

Health and environmental policy issues in Canada: the role of watershed management in sustaining clean drinking water quality at surface sources

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Abstract

Sustaining clean and safe drinking water sources is increasingly becoming a priority because of global pollution. The means of attaining and maintaining clean drinking water sources requires effective policies that identify, document, and reduce watershed risks. These risks are defined by their potential impact to human health. Health and risk are, therefore, indelibly linked because they are in part defined by each other. Understanding pathogen ecology and identifying watershed sources remains a priority because of the associated acute risks. Surface water quality changes resulting from inputs of human waste, nutrients and chemicals are associated with higher drinking water risks. Nutrient input can increase primary production and the resulting increase of organic matter results in greater disinfection by-product formation or requires greater treatment intensity. Many drinking water disease outbreaks have resulted from breaches in treatment facilities, therefore, even with greater treatment intensity poor source water quality intrinsically has greater associated health risks. Government and international agencies play a critical role in developing policy. The goal of maintaining water supplies whose availability is maximized and risks are minimized (i.e. sustainable) should be a vital part of such policy. Health risks are discussed in the context of a multi-barrier perspective and it is concluded that both passive (protection) and active (prescriptive management) management is necessary for sustainability. Canadian aboriginal water systems, British Columbian water policy and US EPA policies are given as examples. The basis for developing effective policies includes a strong reliance on sound science and effective instrumentation with careful consideration of stakeholders' interests. Only with such directed policies can the future availability of clean drinking water sources be ensured.

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1. Introduction

Nowhere does the link between human health and the environment manifest itself more strongly than our reliance on fresh clean drinking water. Management and treatment of waste generated from human activities including industrialization, agriculture, logging, and urbanization, have largely been insignificant in preventing pollution from affecting surface water quality on both local and global scales (Abu-Zeid, 1998). All levels of governments (local, provincial/state, and federal) bear the responsibility for setting policies to ensure the protection of our water resources and for providing instruments for the attainment of

these policies. The policies of governments and international agencies directly impact environmental and human health, and the economic, social and cultural facets of our lives. Water resource management should be based on our scientific understanding of health and environmental risks, associated financial costs, and societal acceptance of these risks and costs.

Canada is bestowed with an estimated 9% of the world's renewable supply of fresh water and lakes account for roughly 7.5% of its inland surface area (Can., Gov., 2001). These surface sources, for example, provide at least three quarters of British Columbian (BC) residents with their drinking water (BC Auditor General, 1999). Given its natural abundance Canadians are accustomed to water that is both plentiful and inexpensive. On a per capita basis Canadians use water at one of the highest rates in the world, while paying the least amount for it (McKanna, 2000).

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Despite having a wealth of water, drinking water sources are usually proximately located to areas they supply. Thus, impacts of industrialization, agriculture, and urbanization are closely linked to drinking water supplies. It is a critical goal to create a sustainable framework for human utilization of the environment and specifically for the protection of drinking water supplies so as to ensure human and environmental health.

Challenges toward achieving sustainable water supplies include a lack of recognition for the role of strong watershed management and discontinuity between policy makers, policy instrumentation, managers and scientists. The goal of this paper is to demonstrate the need for strong policies to direct source water management and the critical role of integrating the traditionally unique areas of policy, management, health and the environment. Given its sensitivity to both short- and long-term pollution, and its prevalence in Canada and elsewhere as a source supply, we examined health and environmental implications of policy regarding surface-sources of drinking water. Water quality is defined from a human health perspective and the major diseases and environmental risks to human health are outlined. From this perspective, Canadian and BC policies are reviewed and specific examples are given. The end of the paper builds on the requirements of sound scientific knowledge and strong policies by stressing the critical importance of effective policy instrumentation and sound risk management. We underscore the philosophy that many managers are acceding to, that drinking water quality issues need to evolve from a strict treatment-based approach (of both raw drinking water and sewage treatment) toward a watershed management approach (Aust. NHMRC, 2002). Only then can we ensure the short and long-term attainment of cost effective, high quality drinking water (Foran et al., 2000).

2. Water quality

Herein, surface-source water is defined as untreated or unfiltered (i.e. raw) water from lakes, streams, and rivers that water utilities or individuals use for drinking. Finished water is that which is delivered to consumers after receiving treatment. Usually, minimum treatment includes disinfection. Quality drinking water is ultimately defined as that which is safe for drinking and cooking (Gadgil 1998). Subjectivity associated with such a holistic definition has led to the functional separation of water quality into three measurable criteria; (1) water free of disease causing organisms, (2) water with harmful chemicals below defined thresholds and physical parameters within acceptable ranges, and (3) water with radioactive compounds below defined thresholds (Health Canada, 1996). Other sub-classifications can include aesthetically pleasing aspects, which is of concern to water purveyors because of consumer water safety perceptions. Governments and agencies, including Environment Canada, the US Environmental

Protection Agency (EPA) and the World Health Organization (WHO) have established guidelines that specify acceptable concentrations and limits (e.g. MCL: maximum contaminant levels; MAC: maximum acceptable concentrations) for many microbiological components, chemical/physical parameters and radiological amounts.

Establishing scientifically-based limits for each of these components has been, and is, a vital objective for providing safe drinking water. Once specific water quality objectives are established it is necessary to determine the appropriate solutions for both short- and long-term attainment of these goals. Water utilities in developed nations have traditionally relied on treatment of water immediately prior to and during distribution. However, the old adage that ‘an ounce of prevention is worth a pound of cure’ is establishing itself in progressive water utilities where multi-faceted protection and treatment plans are being developed to decrease costs, treatment requirements, and health risks associated with drinking water (Chichilnisky and Heal, 1998; Aust. NHMRC, 2002).

3. Health and water quality

The relationship between surface-source and finished water quality, in its simplest form, is that cleaner source water requires less intense water treatment and has lower associated acute and chronic health risks. Common health risks of drinking water include enteric pathogens, disinfection by-products (DBPs), chemical contamination, and other toxic compounds, such as those produced by cyanobacteria. The importance of identifying and breaking pathogen cycles to prevent waterborne illnesses was established in the 19th century (cf. Evans, 1987; Brody et al., 2000). More recent studies in developing nations have demonstrated that breaking pathogen transmission cycles through proper sanitation and sewage management improve health benefits more than simple provision of clean drinking water, although both are desirable (Esrey, 1996). Understanding the reasons for human disease outbreaks include: knowing the human infectious dose of an organism required to produce a disease, knowing the morbidity (or mortality) associated with an infection of the organism, understanding how immunity develops within a population, knowing that if population immunity develops there is less likelihood of disease occurring, and understanding the lifecycles and ecology of human pathogens.

The route of drinking water can be grouped into three main categories, (1) source water environment, (2) treatment, and (3) distribution and delivery (Fig. 1). It is recognized that no single means of treatment is infallible, ideally redundancies within each category should be used to reduce health related risks. Each of these categories, and processes within, that identify and ameliorate risks are considered a barrier in a multi-barrier protection plan. Furthermore treatment intensity is dependent on source

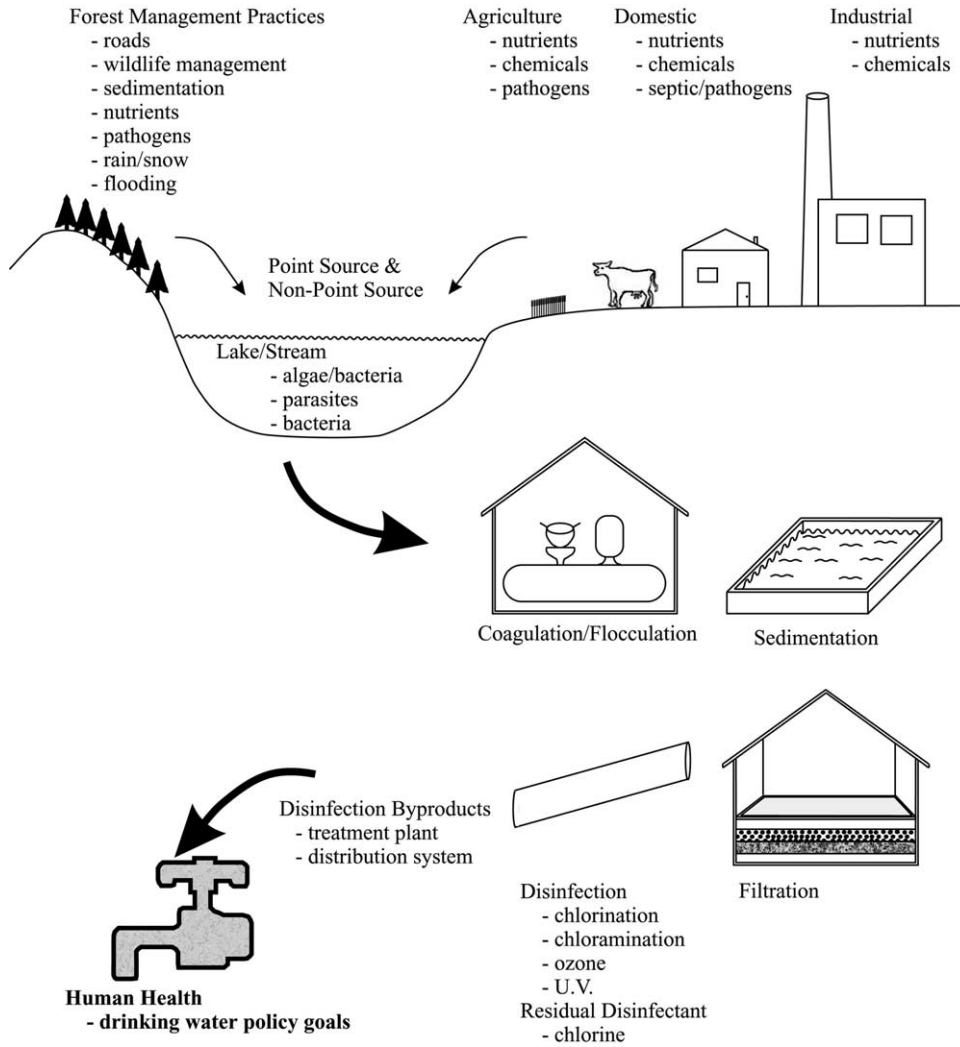


Fig. 1. Schematic of surface source drinking water, treatment and distribution. Water sources are impacted by many natural and anthropogenic activities. Each watershed activity must be considered for water quality risk and stakeholder interest. Less pristine water requires greater treatment to obtain the same water quality. End-of-tap water quality is the principle variable considered for all drinking water policy.

water quality. Pristine source water requires only disinfection, while other sources require further treatment (Fig. 1). Regardless of how developed a watershed is, management strategies should be aimed at reducing health risks in drinking water. Policies, especially of governments, provide specific direction for management strategies.

Environment and human health are inextricably linked at both proximate and extended time scales (Fig. 2). Environmental degradation/negligence can lead to both acute and chronic human health problems. Long-term human health issues are mostly related to chemicals and physical agents (e.g. Radon). Those of particular interest include DBPs and arsenic. Drinking water guidelines are based on our best understanding of the available science, however, this area of science is complex. Inferences based on toxicological studies (microorganisms and animals) regarding the health effects of drinking approximately 1.5 l over approximately 70 years is not exact and relies on consensus building among scientists and arbitrary safety

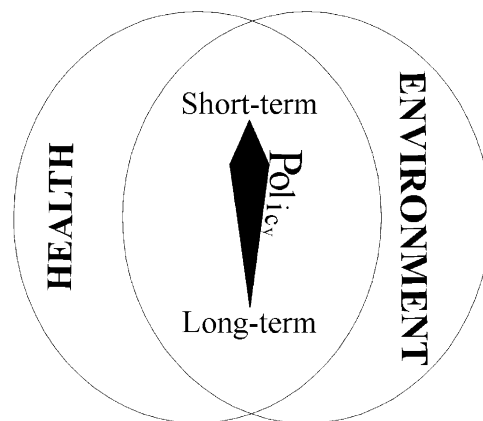


Fig. 2. Relationship between policy, health, and the environment. Policy is a driving force for dealing with both health and environmental issues. Human health and environmental health are strongly related. Both human and environmental health should be considered in the context of temporal scale, moving from the immediate to the long-term.

factors when there is scientific uncertainty. Ignoring long-term issues, especially when implications can be predicted, is not the most efficient policy for sustaining human and environment health. Foresight to implement integrated source water management has the potential to significantly reduce future costs and risks of providing drinking water. Therefore, it should be a priority to create a balance between both short- and long-term policies, as opposed to having a disproportionate amount of policy aimed at solving short-term issues (Fig. 2). There are, of course, many factors and variables to consider, including the major health issues outlined below.

3.1. Enteric pathogens

The intimate link between availability and abundance of safe, clean drinking water and human health has defined economic and social progress in developed nations (WHO, 1999). One of WHO's (cited in WHO (1997)) primary goals is to ensure that clean water is available for all humans. It is estimated that half the population of the developing world is inflicted with the major microbial diseases associated with water supply and sanitation. Over 3 million children under 5 years of age die every year as a result of contracting diarrheal diseases (WHO, 1996). Infection by pathogenic bacteria, protozoa, and viruses are the most prevalent global health risks associated with drinking water. Common organisms in drinking water that have been identified as posing major threats to human health include (1) bacteria: enteropathogenic *Escherichia coli* (notably *E. coli* 0157:H7), *Vibrio cholerae*, *Shigella*, *Campylobacter jejuni*, *Salmonella*, *Yersinia enterocolitica*, (2) protozoans: *Giardia lamblia*, *Cryptosporidium parvum*, *Entamoeba histolytica*, *Toxoplasma gondii*, *Balantidium coli*, and (3) viruses: Norwalk and Norwalk-like, Rotavirus, Hepatitis A and E; (Matsunaga and Okochi, 1998; Ford and Mac Kenzie, 2000; Haas, 2001).

3.2. Disinfection

In developed nations, acute health risks from microbiological pathogens have largely been mitigated through the disinfection of potable water. The goal of water disinfection is to inactivate waterborne pathogens (Braghetta et al., 1997) primarily by some form of chlorination, ozonation, or more recently ultra-violet (UV) radiation. Filtration is often used prior to disinfection to physically remove particles and pathogens. Plotkin and Plotkin (1988) suggest that safe drinking water (as obtained primarily through disinfection) has been the most important historical mode for reducing human mortality, and Craun et al. (1994a) claims Abel Wolman stated no single chemical has saved as many lives as chlorine. Regardless of water purveyor size, chlorine remains the least expensive and most effective treatment for microbiological pathogens (Clark and Adams, 1993).

3.3. Disinfection resistant pathogens

Despite the benefits of disinfection, several pathogens are resistant to traditional chlorination processes. Two of these pathogens, *Cryptosporidium* and *Giardia*, have been subject to increased research over the past ten years because their oocysts and cysts are not wholly inactivated by chlorination or ozonation or completely removed by filtration. They also have a low infective dose and are common in surface water (LeChevallier et al., 1991a,b; Kramer et al., 1995; DuPont et al., 1995; Goldstein, 1996; Isaac-Renton et al., 1996). In Milwaukee, 1993, the largest recorded waterborne outbreak in the US occurred when over 400 000 people became very ill and more than 100 people died after being infected with *Cryptosporidium* originating from the drinking water supply (Mac Kenzie et al., 1994).

Users of surface-derived drinking water are at a higher risk for infection by *Giardia* and *Cryptosporidium*. Exposure to *Cryptosporidium* and *Giardia*, as reflected by human antibodies, was examined in three BC communities (Isaac-Renton et al., 1999). Residents whose communities were served by ground water supply had significantly lower exposures to both pathogens than communities supplied with either a protected or non-protected surface source.

The prevalence of surface water as a source may be a contributing factor to BC having higher reported enteric diseases compared to the rest of Canada (BC Auditor General, 1999). LeChevallier et al. (1991a) found either one of, or both *Cryptosporidium* and *Giardia* in 97% of 66 surface source-drinking water supplies in 14 US states and 1 Canadian province (AB). Rose (1988) found *Cryptosporidium* in 72% of surface water samples in western US, and Isaac-Renton et al. (1996) found 69% of source drinking water supplies in BC tested positive for the presence of *Giardia* cysts. LeChevallier et al. (1991a) found *Cryptosporidium* and *Giardia* distribution to be positively correlated with each other and with other water quality parameters including turbidity, faecal coliform and total coliform bacteria. In a summary of four BC watersheds, it was found that water supplied from a protected (restricted public access) forested watershed had the lowest mean *Giardia* cyst concentration, whereas the mean cyst abundance in a protected (peripheral fencing) agricultural watershed was slightly higher (Ong et al., 1996). Both protected watersheds had lower mean cyst concentrations than the two unprotected watersheds. The study also linked higher cyst numbers in one of the watersheds to a cattle ranch. In a different source water comparison study LeChevallier et al. (1991a) found fully protected watersheds had lower *Giardia*, but not *Cryptosporidium* cyst concentrations in watersheds of limited access, compared to those with recreational and agricultural activities, or those with sewage and industrial discharge.

Identifying and mediating specific sources of *Cryptosporidium* and *Giardia* contamination in watersheds may provide as much risk protection as being able to control

and limit all activities in a watershed. Future studies need to examine the ecology of important drinking water pathogens. This will provide insight into why their abundance increases at certain times and thereby provide water managers with a better understanding of how to resolve problems at the source supply.

The prevalence in surface drinking water sources, persistence in treatment, and health risks make *Cryptosporidium* and *Giardia* especially important to consider when developing policy and strategies for source water management. Presence of these pathogens is especially critical for individuals with compromised immune systems. While most filtration and disinfection processes reduce the number of viable cysts (Trussel, 1993), UV seems to be the best treatment option (Craik et al., 2001). Because most water utilities do not have UV disinfection plants a multi-barrier approach that focuses on reducing high-risk activities within the watershed may provide the most effective means of reducing transmission risks. A multi-barrier approach also offers protection against treatment facilities that have inadequate or interrupted disinfection. Craun (1988) attributed 13–14% of waterborne disease outbreaks in the US to such systems (1971 to 1985). In order to effectively lower risks, watershed programmes should move beyond monitoring for source water pathogens towards an understanding of their ecology and population dynamics.

Recent guidelines established in Australia focus on a multi-barrier process approach. This involves adaptive management aimed at specific critical control points within each drinking water system, including the origin of source pathogens. These points represent system vulnerabilities to specific risks within all stages of the water delivery (Fig. 1) and aims to ameliorate risks where they occur. This differs philosophically from the technologically driven end-of-tap treatment of water pollutants and pathogens common in much of the developed world.

3.4. Disinfection by-products

While acute infection risks are significantly lowered by disinfection processes, the disinfectant (e.g. chlorine, chloramine, chlorine dioxide, ozone) reacts with organic compounds in water to produce secondary compounds known as DBPs. Health Canada (1995) divides DBPs into three main categories; (1) substances that may cause deleterious toxic, carcinogenic, or genotoxic effects, (2) assimilable organic carbon that stimulates bacterial growth in distribution systems and (3) compounds of objectionable taste and odour. Numerous DBPs have been identified (Health Canada, 1995; Richardson, 1998). The best known and most well studied are total trihalomethanes (TTHM)—including: chloroform, bromodichloromethane, dibromochloromethane, and bromoform), and haloacetic acids. Since trihalomethanes (THMs) were first discovered in chlorinated drinking water (Bellar et al., 1974), research has investigated potential health problems associated with these

compounds. Concentration of TTHMs in treated water is a function of temperature, the chlorine demand, total organic carbon concentration (Symons et al., 1975) and contact time. Source water with less organic carbon is considered to be of higher quality because, all else being equal, it has a lower chlorine demand and fewer DBPs will form when the water is treated (Symons et al., 1975; Craun 1993). Growth of bacteria in distribution systems is a function of several factors, but dissolved organic carbon (DOC) (Niquette et al., 2001) and perhaps phosphorus (Sathasivan and Ohgaki, 1999) are the most important. Greater DOC concentration increases bacterial regrowth, and therefore residual distribution disinfection demand, and DBP formation. Understanding the relationship between DOC and bacterial growth in distribution systems is important, especially when employing new disinfection technologies like UV or ozone treatments.

Since their discovery, medical researchers have examined potential health implications of DBPs. Most studies have examined the health effects of DBPs in drinking water, however, it should be noted that drinking water is not the only means of exposure to DBPs. Weisel and Chen (1994) found heated water previously treated with chlorine posed a 50% increase to exposure via inhalation and dermal contact. This can be especially important after bathing or showering (Miles et al., 2002). Risk from inhalation and dermal exposure varies for each DBP, some have lower, similar, or higher calculated cancer risks. Hutcheson et al., (1995) calculated the cancer potential factor of chloroform from heated water to be 13 times greater from inhalation compared to oral ingestion.

Epidemiological and toxicological studies have been used to elucidate relationships between DBPs and health (e.g. primarily cancer). Descriptive epidemiological studies compare groups of people exposed to different water sources (often ground water is used because of its significantly lower DBP content) and rates of cancer within each of those groups. Odds ratios (i.e. the ratio of the odds of a person having a disease in an exposed group to the odds of a person having the same disease in the unexposed group) are commonly used to draw conclusions about exposure to DBP. Studies have shown no increased association of cancer to DBP in drinking water (Lawrence et al., 1984; Young et al., 1987), increased association of cancer to DBP in drinking water (Cantor, 1987; Zierler et al., 1988; Fagliano et al., 1990; Doyle et al., 1997) and association to some cancers, but not others (Bull et al., 1995). Odds ratios in such studies are usually less than 2, meaning that the strength of association between DBPs and cancer is undetectable (1.0–1.2), weak (1.2–1.5) or at best moderate (1.5–3.0) (Monson, 1990). Detection of weak associations requires more rigorous experimental studies because of natural variability and confounding bias in such studies (Monson, 1990).

Toxicological studies have mainly focused on associations between THMs and cancer risk (Booreman et al.,

1999). Many DBP compounds have been demonstrated to produce carcinogenic or mutagenic effects. Implications for human exposure, however, remain largely unknown because these studies typically test compounds on animals for shorter periods and at levels several magnitudes higher than typical human exposures. Results are often linearly extrapolated to human exposure (Craun et al., 1994b). Despite weaknesses of both epidemiological and toxicological studies a growing number of researchers are finding increased health risks associated with exposure to DBPs suggesting, but not proving, that DBPs increase incidence of certain cancers (Bull, 1993).

A recent review (Graves et al., 2001) of both epidemiological and toxicological studies examining effects of DBP on human reproduction and development found no evidence of association for many parameters (including: neonatal death, low birth weight, pre-term delivery, and congenital, cardiac, gastrointestinal, genital, integument, musculoskeletal and chromosomal abnormalities) and only a few with suggestive or positive associations (in utero-growth retardation, urinary tract defects). There were mixed or inconsistent results for studies examining the relationship of DBP with still birth/foetal death, spontaneous miscarriage, all central nervous system anomalies, and congenital abnormalities/birth defects. ILSI Risk Science Institute's, 1998 report on toxicity of exposure to DBPs concluded that on-going and continued interdisciplinary research with epidemiologic, toxicologic, and mechanistic foci is necessary to further our understanding of risks associated with DBPs. Regardless of the relationship between exposure to DBPs and human health, one assured approach to mitigate this risk is to reduce organic precursors in raw source water.

3.5. Chemical contamination

It could be argued that the use of chemicals and their introduction into the environment results in the most obvious alteration/contamination of surface waters. Of the chemicals listed in the Canadian Drinking Water Guidelines (Health Canada, 1996) most are used in agriculture or industry. Numerous organic chemicals were found in a US national survey of streams susceptible to contamination (Kolpin et al., 2002). Chemical introduction into surface waters either directly, or indirectly through deposition in watersheds or the atmosphere, decreases the quality of the surface water. For example inorganic nutrients from fertilizers, especially nitrogen and phosphorous, can stimulate aquatic productivity (OECD, 1982). Numerous studies have examined the causes and effects of excessive nutrients on eutrophication. Eutrophication results in unfavorable changes to water quality, including: higher dissolved organic and particulate carbon concentrations, higher bacterial numbers, shifts in phytoplankton species composition and formation of algal blooms, deoxygenation

of hypolimnetic waters, unpleasant tastes and odours, and changes in food web structure and fish species composition (OECD, 1982).

Algae and algal exudates (DOC) are important precursors of THM production (Hoehn et al., 1980; Karimi and Singer, 1991). Studies, such as those linking algae and DOC to THMs, underscore the critical link between source water quality parameters and health risks. Such studies also provide directives for the management of both surface sources and water treatment. For example, an experiment with chlorine as a primary treatment found that there was an increase in DOC concentration from ozone pretreated algal cultures. This resulted in higher chloroform levels compared to cultures without ozone pretreatment (Plummer and Edzwald, 2001). The particulate biomass, however, was still attributed as being the major precursor of DBPs (ca. 70%). This emphasizes that source water quality and treatment methods are both important variables in the overall quality of water.

The introduction of agricultural and domestic pesticides, industrial and domestic cleaners, and private and industrial waste into surface waters pose an increased risk to human health because many of these chemicals are considered toxic, carcinogenic, or genotoxic (Health Canada, 1996). Water quality criteria for drinking water supplies for many of these compounds have been established. The risks associated with chemicals can most effectively be abated by reducing their use and managing their disposal at the source. If multi-barrier critical control point policy of surface source drinking water is established then specific strategies regarding both point-source and non-point source pollution would be a priority and would result in lower risks of pollutants in drinking water.

3.6. Cyanobacteria

The abundance of cyanobacteria (blue-green algae) in source drinking water is an important health issue. For centuries people have associated cyanobacterial blooms with poor water quality, however, only in the past couple of decades have we begun to understand and appreciate the importance of toxins and taste and odour production from these algae (Chorus, 2001). Other algal groups are known to produce toxins (e.g. Pymnesiophyceae and Dinophyceae), however, cyanobacteria represent the greatest risk in freshwater (Carmichael and Falconer, 1993). Toxicogenic species occur in at least 18 genera (Skulberg et al., 1993) although species of *Anabaena*, *Aphanizomenon*, *Nodularia*, *Oscillatoria*, *Microcystis* are the principle ones associated with health risks (Carmichael and Falconer, 1993). Prolific cyanobacterial growth is associated with nutrient rich waters, warm temperatures and sufficient light (Reynolds, 1984; Carmichael, 2001).

Cyanobacteria are known to produce acute hepatotoxins, cytotoxins, neurotoxins, and gastrointestinal disturbances

and respiratory and allergic reactions (Falconer, 1999; Carmichael, 2001). The principle cyanobacterial toxin considered in drinking water guidelines is microcystin-LR. Falconer (1999) reported a provisional drinking water guideline of 1 µg/l for the US, while Canada recently approved a guideline concentration of 1.5 µg/l. Microcystin-LR specifically targets the liver, kidney and small intestine (Falconer, 1993) and involves acute hepatotoxicosis. Livestock deaths, (Puschner et al., 1998), and occasionally human deaths have been attributed to cyanobacterial-derived toxins. In 1996 the deaths of 76 people were attributed to cyanotoxin-contaminated water used for treatment in a Brazilian dialysis centre (Carmichael et al., 2001). In addition to microcystin, Australia has guidelines for anatoxin-a, saxitoxin and cylindrospermopsin.

Acute large-scale impacts are not common because people generally avoid consuming water with obvious bloom formations. Health consequences of consuming sublethal toxin concentrations are therefore an important health issue. While cyanotoxin toxicological tests clearly demonstrate these toxins have adverse health effects, epidemiological studies are more complicated because of the influence of other variables including: enteric bacteria, protozoa, viruses, DBPs, seasonality of cyanobacterial abundance, and variance in toxin consumption. A sudden release of toxins can occur when cyanobacterial blooms die. This occurs when environmental conditions become unfavorable for the bloom or if algacides are used to 'improve' water quality. Because human intake of toxins is higher under such conditions their effects are more pronounced in the short term, for example, increased liver damage was associated with the treatment of a *Microcystis* bloom with copper sulphate (Falconer et al., 1983). Liver damage and tumor growth are two of the primary health problems associated with the consumption of cyanotoxins (Falconer, 1991, 1993). The few long-term epidemiological studies on the effects of human health are suggestive, but not conclusive, that cyanobacteria in source water is associated with greater health risks (Shun-Zhang, 1989).

Cyanotoxins normally pass through water treatment processes and are resistant to boiling (Falconer et al., 1989). Therefore, the prevention of cyanobacterial blooms is a more effective means of reducing toxins than is the typical water treatment process (Bischoff, 2001). Eliminating the ecological competitive advantages of cyanobacteria by lowering nutrient discharge, especially phosphorous (Downing et al., 2001), or disrupting water column stability should be the primary goal for reducing both acute and chronic health risks associated with cyanobacterial blooms. Such strategies eliminate infrastructure costs associated with treating drinking water, reduce risks by reducing or eliminating the toxin source, contribute to other improved water quality parameters (e.g. reduced organic carbon) and in multipurpose lakes improve the aesthetic value.

3.7. Radionuclides

Although radionuclides have the potential to seriously affect health, we will not discuss them at length in this paper. Radionuclides that occur in drinking water include Radon-222 and Radium, both of which occur primarily in ground water. Uranium and up to 200 human-made radionuclides that are potential surface water contaminants can be found in both ground and surface water, (Lowry and Lowry, 1988). The presence of harmful radioactive elements in surface-source drinking water is, to a large extent based upon the past and current policies of government nuclear programmes. Nuclear programmes of all governments and organizations should consider both short- and long-term risks to human health.

4. Policy

4.1. Background—Canadian and BC water policy

The process of establishing safeguards and guidelines necessary for the continued attainment of high drinking water quality primarily depends on government policy. Policies are instruments through which governments can wield their power and provide directives for action (Elmore, 1987), such as establishment of specific procedures and rules, which in turn are used by regional, and local governments and water purveyors. Policies should be based on the best available information and result in action based on these principles (Forsberg, 1998). The Canadian Federal Water Policy has two principle goals, (1) to protect and enhance the quality of water, and (2) to promote the wise and efficient management and use of water (Env. Can., 1987). It includes a specific policy statement regarding safe drinking water stating that it will continue to establish safe drinking water guidelines (e.g. the Canadian Drinking Water Quality Guidelines), to aid jurisdictions, conduct research, promote public awareness, and consider legislation relating to federal jurisdiction. Health Canada also serves as Secretariat to the Federal-Provincial Subcommittee on Drinking Water—a committee with representatives from the provinces, territories and Environment Canada that reviews and proposes new drinking water guidelines.

In Canada there is a division between the federal and provincial governments' roles and jurisdictions in protecting drinking water. The provinces, under the *Constitution Act*, have proprietary rights to water resources (surface and ground water) and are responsible for authorization and use of water, development relating to water, flow regulations, and they have the authority to legislate water supply and pollution control (Env. Can., 1987). The federal government maintains jurisdiction involving navigation and fisheries (e.g. section 35 under the Fisheries Act), national parks, and aboriginal reservations.

Recent changes in BC drinking water policy are used to highlight the importance of policy in shaping management, the need for strong instrumentation (see below) and the need to improve our scientific understanding of watershed processes. British Columbia passed the Safe Drinking Water Regulation (SDWR) under the *Health Act* in 1992 (BC Gov., 1992). The SDWR placed the responsibility of safe drinking water provision on water purveyors subject to approval of Medical Health Officers and set the microbiological limits of bacteria in finished water. The mechanism of enforcement in BC has, for example, involved putting conditions on operating water permits. In April 2001 the *Drinking Water Protection Act* (DWPA) was enacted and it, in part, outlined development of drinking water protection plans within BC (BC Gov., 2001a). If a watershed area was established, the plan was designed to prohibit contaminant introduction or anything that would result in a health hazard. In its present form the DWPA is only a framework. In September 2001, under a new provincial government, this Bill was placed under review by the Minister of newly named Ministry of Water, Land and Air Protection (WLAP; formerly named Ministry of the Environment Land and Parks (MELP). NB: due to the change in government in 2001, we have chosen to differentiate NDP and Liberal initiatives by using both the old (MELP) and new (WLAP) environment ministry acronyms). The review concluded that BC ‘urgently needs the consolidated legislation that the DWPA provides’ (Marshall, 2002). A complicating political issue is that protection of surface-source drinking water also falls under the jurisdiction of any Ministry in contact with watersheds, lakes, and rivers, including Ministries of Environment, Forests, Health, Energy and Mines, and Transportation and Highways (BC Auditor General, 1999). Therefore, if the recommendations of the DWPA review panel are followed and a new Drinking Water Protection Agency is formed, each of these ministries would be required to relinquish some of their current jurisdictional power. BC Ministry of Health Services has recently been designated as the lead agency responsible for the safety of drinking water but no Drinking Water Protection Agency has been formed.

Regulations that are needed to make the DWPA enforceable are currently being drafted, although the administrative and policing resources have not yet been allocated. This new legislation will further strengthen the ability to improve water quality by means of enforcement (Table 1). If all the legislation and policies are implemented, BC will have one of the strongest drinking water regulations in the country (including source water protection). Regulations do not necessarily equate with compliance, but they should be a manifestation of water policy objectives and provide an enforceable structured framework for those objectives.

MELP recently established a policy regarding the protection of freshwater (BC MELP, 1999a). This MELP report outlines strategies related to water pollution control,

water-use planning, fish protection, bulk water transport, non-point source pollution, water education and stewardship, flood safety, dam strategies and drinking water protection. The overlying goal is ‘healthy aquatic ecosystems, assured human health and safety, sustainable social, economic, and recreational benefits of water’. The process by which the government of BC plans to attain these goals is, by nature, an on-going process. One key component of developing effective policies is public participation. A recent consultation process conducted by MELP (BC MELP, 2001) suggests that the BC public wants enactment of strong legislation, including raw and finished water standards, increased research on drinking water issues, public education, and a greater emphasis on watershed protection. This sentiment, reflects some of the legislation in the DWPA and such directives will further establish links between source water quality, drinking water quality, and health in BC.

4.2. Policy instruments

Instruments represent the means by which policy goals are attained. Categories of policy instrumentation include (1) regulatory, (2) market and incentive-based, and (3) information provision. Each have affirmative (e.g. prescriptive, subsidies, encouragement) and negative (e.g. fines, fees or taxes, warnings) variants (Bemelmans-Videc and Vedung, 1998). The achievement of policies depends primarily on the effectiveness, efficiency, legality, legitimacy, and underlying democracy of these instruments (Bemelmans-Videc, 1998).

Ecological studies have identified nitrogen and phosphorous as key elements in eutrophication, so present day policy reflects this knowledge and focuses on reducing the loading of these elements into water bodies (Forsberg, 1998). This is primarily conducted through legislation on discharge of point-source pollution (Johns, 2001) that includes public and corporate information campaigns, provision of incentives and financial assistance to achieve compliance, and the dispensing of fines. Without more comprehensive policy instruments water quality objectives will not be attained. If left unabated non-point source pollution, increased urbanization, intensive agriculture practices, increased anthropogenic nitrogen fixation and large-scale phosphorous consumption will continue to pollute surface waters (Forsberg, 1998).

At worst policies are politically motivated gestures, at best they generate specific strategies, define instruments of implementation, identify local action plans and, ultimately, meet their mission statements. A fundamental shift in focus to economic and health values associated with protection of surface waters is necessary to provide incentive and justification for the protection of surface-source waters (Newsome and Stephen, 1999). Policies in both Canada and BC have been established and outline a commitment for the assurance of both quality finished drinking water

Table 1
Comparison of current water quality regulatory limits for British Columbia, Canada, the US and the World Health Organisation

Criterion	BC Regulations	Canada guidelines	USEPA regulations	WHO guidelines
Microbiological				
Faecal coliform	✓	✓	✓	✓
<i>Giardia</i>	×	0 is desirable	✓	✓
<i>Cryptosporidium</i>	×	0 is desirable	✓	✓
Chemical				
Specific chemical targets	NOEL—DMO ^a	✓	✓	✓
Turbidity	NOEL—DMO ^a	Some guidelines	✓	✓
Disinfection by-products	NOEL—DMO ^a	TTHM guidelines	✓	✓
Algal Exudates				
Microcystin-LR	×	✓	✓	✓
Taste and Odour	×	Suggested, no standard	Odour Threshold 3: federally non-enforceable, states can choose	Suggested, no standard
Source water protection				Some countries use and enforce WHO guidelines
Legislated	✓ ^b		✓	
Enforceable	Not directly ^b	Only in federal jurisdictions, often indirect ^c	✓	
Focus on multibarrier Protection ^d	×	×	×	Suggested
			BMP codes of practices ^e	

Note: at time of writing. Enforceable standards and legislation can change.

^a NOEL—DMO: No Official Enforceable Legislation—at the Discretion of the regional Medical Officer. BC will soon be set to have stronger standards, however, whether the regulations necessary for enforcement will be written for the standards is, as of yet, unknown.

^b The DWPA (see text) is legislated but in its present form is a framework only. Regulations needed to make the DWPA enforceable are being drafted. In the interim source water protection can only be maintained through less direct means such as pollution legislation and, for example, the Forestry Practice Code’s designation of community watersheds.

^c e.g. under the *Fisheries Act* the federal government has jurisdiction over fisheries which includes the destruction of habitat or addition of substances deemed deleterious to fish. Fisheries destruction, either physical or resulting from the addition of deleterious substances could, in theory, be used as enforceable legislation in drinking water source protection. However, because the provinces have proprietary rights to both the land and water resources, any action the federal government might take would undoubtedly interfere with provincial jurisdictions.

^d Although certain jurisdictions have source water protection, in general the only mandated drinking water quality objective is at the tap. Note, in order to be exempt from filtration during treatment in the US watershed management is a requirement. Recent Australian drinking water policies adopt a process approach and identify critical control points in an ecosystem framework that include the source watershed, the source water, the treatment process and the distribution system. These policies are currently among the most integrated multibarrier approaches.

^e Best Management Practice. Focus on end-of-tap objectives quantity and quality objectives for individual water parameters, e.g. maximum contaminant levels.

and the protection of surface waters. It is therefore imperative that we understand impacts on the sustainability of both water quantity and quality, the relationship between quality of surface-source water and the quality of finished water, the relationships between finished water and consumer health, and both the short- (Harrington et al., 1989) and long-term costs (Havelaar et al., 2000) of protecting our drinking water supplies (World Bank, 1993). Such knowledge forms the foundation for effective policy instrumentation because, in combination with public participation, the instruments will be legitimate, legal, and democratic.

4.3. Policy examples

Canada. Since the development of a Water Policy in 1987, the Canadian federal government has played an active role in establishing and updating drinking water guidelines.

Pressing water quality issues, however, do remain within its legal jurisdiction. Moore (1999) examined drinking water systems in aboriginal communities across Canada and found that 25% posed health and safety risks. As both the responsible and regulatory agency, the federal government needs to maintain incentive for managing these systems.

British Columbia. British Columbian water sources were identified by the Auditor General as being strained (BC Auditor General, 1999). Enteric diseases in BC are higher than in the rest of Canada, in part due to lack of filtration, predominance of surface water as a source (as opposed to ground water), and the presence of *Cryptosporidium* and *Giardia*. Smaller communities and towns are at a greater risk because they lack the finances to build extensive water treatment facilities. A key conclusion of the Auditor General was that BC lacks an effective and integrated approach to land-use management with respect to protection of drinking water sources. This concern was intended to be addressed by the DWPA.

The importance of non-point source pollution is recognized by the BC government and it is the only province in Canada to develop an action plan to address this issue (BC MELP, 1999b). Ecological directives for drinking water management will continue to face challenges because environmental problems are usually not identified conclusively and disagreements on the impacts and practicalities of solutions will always exist. Further complications can arise; for example, when solutions such as nutrient reduction are identified then questions regarding specific targets (e.g. nitrogen or phosphorus-which one and how much?) will remain (Sims et al., 1999). Understanding the detailed relationships between environment and health is important because changes in policies and regulations will negatively affect some stakeholders. This action plan (BC MELP, 1999b) represents a promising step towards managing surface water quality because it identifies educational, on-going assessments, economic incentives and legislation as being key instruments to successfully reaching water quality objectives.

Within BC small systems are considered most at risk for waterborne illness because they lack the financial resources to construct and maintain filtration plants and for the most do not have protected watersheds. If situated in the US these systems would not comply with the non-filtration rule (see below). Establishing sound partnerships and agreements with land owners and users requires effective instrumentation by the government and backed by enforceable legislation.

United States. Due to both its global influence and proximity US regulations are often used for comparison in Canada. The US Safe Water Drinking Act (SWDA) amendments of 1986 and 1996 are important because (among other things) they recognize the relationship between treatment intensity and water sources. One of the requirements of the SWDA is that filtration of surface sources are required unless water suppliers can demonstrate that their source water is of high quality. Maintaining non-filtration includes meeting raw water coliform bacteria requirements, turbidity requirements, having an appropriate disinfection system using a minimum of two disinfectants, meeting protozoan and viral disinfection criteria, and maintaining an effective watershed control programme. Effective watershed programmes are designed to minimize risks from transportation (especially spills), residential (especially sewage/septic), industrial (primarily waste), agriculture and forestry (nutrients, chemicals, roads), recreational (public access and the concomitant risks of enteric pathogen introduction), and natural (animals, landslides) sources (Leland and Berg, 1988). New York city has decided to invest in a watershed management programme to maintain high water quality from its source water so as to avoid filtration costs in the future (Chichilnisky and Heal, 1998; Foran et al., 2000).

The US principally relies on treatment to reach water quality objectives and only when treatment intensity is less

than that required (e.g. filtration) do the strict watershed rules apply. Thus, the US primarily depends on technology to ensure that pathogens and pollutants remain below guideline levels. Development of policies to adopt a multi-barrier plan and focus on risk amelioration at critical control points from source to tap (e.g. Aust. NHMRC, 2002) would serve to reduce immediate risks and enhance long-term sustainability of drinking water resources.

5. Risk assessment and cost

Health risks associated with drinking water can be reduced to the following equation: risk equals the likelihood of an event occurring (probability) multiplied by the consequence (the measurable effect). Health risks of contracting a disease from untreated drinking water is high in probability and high in consequence, whereas health risks of contracting a disease from disinfected water are lower in probability and, in the immunocompetent, lower in consequence. Drinking water that is free of pathogens and harmful chemicals is not a practical or desirable goal, rather water purveyors should ensure that water is free of human pathogens and any chemicals present are below the concentrations where science suggests they are not of health concerns. Water treatment plants and water strategies are not 100% effective. In developed nations water-borne diseases and chemical contamination from drinking water occur every year (viz. Haas, 2001). The practice of water treatment to disable pathogens decreases the health risks, but does not eliminate them. Recent examples, including the *Cryptosporidium* outbreaks in Milwaukee in 1993 and Nevada in 1994 occurred despite water treatment using filtration and chlorination. Communities and governments need to assess their priorities and balance risks with costs when developing surface-source drinking water policies. The potential economic costs associated with drinking water-borne illnesses were assessed in a commissioned paper by Livernois (2002) following an outbreak of *E. coli* in Walkerton Ontario that resulted in seven people's deaths and 2300 people becoming ill. In this small Canadian community the tangible economic impact was estimated to be \$64.6 million (Livernois, 2002).

Health risks in unprotected watersheds are considered to be greater than those in protected watersheds because there are fewer checks-and-balances. Risks include the introduction of chemicals and nutrients (through industrial, personal, or accidental means), unknown handling of sewage (human and agricultural), and increased sediment load from land-clearing and road building. Leaching of human and animal wastes into source waters increases the acute risks of infection by enteric pathogens. Disposal of toxic, carcinogenic or mutagenic chemicals increases the risk of long term health problems. Increased nutrient loads cause higher biomass in source water and may result in either increased DBPs or require increased treatment levels (i.e. filtration)

and can cause shifts to less desirable potentially toxic algal species. All these activities have the potential to degrade water quality parameters.

There still exists great uncertainty linking the degradation of water quality to health. Activities should be audited and their effects estimated (Fewtrell et al., 2001) so that risks are better understood and policies are directed towards the goal of sustaining water supplies, maximizing health, and minimizing costs. For example, the BC Auditor General (1999) estimated that adding filtration systems to the smaller water systems outside Vancouver and Victoria would initially cost around \$CDN700 million with an additional \$30 million for annual maintenance. Other estimates suggest initial costs may be as high as \$2 billion (BC Gov., 2001b). For economic reasons this investment is not likely to be made soon, so municipalities along with the provincial government need to find other means of reducing health risks. It is in BC's interest to conduct studies examining source-water supply on human health so that watershed effects can be estimated and risks better understood. While short term costs may be lower, unchecked development can lead to increased risk through environmental degradation and therefore increase costs in the future.

6. Role of science

Implicit in this paper is the requirement for sound science in all aspects of drinking water management. For example scientific studies form the basis of treatment development, setting MCLs/MACs and understanding source water and watershed ecology. The effectiveness of management and policy development is dependent upon a concerted scientific effort to understand all aspects of drinking water systems. Sound science forms the basis of the legitimacy, equitability and legality of implementing water management strategies. A major struggle in developing science-based policy is the lack of effective mechanisms to integrate current science into policy.

7. Conclusion-health, policy and the environment

Ultimately drinking water management must be based on sound science, strong policy, effective policy instrumentation and a clear understanding of risk. The current crux of quality drinking water focuses on the end product, however, water quality is a consequence of water source, treatment, and distribution. The attainment of safe drinking water should employ several strategies (Table 2).

Ideally drinking water protection should focus on raising the quality of source water rather than increasing the sophistication of treatment (Gostin et al., 2000). Treatment alone is not failsafe (Craun, 1988; Goldstein et al., 1996) but rather should be used as part of a multi-barrier approach.

Table 2
Strategies for attainment of sustainable clean drinking water sources

Prevention and treatment

Source-water and treatment are both important for determining water quality

Inactivation/removal of acute enteric pathogens is a priority

Disinfection has inherent health risks, including DBP formation and resistant pathogen transmission (e.g. *Cryptosporidium* and *Giardia*)

Presence of anthropogenically derived chemicals (including agricultural and domestic pesticides and industrial products) increases the health risk of drinking water

Source water ecology

Understanding pathogen ecology is necessary for effective environmental management

Addition of nutrients decreases surface source water quality

Cyanobacteria can produce dangerous toxins and may present an important health risk

Policy, risk assessment and sustainability

Multi-barrier approach with adaptive management of critical control points

Effective policy requires effective instrumentation

Risk and cost assessment provide a means of prioritizing management strategies;

Strategies for water provision should contain objectives for long-term sustainability.

Protecting surface source waters can reduce the number of pathogens and organic matter entering treatment facilities, thus reducing acute enteric risks, lowering DBPs and reducing DOC substrates that promotes bacterial growth in distribution systems. Protection and management can also serve to reduce cyanobacterial toxins. The link between source water quality and need for treatment is recognized by the US SWDA. Assessments have demonstrated that effective management can reduce, delay, or avoid substantive costs associated with water treatment beyond disinfection (Chichilnisky and Heal, 1998). It is especially critical to understand the ecology of human pathogens and manage them by prevention of source-water contamination.

In certain systems more direct management may be desirable, such as construction of pre-impoundments to trap sediment and phosphorous, wet-land restoration and construction, and lake mixing and aeration (Straškraba, 1996). Settling in pre-impoundments can reduce biomass and pathogens in reservoirs, for example by reducing protozoan cysts (Isaac-Renton et al., 1996). More actively managed watersheds effectively use natural ecosystems to do work (that would otherwise require more intensive treatment facilities) and should be considered financial assets.

Few water utilities have the resources to implement comprehensive watershed programmes without assistance. This is especially true of utilities servicing small populations with watersheds owned and used by numerous stakeholders. Since BC has relatively abundant and clean surface sources it should protect these in a sustainable manner. The US SWDA specifies that filtration is needed unless the water supply is of high quality. BC needs to formally recognize the critical role of source water protection by providing instrumentation to protect

the health of water and, where ever possible, avoid constructing filtration plants. Watershed environmental degradation costs need to be evaluated so that higher value is placed on maintaining quality water sources. It is also important to examine watershed stakeholders whose use may not be assessed at the appropriate resource cost. Higher short term user costs to develop integrated watershed programmes can lower both risk and long-term human and environment health costs. The disparity between policies outlining watershed protection and the ability of water utilities to implement watershed programmes underlies the critical role of government. Policy must move beyond statements and provide instruments for the practical attainment of policy objectives.

The recent BC provincial health officer's report on drinking water quality (BC Gov., 2001b) outlines, in a more comprehensive manner than the 1999 Auditor General's report, specific steps required to attain water quality objectives. Governments must develop strategic plans and site-specific solutions and ultimately issue permits and licenses. In BC, policy for source-water protection has been developed (BC MELP, 1999a,b; BC Gov., 2001a) and some key principles established (BC Gov., 2002). It is still too early to know the specific instrumentation to be employed or to assess the effectiveness of these strategies.

All countries need to consider both the short and long term implications of water resource management. Effective management of drinking source water is especially critical for systems that do not have the financial resources to build and maintain treatment facilities other than the use of chlorine as a disinfectant. However, even those systems with greater financial resources benefit by having cleaner source water. Long term water quality implications of emphasizing treatment alone compared to surface source water protection as part of a multi barrier approach are unknown. However, there is greater risk of disease outbreak from source water that is of lower quality, there are increased costs associated with treating lower quality water and a greater prevalence of treatment by-products that can affect health. Prevention of water pollution seems a more wise and prudent management directive than does cleaning our water sources in the future. Water is essential for sustainability, so policies should necessarily be aimed to manage and use water in a sustainable manner.

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