality

WHO Guidelines (2004) note that “there has been increasing recognition that only a few key chemicals cause large-scale health effects through drinking water exposure. These include fluoride and arsenic. Other chemicals such as lead, selenium and uranium may also be significant under certain conditions.” International and Canadian guidelines also cover a wide variety of physical characteristics and chemical substances that have the potential to cause unsafe drinking water. Two of the major challenges experienced in BC are discussed in this section.

9.2.1 Turbidity

The *Guidelines for Canadian Drinking Water Quality, Supporting Documentation: Turbidity* (CDW, 2003) notes that

waterworks systems that use a surface water source or a groundwater source under the direct influence of surface water should filter the source water to meet the following health-based turbidity limits. Where possible, filtration systems should be designed and operated to reduce turbidity levels as low as possible, with a treated water turbidity target of less than 0.1 NTU (nephelometric turbidity units) at all times. Where this is not achievable, filtration effectiveness should be (by type of technology):

- less than or equal to 0.3 NTU for chemically assisted filtration.
- 1.0 NTU for slow sand or diatomaceous earth filtration.
- 0.1 NTU for membrane filtration.

Turbidity is easy and inexpensive to measure. In addition to being an indicator for determining the relative safety of drinking water, it is a useful tool for assessing the performance of water treatment processes. “The best means of reducing turbidity and safeguarding a drinking water supply is to apply a multiple-barrier approach to protect drinking water.... Treatment plans can reduce turbidity by filtering particles out of the water. All filtration systems should be designed and operated to reduce turbidity levels as low as possible” (CDW, 2003).

“The municipal water system in Kamloops is subject to times of high turbidity, up to 500 NTU. The source is probably increased silt and debris in the South Thompson River, which feeds the town’s water intake” (PHO, 2001). The local medical health officer (MHO) conducted a study and found that visits to local physicians for gastrointestinal complaints were associated with increases in water turbidity. The MHO issued orders to the city to reduce the level of contamination and risk level for residents. The city had an automatic water quality advisory in times of high turbidity, and the local media routinely reported turbidity levels. Turbidity advisories, along with streamside protection measures in the watershed, coincided with a decrease of 19 per cent in physician office visits for intestinal illness in Kamloops (PHO, 2001). The City of Kamloops subsequently built a water filtration plant to further protect its residents,

and the rate of intestinal illness was further reduced by 10 per cent following its implementation. Supporting data from the Medical Services Plan clearly supported the evidence linking high turbidity levels and gastrointestinal-related complaints.

The Interior Health Region “4-3-2-1-0” objectives are considered by BC experts as an important best practice in areas with elevated turbidity.

The US EPA conducted a review of studies on the relationship between turbidity levels and pathogen rates. The results are described in Appendix 2.

9.2.2 Arsenic

Arsenic in groundwater has become recognized as a problem in BC and the Western United States during the last couple of decades, as noted in Part I of this paper. The maximum acceptable concentration for arsenic in drinking water is 0.010 mg/L based on municipal- and residential-scale treatment achievability (CDW, 2006a).

The selection of an appropriate treatment process for a specific water supply will depend on the characteristics of the raw water supply and many other factors. It is important to determine what, if any, pre-treatment is required. Because arsenic is a human carcinogen, every effort should be made to maintain levels in drinking water as low as reasonably achievable (CDW, 2006a).

Arsenic can be effectively treated in municipal-scale treatment facilities through a number of well-documented methods. The technologies available are discussed in the *Guidelines for Canadian Drinking Water Quality: Guideline Technical Document. Arsenic* (CDW, 2006a), which also provides an extensive bibliography. It is noted that “the most practical municipal-scale technologies for the removal of arsenic include coagulation/filtration, lime softening, activated alumina, ion exchange, reverse osmosis, and manganese greensand filtration” (CDW, 2006a). The US EPA has also identified electro dialysis reversal as a best available technology for arsenic removal. “Removal efficiency can be very good for some of these technologies; however manganese greensand filtration and electro dialysis reversal usually achieve lower removal rates.” (CDW, 2006a).

“Certified residential treatment devices are commercially available to remove arsenic below the Canadian maximum acceptable concentration” (CDW, 2006a).

The US EPA tightened the standard for arsenic in the United States from 50 parts per billion (ppb) to 10 ppb, effective January 2006. The State of Washington adopted this rule in January 2004.

9.2.3 Nitrate/Nitrite

The *Guidelines for Canadian Drinking Water Quality, Supporting Documentation: Nitrate/Nitrite* (CDW, 1987) specify that “the maximum acceptable concentration for nitrate in drinking water is 45 mg/L. (in cases where nitrite is measured separately from nitrate, the concentration of nitrite should not exceed 3.2 mg/L)”. Although most municipal water supplies

have generally low levels of nitrates, they can be higher in heavily-farmed areas. A 1992 Environment Canada survey of groundwater in the Fraser Valley found “60 per cent of wells (450 samples in 125 locations), were found to have nitrate levels exceeding 45 mg/L.... Concentrations of nitrate in BC groundwater appear to have gradually increased between 1975 and 1990 because of increased population and intensive agricultural use” (Liebscher, Hii, & McNaughton, 1992).

Treatment technologies for removing nitrates and nitrites from drinking water include ion exchange and reverse osmosis.

In one full-scale ion exchange plant, the nitrate concentration was reduced from 16 to 2.6 mg/L. Other treatment methods such as biological denitrification and electro dialysis have also been suggested. Nitrite is normally rapidly oxidized to nitrate in the presence of oxygenated water, and the removal of nitrite may be facilitated by the addition of oxidation agents, if required (CDW, 1987).

9.2.4 Disinfection By-Products

The addition of chlorine as a disinfectant to water supplies over the last century has dramatically reduced the rates of illness and death caused by water-borne pathogens. While the health benefits have been enormous, there has been concern in recent years about the by-products that may harm human health. By-products are created when chlorine reacts with dissolved organic material. A number of studies have raised suspicions that exposure to disinfection by-products over many years may elevate the risk of developing cancer, particularly bladder cancer (PHO, 2001).

Concentrations of disinfection by-products can be considerably reduced by pre-treatment of the water through sedimentation or coagulation to remove dissolved organic carbon from the water, or by filtration (PHO, 2001).

10.0 DISTRIBUTION SYSTEM

The Canadian document *From Source to Tap*, notes that

Water transmission and distribution mains are also a vital component of the waterworks system to ensure safe delivery of drinking water. To ensure water transmission and distribution mains do not adversely affect the quality of the water being conveyed, standards and guidelines have been established for pipe sizing, material, layout and burial. Cross-connection control and disinfection are also important. In establishing standards and guidelines for water transmission and distribution mains, the principal intent is to protect against contamination. In this regard, it is important for the standards and guidelines to be based on both good engineering practices and on standards and guidelines that have either been set by standards/guidelines-developing agencies/associations such as the Canadian Standards Association, the American Water Works Association, or the NSF (a non-for-profit NGO which develops standards in public health and safety, often for the American National Standards Institute) (CDW & CCME, 2004).

From Source to Tap (CDW & CCME, 2004) describes the range of considerations that should be included in assessing a water distribution system. These include:

- Design and layout.
- Secondary disinfection.
- Fire flows and hydrants.
- Frost protection.
- Cross-connection controls.
- Horizontal separation of water mains and sewers.
- Backflow prevention and control.
- Plumbing.
- Potable water storage.
- Disinfection of mains and reservoirs.

Appendices in *From Source To Tap* discuss specific issues and procedures for dealing with flushing and pipe cleaning, inspecting and maintaining valves and hydrants, locating and re-mediating line breaks, processes for detecting leaks, measurement instruments, alarms, status indicators, etc.

It should be noted that the recommendations from *From Source To Tap*, summarized above, are strongly reflected in water quality literature, including the WHO, and the Australian and New Zealand guidelines.

11.0 OPERATIONAL MONITORING AND CONTROL SYSTEMS

11.1 Operational Procedures

The Australian Guidelines note the importance of documentation and recommend that an operational manual include descriptions of: preventive measures and their purpose; operational procedures for relevant activities; operational monitoring protocols, including parameters and criteria, schedules and timelines; data and records management requirements; corrective actions to be implemented; maintenance procedures, responsibilities and authorities; and internal and external communication and reporting requirements (Australian Government, 2004).

New Zealand's Draft Guidelines also discuss the need for water systems to document policies, objectives, and procedures. A manual is required to include descriptions of the processes that contribute to a quality system including:

- Work instructions – Specific tasks that are necessary to control the quality of the process including: procedures; qualifications/experience necessary for authorization to undertake a task; processes for checking that work has been completed correctly; processes for reviewing, authorizing, distributing and updating the work instructions, etc.
- Supporting documentation – Manufacturers' manuals, reference standards and operating manuals.
- Records that demonstrate the system is working correctly – Maintenance records, results of tests and measurements, internal audits, relevant correspondence (New Zealand Ministry of Health, 2005).

Although clear operation systems are desirable, a cautionary note is offered by Hrudey and Hrudey (2004) in *Safe Drinking Water: Lessons from Recent Outbreaks in Affluent Nations*:

a management system primarily focused on monitoring specific numerical water quality targets (conventional drinking water guidelines or standards) is doomed to be reactive because data cannot be obtained in real time for most parameters. Important exceptions are process control parameters like chlorine residuals and turbidity monitoring, which can be used to provide assurance, in real time, that treatment processes are functioning as intended.

Discussion with BC experts in the field also raised cautions about over-reliance on strict procedures and processes. They note that not all water quality problems can be anticipated and that an emphasis on routines and procedures could undermine the necessary initiative required for trained staff to manage issues in a proactive manner.⁷

11.2 Operational Monitoring

In BC, regular monitoring is required under the *BC Drinking Water Protection Act* and Regulation, at specific frequencies as determined by a regional health authority drinking water

⁷ Discussion held with members of the BC Working Group on Water Quality.

officer. The conditions that require immediate reporting and public notification are set out in the legislation.

Routine reporting to a regulatory agency is typically part of the operating system approval process (CDW & CCME, 2004). *Guidance for Safe Drinking Water in Canada* (FPT on Drinking Water, 2001) notes that

Compliance monitoring should be carried out using various methods to ensure test results are accurate and reported properly. Each jurisdiction should have approval processes in place for selecting laboratories, or quality assurance/quality control programs, for routine testing of drinking water samples for all relevant substances, especially those which indicate the microbiological quality of drinking water.

Furthermore

It is imperative that clear lines of communication be established between the laboratory, the agency operating the treatment plant and the regulator, so test results which may affect public health can be dealt with in an open, timely and effective manner. Ideally, the local health officer in each jurisdiction, or his or her designated official, would be one of the first points of contact for the laboratories to report any unacceptable water quality results (FPT Subcommittee on Drinking Water, 2001).

The WHO and Australian Guidelines note the “key elements of operational monitoring include:

- Development of operational monitoring plans from catchment to consumer, detailing strategies and procedures.
- Identification of the parameters and criteria to be used to measure operational effectiveness, and where necessary, trigger immediate short-term corrective actions.
- Ongoing review and interpretation of results to confirm operational performance (Australian Government, 2004).

Operational parameters should be selected that reflect the effectiveness of each process or activity, and provide an immediate indication of performance. Typically, operational monitoring should focus on parameters that can be readily measured and enable a rapid response. To fulfill these requirements, surrogates are often used as operational parameters rather than direct measurement of the hazards themselves. For example, turbidity may be used as a surrogate for *Cryptosporidium* and *Giardia*... Online and continuous monitoring should be used where possible, particularly at critical control points (Australian Government, 2004).

The WHO and Australian Guidelines further suggest that “once operational parameters are identified, target criteria (performance goals) should be established for each preventive measure”

(Australian Government, 2004). Critical limits must be defined and validated for the critical control points throughout the water system.

A critical limit is a prescribed tolerance that distinguishes acceptable from unacceptable performance at a critical control point. Any deviation of performance from established targets should result in appropriate action to resolve potential problems...Setting target criteria that are more stringent than critical limits for critical control points, will enable corrective actions to be instituted before an unacceptable health risk occurs (Australian Government, 2004).

When critical limits are exceeded, correction action is immediately required and the health regulator must be notified (Australian Government, 2004).

Hrudey and Hrudey (2004) note the difficulty of relying on monitoring as a primary means of prevention, pointing out that many of the tools available for monitoring drinking water quality are not currently able to monitor fecal indicators or pathogens in “real-time”. In most cases, the tools yield results many hours, if not days, after sampling, and consumers will already have been exposed to pathogens. As well, sampling typically represents a miniscule factor of the water, and since fine particles and associated pathogens are not distributed uniformly, the test results may not be accurate. To overcome some of these problems, the *Cryptosporidium* monitoring regulation for England and Wales now requires continuous sampling.

The WHO has published extensive supporting literature on monitoring processes, including selection of operational monitoring parameters, operational and critical limits, verification processes for a range of sources and systems and quality assurance and quality control measures.⁸

11.3 Corrective Action

Appropriate procedures should be developed for immediate corrective action that is required to re-establish process control following failure to meet target criteria or critical limits. The procedural manuals should include instructions on required adjustments, process control changes and additional monitoring. Responsibilities and authorities, including communication and notification requirements, should be clearly defined. Following implementation of a corrective action, effectiveness of the action will need to be verified, and secondary impacts should be considered (Australian Government, 2004).

The WHO Guidelines note that much of a management plan will describe actions to be taken in response to “normal” variations in operational monitoring parameters in order to maintain optimal operation. A significant deviation in operational monitoring, where a critical limit is exceeded, is often referred to as an “incident”. Incident response plans have a range of alert levels, from minor early warning, through to emergency plans. These are discussed in Section 5.5.

⁸ More information on the WHO’s supporting literature can be found at http://www.who.int/water_sanitation_health/dwg/gdwq3/en.

12.0 REGULATORY OVERSIGHT

Drinking water officers in BC have the authority under the *BC Drinking Water Protection Act* and Regulation to approve construction and operating permits, to conduct monitoring, inspections, investigations and reporting, as well as to take preventive and remedial action. Specific conditions, processes and procedures are outlined in the legislation and further articulated in the *BC Drinking Water Officers' Guide*. The legislation is outcome-based and allows for discretionary decision-making by drinking water officers.

A literature review yielded little information on effective approaches in regulating drinking water suppliers. However, several sources may prove helpful in assessing appropriate measures. First, a recent survey of drinking water practices of Canadian public health agencies, by Jalba and Hrudey (2006), describes some of the current problems and points to solutions. Second, descriptions of general regulatory approaches related to controlling risks may be useful in considering the healthy authority's oversight role in drinking water quality.

Jalba and Hrudey (2006) conducted a survey and interviews with public health agencies across Canada about their role, the challenges in assuring drinking water safety, and the most common public health actions taken in this field. Respondents perceived their primary role to be as follows: 74 per cent considered enforcement of regulations/standards and follow-up on adverse results to be primary; 48.6 per cent considered the inspection of small, unregulated water plants and advising operators to be most important; and 15 per cent perceived their primary role as assuring safe drinking water. Many problems were identified including: drinking water has a low priority among health issues, which is often reflected in limited resources and a lack of specialized staff; the absence of specific safe water legislation and/or standards of best practices; small drinking water operations face serious obstacles such as limited funding, high costs per capita, the absence of trained operators and lack of awareness among consumers; old treatment and distribution infrastructure affects many small systems, as well as some medium and large systems, etc.

Overall, the authors conclude that, "except for a few regional initiatives, public health agencies still tend to play a largely reactive role in assuring drinking water safety. Public health professionals should be supported and trained to participate in a truly proactive, upstream prevention approach to drinking water safety" (Jalba & Hrudey, 2006). They propose that risk management principles be adopted as a first step in a proactive preventive approach that includes: involvement of stakeholders in developing non-regulatory risk management approaches; recognition of drinking water operators as public health professionals and empowerment of them to become more proactive and effective; and elevation of small drinking water systems to the same safety standards as large systems, to ensure equity among all citizens regarding a basic human need (Jalba & Hrudey, 2006).

BC's drinking water legislation is performance-based, with a focus on outcomes. The literature on regulatory oversight notes that many jurisdictions are moving toward this approach from rules-oriented, prescriptive legislation. This shift has taken place in many Canadian provinces, the United Kingdom, American States, and Australia. Although performance-based legislation aims to specify the intended outcomes and allow the providers to decide how to achieve them, it

is often balanced with some minimum requirements. It is not uncommon to find performance-based legislation accompanied by: acceptable solutions, which will ensure that the provider meets the performance criteria; best practice guidance that provides advice on complying with regulatory requirements; and/or minimum standards that must be met by the regulated. Performance-based legislation is seen as advantageous as it provides an opportunity for greater flexibility and encourages innovation in achieving desired outcomes.

Walshe (2003) points out that although there is little empirical evidence that identifies what constitutes effective regulation, the UK Better Regulation Unit promulgated five principles of good regulations, synthesized from their experience in reviewing regulatory arrangements. These are: transparency, accountability, targeting, consistency and proportionality. Although “these might appear to be self-evident.., they have been influential in shaping ideas internationally about the nature and characteristics of effective regulation.”

Ten dimensions or factors that are characteristic of effective regulation practices in health care are identified in Walshe (2003). These were based on empirical evidence on American health care regulation, and took into account both the ideas of responsive regulation and the work of the UK Better Regulation Unit. They are:

- An improvement focus – Improvement is a primary objective.
- Responsiveness – Adaptable to individually regulated organizations depending on their response and behaviour, with access to a range of different detection and enforcement mechanisms.
- Proportionality and targeting – Focus on areas where performance problems are known or suspected, and interventions are appropriately matched to the size and importance of the problems or issues.
- Rigour and robustness – Decisions are developed through a rigorous process, based on available evidence, and tested for validity and reliability in use.
- Flexibility and consistency – Sufficiently flexible to allow discretion in responding to situations, while also ensuring consistency.
- Cost-consciousness – Costs and benefits to the regulatory agency, and to regulated organizations, are calculated and taken into account.
- Openness and transparency – Information on the regulatory process, and on findings, is easily available to stakeholders and the public.
- Enforceability – The regulator has access to a wide range of incentives and sanctions to secure change.
- Accountability and independence – There are mechanisms for holding the regulator accountable for its actions to patients, the public, funders, providers and policy-makers, while also ensuring independent decision-making on the part of the regulator.

- Formative evaluation and review – Systems are in place to monitor and evaluate regulation systems and their impact.

With respect to non-compliance, the Brookings Institute monograph *Regulatory Craft: Controlling Risks, Solving Problems, and Managing Compliance* (Sparrow, 2000), Sparrow conceptualizes graduated responses to non-compliance in the form of a pyramid. Rather than a continuum, Sparrow discusses a hierarchy of responses and a balance among them, “wherein the softer approaches (at the base of the pyramid) are employed more frequently, and the tougher sanctions (at the apex) are applied, but applied least often.” The enforcement sanctions (starting at the bottom of the pyramid) are:

- Persuasion.
- Warning letter.
- Civil penalty.
- Criminal penalty.
- License, or permit, suspension.
- Licence, or permit, revocation.

13.0 OPERATOR AWARENESS AND TRAINING

In BC, the qualification standards for persons operating water supply systems are addressed in the *Drinking Water Protection Act*. Water operators operating or maintaining a level 1 through 4 water treatment or distribution system must be certified by the Environmental Operators Certification Program as certified operators at the appropriate level, prior to being able to operate the given system. Most provinces and territories now require drinking water treatment plant operators to be certified and to maintain their waterworks education requirements.

It is widely acknowledged that operator training is an important best practice in ensuring safe drinking water. As stated in *From Source to Tap* (CDW & CCME, 2004), “the successful operation of any drinking water supply system—from private wells to managing large watersheds or complex treatments plants servicing large cities—depends on the skills, abilities, and knowledge of the responsible owners and employees.” Similarly, the US EPA notes that “ensuring the knowledge and skills of public water system operators is widely considered one of the most important, cost-effective means to strengthen drinking water safety” (US EPA, 2006). As well, the *Report of the Walkerton Inquiry* (O’Connor, 2002) notes that “Ultimately the safety of drinking water is protected by effective management systems and operating practices, run by skilled and well-trained staff.”

Although the level of knowledge required by a homeowner regarding their individual well will differ from a member of a source water protection committee, or a city employee operating a large plant, each needs to understand certain basic aspects of drinking water supply management...because of the complexity of the water quality issues, and because public health is at stake, it is critical that all members of a drinking water program—whether elected officials, regulators, scientific staff, utility operators or others—have appropriate levels of knowledge and understanding of the impact of their activities and decisions on the quality of the water. To this end they need access to continuing education in this field.

Training can include formal training at post-secondary institutions, water association training course, in-house training and mentoring programs, on-the-job experience in consultation with other trained operators or government specialists, workshops, seminars, courses and conferences. Operator certification ensures that operators are appropriately trained to the level required for the system they are responsible for... Because training is an ongoing process, employee training needs to be a continuous commitment (CDW & CCME, 2004)

When the United States *Safe Drinking Water Act* legislation was adopted in 1996, State programs were required to have two main components:

- Legal authority to ensure that new water systems have sufficient technical, managerial and financial capacity to meet drinking water standards.
- A strategy to identify and assist existing water systems needing improvements in managerial, technical or financial capacity or aid to comply with standards.

Core Public Health Functions for BC: Evidence Review
Water Quality (Drinking Water)

States are required to identify water systems in significant non-compliance status and report to the US EPA on the success of capacity development efforts in assisting such systems. The legislation also requires all States to carry out a program of operator certification...Operators must be trained and certified to the right level that each State determines is appropriate to the functions, facilities and operations of that specific systems (US EPA, 2006).

Training programs for water suppliers are also highlighted as essential requirements in the WHO, Australian and New Zealand guidelines for safe drinking water. For example, the Australian Guidelines note that “where possible, accredited training programs and certification of operators should be employed” (Australian Government, 2004).

14.0 COMMUNICATIONS

14.1 Community Involvement

The 2000 PHO Annual Report recommended that local health officials (in collaboration with Ministry of Health) “develop information and tools to help communities make decisions about upgrading their water systems – before problems can occur” (PHO, 2001).

From Source to Tap (CDW & CCME, 2004) notes that public

awareness and involvement in the drinking water program is extremely important for achieving the program’s goals and objectives and should not be underestimated. Effective public involvement ensures stakeholders recognize and understand the drinking water program’s policies and activities. It also enhances the legitimacy of decisions made and ensures the program’s goals reflect public concerns, values and priorities.

More specifically it states

there is growing recognition that unilateral decisions on water quality issues no longer work... many utilities have found that stakeholder alliances can be an effective forum for open dialogue with potential adversaries and could:

- Improve community relations, help initiate new ideas.
- Help promote learning and understanding by all parties.
- Help protect water rights and improve supply reliability and ability to meet demand.
- Minimize liability claims.
- Help develop legislative allies.
- Help protect or enhance water quality (CDW & CCME, 2004).

Public consultation may be structured between the health authority, or water utility, and the public. The goal of consultations is to receive input and achieve a common understanding of an issue or policy in order to develop acceptable solutions. Consultation can be done in person through steering committees, advisory groups, and task groups, or more informally through the solicitation of comments or feedback on documents provided to interested parties. It is important that water utilities learn to work with other groups concerned with or who could potentially impact water-related decisions, especially if systems are going to meet future challenges such as increased demands for water, cleaner water and adequate infrastructure” (CDW & CCME, 2004).

Other forms of public involvement may include: direct involvement of stakeholders in planning committees; involvement in general public informational meetings or community events such as demonstration projects. Educational initiatives such as resource materials, seminars, workshops

and speakers can facilitate informed involvement and encourage community dialogue (CDW & CCME, 2004).

The WHO, Australian and New Zealand guidelines also stress the importance of public involvement. The WHO (2004) explains that “experience has shown the necessity of recognizing the important roles of many different stakeholders in ensuring drinking water safety.” The Australian Guidelines note that decisions made by a drinking water supplier and the regulatory authorities must be aligned with the needs and expectations of consumers: “discussions should include the establishment of levels of service, costs, existing water quality problems and the options for protection and improvement of drinking water quality, including constraints on land use and changes in treatment or infrastructure” (Australian Government, 2004).

14.2 Public Education

From Source to Tap (CDW & CCME, 2004) advises that

involving the media during the development of initiatives can assist the process in a variety of ways. In addition to helping inform stakeholders and the public and increasing public involvement, the media can play a role in encouraging community support and communicating the value of source water protection.

Public education can increase awareness of drinking water quality issues by:

informing the public about its impact on source water quality and about available pollution mitigation measures; informing the public about health risks and by providing education material on issues such as water disinfection, guidelines, conservation issues, and costs of providing services; and issuing regular reports about drinking water systems, including improvements and areas that need further attention (CDW & CCME, 2004).

In the United States, the *Safe Drinking Water Act* (1996) also highlights the importance of public involvement in safe drinking water, founded on the idea that “the understanding and support of the public will be vital to address and prevent the growing threats to drinking water quality in the years ahead” (US EPA, 2006).

The WHO, Australian and New Zealand guidelines all note the importance of educating the public on drinking water quality. For example, the Australian Guidelines (Australian Government, 2004) note that

effective communication to increase community awareness and knowledge of drinking water quality issues and the various areas of responsibility is essential. Communication helps consumers to understand and contribute to decisions about the service provided by a drinking water supplier or land-use constraints imposed in catchment areas. A thorough understanding of the diversity of views held by individuals in the community is necessary to satisfy community expectations....A coordinated consumer information program should include:

- Discussion of issues on drinking water quality, public health and risk assessment, cost of treatment and levels of service.
- Details of the water supply system and the drinking water quality management system.
- Incident and emergency response plans, including procedures for notification when drinking water quality poses a health risk.
- Consumer responsibilities and how drinking water quality may be affected in household distribution and use (e.g., use of suitable plumbing material, point-of-use treatment, prevention of backflow).
- The need for further treatment of water for special purposes.
- The role and responsibility of the community in protecting water supply catchments, and water conservation.
- Commercial and industrial consumer responsibilities (e.g., responsibility for design, maintenance, education of managers, codes of practice, etc.).

The US EPA (2006) recommends that

procedures for disseminating information to promote awareness of drinking water quality issues to the community should be established. Possible methods include annual or other periodic water quality reports, newsletters, notices in bills, workshops, seminars or briefings, media programs targeting radio and television, websites, treatment plant tours, catchment signage and school education programs. Additionally, mechanisms such as service line or a complaint handling system should be established to provide opportunities for consumers to communicate their needs and expectations.

14.3 Public Reporting

The 2000 PHO Annual Report noted that the public has the right to know the monitoring results of their drinking water and that dissemination of the information is a requirement for true public accountability for water managers. It recommended that

a) water suppliers provide the public regularly with results of chemical, physical, and microbiological monitoring of their drinking water supply and with an interpretation of the health significance of these results, with the assistance of the Medical Health Officer; and b) local health authorities make regional information on water quality and water systems available to both professionals and interested members of the public including information on what to do during boil water advisories (PHO, 2001).

This approach is becoming common practice in many other jurisdictions. *From Source to Tap* (CDW & CCME, 2004) advises that it is important to make monitoring results, or summaries,

easily available (such as on the Internet) and to relay information about what the authority is doing to address the risks.

In the United States, the federal *Safe Drinking Water Act* requires:

- Consumer confidence reports – Community water systems must prepare and mail to each customer at least annually, a report with information about the systems source water and the level of contaminants in the drinking water purveyed (newspaper notice for communities under 10,000).
- Public notice must be given within 24 hours of any violation of a national drinking water standard that has the “potential to have serious adverse effects on human health as a result of short-term exposure, and written notice of any other violations within one year.”
- Annual reports on violations by public water systems within a State must be “readily available to the public” (PHO, 2001).

New Zealand issues an *Annual Report on Quality of Drinking Water* which provides a public statement of the extent to which a community water supply complies with the requirements of the Drinking Water Standards of New Zealand. The reports are also provided on a website for easy access. (New Zealand Ministry of Health, 2005).

15.0 MANAGEMENT OF SMALL DRINKING WATER SYSTEMS

Small drinking water systems are defined in BC as systems which serve under 500 individuals during any 24-hour period. Extensive revisions to the *Drinking Water Officer's Guide* were recently made to guide how drinking water officers can consider the use of point-of-entry (POE), and point-of-use (POU) systems at individual households as an option over centralized treatment for these smaller systems.

The Australian and New Zealand (as well as WHO) guidelines discuss the management of small drinking water systems in some detail. For example, they suggest that small systems adhere to a management framework as much as possible, although it is recognized that a number of measures may not be practical or necessary. As frequent monitoring may be difficult, a preventive approach for all drinking water systems is considered especially important. Analysis of the water supply system, identification of potential hazards and risk assessment are essential. Development of a management framework, or public health risk management plan, is also emphasized, including the development of operational procedures, monitoring and corrective action plans. Detailed guidelines for small systems are described in the New Zealand Draft Guidelines with many examples to ensure the removal of contaminants and protection from further contamination (New Zealand Ministry of Health, 2005).

In the United States, legislation recognizes the often-difficult economics of small systems. The 1996 *Safe Water Drinking Act* specified the importance of technologies that comply with the standard and are affordable for groups of smaller systems. Where such technologies do not exist for a certain group of smaller systems or related source waters, a “variance” technology must be identified; it need not meet the standard, but must provide the maximum protection affordable for such groups of smaller systems and source water. States must assess whether specific changes could practicably enable a system to meet a national standard, before a “variance” is authorized. This is considered a step forward to the previous “all-or-nothing” legislation of the previous law (US EPA, 2006).

The US EPA has developed best practices guides for owners and operators of water systems serving less than 10,000 people. They are designed to help operators run sustainable systems for delivering safe drinking water. Topics include best practices for general operating procedures, maintenance of distribution systems, vital record keeping and building good working relationships with decision makers. The guides are available on the EPA website (<http://epa.gov>) or the Safe Drinking Water hotline at 800-426-9198.

The WHO notes that for households using non-piped water supplies such as private wells and rainwater, appropriate efforts are needed to ensure safe collection, storage and perhaps treatment of the drinking water. In some circumstances, households and individuals may wish to treat water in the home to increase their confidence in its safety, not only where community supplies are absent, but also where community supplies are known to be contaminated or causing water-borne disease. Guidance from public health, surveillance and/or other local authorities is often required “to support households and individual consumers in ensuring the safety of their drinking water. Such guidance is best provided in the context of a community education and training programme” (WHO, 2004).

16.0 RESEARCH AND DEVELOPMENT

Growing demands on drinking water quality and quantity are creating an urgent need to link research from a wide range of sources in order to improve drinking water quality from source to tap. Existing uncertainties in the drinking water field can only be overcome by a greater scientific understanding of issues. This understanding is normally attained through research and development which enhances our understanding of threats to water supplies... In addition, it is recognized that investment in prevention will always be far less costly than remediation of problems or dealing with situations of irreversible harm... It is important for regulators, consultants, facility operators, and other stakeholders to commit to continually bettering the information and knowledge-base on water treatment processes and hazards, new processes and emerging issues, improved analytical methodologies, the relationship between water quality and health outcomes, and local water quality and treatment data gathering. Government needs to actively participate with institutional and public sector researchers and monitor the results of research to ensure priorities are being met (CDW & CCME, 2004).

The 2000 PHO Annual Report made a number of recommendations related to research and evaluation, including:

- Carry out further research into public health impacts of watersheds and groundwater sources.
- Review the implications of the final report of the Walkerton inquiry for improving the quality of drinking water in BC.
- Establish a mechanism to assess the long-term effectiveness of BC's drinking water activities and evaluate the need for changes to be made (PHO, 2001).

It is also generally recognized that additional monitoring and surveillance is required to support the research and development process. For example, the BC Centre for Disease Control is currently conducting a surveillance study through a grant from the Canadian Institute for Health Information. The study is entitled *Safe Drinking Water through Source Surveillance: Assessing Impacts of Environmental Factors and Microbial Contamination of Watershed on Community Health*.⁹

⁹ Study in progress by Dr. Judy Isaac-Renton, BC Centre for Disease Control, through a CIHI grant

17.0 CONCLUSION

17.1 Part I

With the exception of at-home devices, there were no scientific studies found that examined the effectiveness of interventions on reducing enteric illness.

Several water treatment interventions set in place following the outbreaks in BC in 1996, proved successful in reducing rates of intestinal illness. Since a large percentage of British Columbians obtain their drinking water from surface water, which is vulnerable to contamination by parasites such as *Cryptosporidium* and *Giardia*, any measures that reduce the likelihood of exposure to these pathogens would be in the best interest of public health. These interventions include filtration and the issuance of turbidity advisories. Although there is not enough evidence to recommend the implementation of these measures at all water systems, any watersheds that are at a high risk of contamination by wildlife and developmental activities may benefit from filtration and turbidity advisories.

With the large number of water systems in existence, it is probable that interventions for source water, water treatment and distributions systems have been set in place. The effect of these interventions on rates of enteric illness has never been published. There is a very large amount of information to be gathered from the grey literature that deals with the safety of drinking water. Collecting this information will require contacting water system managers and public health officials in various communities. A coordinated effort is needed to ensure that future research on drinking water safety is available to interested parties.

17.2 Part II

Recently released recommendations and guidance from international agencies such as the World Health Organization and the International Water Association, highlight the importance of a management framework and comprehensive water safety planning, in particular risk assessment and risk management. The emphasis on these measures is reflected strongly in guidelines newly developed, or at a draft stage, by the governments of Australia and New Zealand. This quality management approach is presented as an important framework for managing and ensuring safe drinking water.

A multi-barrier approach is a fundamental “best practice”, repeatedly recommended in the literature, by experts in the field and reflected in the statutes and advice of leading jurisdictions in water quality (e.g., the WHO, International Water Association, Canada, the US EPA, Australia and New Zealand). A multi-barrier system provides a preventive, integrated approach to reduce risk of contamination at key points in the water supply system: source water protection, treatment and distribution. Monitoring continues to be key protective barrier, but rather than relying on the traditional approach of compliance monitoring alone, the multi-barrier system minimizes the likelihood of contaminants passing through the entire system and being present in sufficient amounts to cause harm to consumers before they are detected.

Additional preventive measures are highlighted in the literature and practices of other jurisdictions. These include the importance of public education and consultation, as well as

strengthened surveillance, research and evaluation strategies. The importance of additional research on effective planning, management and oversight of drinking water systems is particularly relevant, given the gaps in current evidence. A major challenge for many jurisdictions is safeguarding water supplies for small communities and rural populations. Approaches taken by other jurisdictions are noted for consideration.

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Core Public Health Functions for BC: Evidence Review
Water Quality (Drinking Water)

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APPENDIX 1: BRITISH COLUMBIA DRINKING WATER ROLES AND RESPONSIBILITIES

The BC *Drinking Water Protection Act* and Regulation set out the requirements for safe drinking water in the province. The *Drinking Water Officers' Guide* (BC Drinking Water Leadership Council 2006) provides guidance on monitoring water quality, advising/supporting water suppliers and enforcing the legislation.

The roles and responsibilities of the Ministry of Health, health authorities and water suppliers are as follows:

- The Ministry of Health has responsibility for: advising the Minister on policies and legislation; coordinating the development of plans and strategies with health authorities to improve water quality practices; and facilitating collaborative partnerships with other provincial ministries, the federal government and Federal/Provincial/Territorial forums. The Provincial Health Officer has an oversight role and is responsible for ensuring accountability in fulfilling the legal requirements for water quality.
- The Provincial Health Services Authority is responsible for surveillance, knowledge transfer and research, on water quality. In particular, the BC Centre for Disease Control provides: technical guidance; advice on drinking water legislation, quality assurance working groups; epidemiological surveys; analysis and interpretation of microbiological samples; approval of laboratories, and public awareness materials on water issues.
- The regional health authorities' role (the responsibility of the medical health officer for safe water is mandated by legislation), includes: advising municipalities and water suppliers on appropriate prevention, maintenance and quality improvement measures for local water supplies; advocacy with government and community partners to increase the safety and protection of water supplies on a local and regional level; public education to raise awareness about safe water and water quality risks; and surveillance, monitoring and enforcement of water quality standards.
- Local governments have direct responsibility for the development and operation of water treatment and water supply systems. In rural areas, there are a variety of approaches ranging from: a local improvement area may manage a small water system for the area, private individuals (over 5 people) may incorporate as a "water user community", or private utilities may provide services to new developments. Construction permits and operating permits are issued by the health authorities for local water supplies.

In 2002, the BC government adopted *An Action Plan for Safe Drinking Water in British Columbia* (Ministry of Health 2002), which highlighted a commitment to a multi-faceted and multi-agency approach to the protection of drinking water quality. A Memorandum of Understanding (MOU) was established in October 2006 to formalize plans for accountability and coordination among key provincial ministries (i.e., Ministries of Health; Energy, Mines and Petroleum Resources; Environment; Community Services; Forests, Range and Housing; and Transportation), and the health authorities. The MOU specifies the respective roles and accountabilities based on guiding principles including: constructive working relationships,

Core Public Health Functions for BC: Evidence Review
Water Quality (Drinking Water)

proactive initiatives, information sharing, respect for mandates, partnerships, efficiency and practicability. A key feature of the MOU is establishment of regional drinking water teams with representation from each agency that is party to the agreement and local governments, to be coordinated by a health authority drinking water officer.

APPENDIX 2: STUDIES ON TURBIDITY

A review of the relationship between turbidity and disease outbreaks was conducted by the United States Environmental Protection Agency (US EPA). The following tables are from the EPA Guidance Manual for Compliance with the Interim Enhanced Surface Water Treatment Rule: Turbidity Provisions (US EPA 1999). The material in this appendix is taken from Chapter 7: “Importance of Turbidity.”

Table 7-1 displays several instances of past outbreaks of cryptosporidiosis in systems using surface water as a source, along with general information about the plant and turbidity monitoring. In three out of four of the cases displayed in the table (Milwaukee, Jackson County, and Carrollton), turbidity over 1.0 NTU was occurring in finished water during the outbreaks.

Table 7-1. Cryptosporidium Outbreaks vs. Finished Water Turbidity

Location of Outbreak	Year	General Plant Information	Turbidity Information
Las Vegas, Nevada (CDC, 1996)	1993-1994	No apparent deficiencies or problems with this community system; SWTR-compliant; system performed pre-chlorination, filtration (sand and carbon), and filtration of lake water; outbreak affected mostly persons infected with the human immunodeficiency virus (HIV).	The raw water averaged 0.14 NTU between January 1993 and June 1995, with a high of 0.3 NTU; the maximum turbidity of finished water during this time was 0.17 NTU.
Milwaukee, Wisconsin (CDC, 1996, Logsdon, 1996)	1993	Community system; SWTR-compliant; however, deterioration in source (lake) raw-water quality and decreased effectiveness of the coagulation-filtration process.	Dramatic temporary increase in finished water turbidity levels; reported values were as high as 2.7 NTU (turbidity had never exceeded 0.4 NTU in the previous 10 years).
Jackson County, Oregon (USEPA, 1997)	1992	Poor plant performance (excessive levels of algae and debris); no pre-chlorination before filtration.	Earlier in the year when outbreak occurred, filtered water had averaged 1 NTU or greater.
Carrollton, Georgia (USEPA, 1997, Logsdon, 1996)	1987	Conventional filtration plant; sewage overflowed into water treatment intake, followed by operational irregularities in treatment; filters were placed back into service without being backwashed.	Filtered water turbidity from one filter reached 3 NTU about three hours after it was returned to service without being washed.

The Relationship Between Turbidity Removal and Pathogen Removal

Low filtered water turbidity can be correlated with low bacterial counts and low incidences of viral disease. Positive correlations between removal (the difference between raw and plant effluent water samples) of pathogens and turbidity have also been observed in several studies. In fact, in every study to date where pathogens and turbidity occur in the source water, pathogen removal coincides with turbidity/particle removal (Fox, 1995).

Core Public Health Functions for BC: Evidence Review
Water Quality (Drinking Water)

As an example, data gathered by LeChevallier and Norton (1993) from three drinking water treatment plants using different watersheds indicated that for every log removal of turbidity, 0.89 log removal was achieved for the parasites *Cryptosporidium* and *Giardia*.... Of course, this exact relationship does not hold for all treatment plants. Table 7-2 lists several other studies in addition to LeChevallier and Norton's, and their conclusions on the relationship of turbidity to protozoan removal.

Table 7-2. Studies on the Relationship between Turbidity Removal and Protozoa Removal

Reference/Study	Discovery/Conclusion on Turbidity
Patania et al. 1995*	Four systems using rapid granular filtration, when treatment conditions were optimized for turbidity and particle removal, achieved a median turbidity removal of 1.4 log and median particle removal of 2 log. The median cyst and oocyst removal was 4.2 log. A filter effluent turbidity of less than 0.1 NTU or less resulted in the most effective cyst removal, by up to 1.0 log greater than when filter effluent turbidities were greater than 0.1 NTU (within the 0.1 to 0.3 NTU range).
Nieminski and Ongerth 1995*	<u>Pilot plant study</u> : Source water turbidity averaged 4 NTU (maximum = 23 NTU), achieving filtered water turbidities of 0.1-0.2 NTU. <i>Cryptosporidium</i> removals averaged 3.0 log for conventional treatment and 3.0 log for direct filtration, while <i>Giardia</i> removals averaged 3.4 log for conventional treatment and 3.3 log for direct filtration. <u>Full scale plant study</u> : Source water had turbidities typically between 2.5 and 11 NTU (with a peak level of 28 NTU), achieving filtered water turbidities of 0.1-0.2 NTU. <i>Cryptosporidium</i> removals averaged 2.25 log for conventional treatment and 2.8 log for direct filtration, while <i>Giardia</i> removals averaged 3.3 log for conventional treatment and 3.9 log for direct filtration.
Ongerth and Pecoraro 1995*	Using very low-turbidity source waters (0.35 to 0.58 NTU), 3 log removal for both cysts were obtained, with optimal coagulation. (With intentionally suboptimal coagulation, the removals were only 1.5 log for <i>Cryptosporidium</i> and 1.3 log for <i>Giardia</i> .)
LeChavallier and Norton (in Craun 1993)	Data gathered from three drinking water treatment plants using different watersheds indicated that for every log removal of turbidity, 0.89 log removal was achieved for <i>Cryptosporidium</i> and <i>Giardia</i> .
Nieminski 1992	A high correlation ($r^2=0.91$) exists between overall turbidity removal and both <i>Giardia</i> and <i>Cryptosporidium</i> removal through conventional water treatment.
Ongerth 1990	<i>Giardia</i> cyst removal by filtration of well-conditioned water results in 90 per cent or better turbidity reduction, which produces effective cyst removal of 2-log (99 per cent) or more.
LeChavallier et al. 1991*	In a study of 66 surface water treatment plants using conventional treatment, most of the utilities achieved between 2 and 2.5 log removals for both <i>Cryptosporidium</i> and <i>Giardia</i> , and a significant correlation ($p=0.01$) between removal of turbidity and <i>Cryptosporidium</i> existed.
LeChavallier and Norton 1992*	In source water turbidities ranging from 1 to 120 NTU, removal achieved a median of 2.5 log for <i>Cryptosporidium</i> and <i>Giardia</i> at varying stages of treatment optimization. The probability of detecting cysts and oocysts in finished water supplies depended on the number of organisms in the raw water; turbidity was a useful predictor of <i>Giardia</i> and <i>Cryptosporidium</i> removal.
Foundation for Water Research 1994*	Raw water turbidity ranged from 1 to 30 NTU, and <i>Cryptosporidium</i> removal was between 2 and 3 log. Investigators concluded that any measure which reduces filter effluent turbidity should reduce risk from <i>Cryptosporidium</i> .
Hall et al. 1994	Any measure which reduces filtrate turbidity will reduce the risk from <i>Cryptosporidium</i> ; a sudden increase in the clarified water turbidity may indicate the onset of operational problems with a consequent risk from cryptosporidiosis.

Core Public Health Functions for BC: Evidence Review
Water Quality (Drinking Water)

Reference/Study	Discovery/Conclusion on Turbidity
Gregory 1994	Maintaining the overall level of particulate impurities (turbidity) in a treated water as low as possible may be an effective safeguard against the presence of oocysts and pathogens.
Anderson et al. 1996	In a pilot plant study, the removal of particles > 2 μm was significantly related to turbidity reduction $r=0.97$ ($p<0.0001$); the removal of <i>Cryptosporidium</i> oocysts may be related to the removal of <i>Giardia</i> , $r=0.79$ ($p<0.14$); the reduction of turbidity may be related to the removal of <i>Giardia</i> cysts, $r=0.67$ ($p<0.13$) and <i>Cryptosporidium</i> oocysts ($p<0.08$)

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