Urban Drinking Water Quality: A Survey of Selected Literature

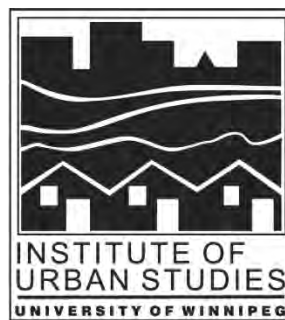**Issues in Urban Sustainability No. 1**

_____

By Eva Pip
1993

_____

The Institute of Urban Studies

FOR INFORMATION:

The Institute of Urban Studies
The University of Winnipeg
599 Portage Avenue, Winnipeg
phone: 204.982.1140
fax: 204.943.4695
general email: ius@uwinnipeg.ca

Mailing Address:
The Institute of Urban Studies
The University of Winnipeg
515 Portage Avenue
Winnipeg, Manitoba, R3B 2E9

The Institute of Urban Studies is an independent research arm of the University of Winnipeg. Since 1969, the IUS has been both an academic and an applied research centre, committed to examining urban development issues in a broad, non-partisan manner. The Institute examines inner city, environmental, Aboriginal and community development issues. In addition to its ongoing involvement in research, IUS brings in visiting scholars, hosts workshops, seminars and conferences, and acts in partnership with other organizations in the community to effect positive change.

URBAN DRINKING WATER QUALITY: A SURVEY OF SELECTED LITERATURE

Issues in Urban Sustainability 1

Eva Pip

Institute of Urban Studies

1993

PUBLICATION DATA

CONTENTS

PREFACE TO THE SERIES

The IUS Publications series Issues in Urban Sustainability is a follow-up to the *Select, Annotated Bibliography on Sustainable Cities* published by the Institute of Urban Studies in 1992.* One outcome of work on the bibliography was the insight that much of the now-vast literature relevant to the multifaceted topic of sustainable urban development (SUD) remains to be reviewed, classified and synthesized in a manner accessible to the wide range of professionals, policy-makers and academics engaged in the study and implementation of urban sustainability.

In order to begin to fill this gap in the literature, the Institute of Urban Studies has commissioned a series of reviews of the literature on topics relevant to SUD, to be published in 1993-94. The first review in the series, by distinguished scientist Dr. Eva Pip of the Department of Biology, The University of Winnipeg, is on the topic of urban drinking water quality. Future publications in the series will include literature reviews on sustainable subdivision design, urban environmental impact assessment, sustainable uses of urban open space, SUD in Third World cities, the rural/urban fringe and SUD, urban waste management, SUD policy, and planning for SUD.

The topics covered in this series, as identified to date, of course by no means exhaust the issues relevant to urban sustainability, and, admittedly, there is bound to be—and should be—some overlap in the areas covered by the nine reviews (for example, the "sustainable subdivision" would naturally involve planning, policy, waste management and urban open space issues). However, the reviews in this series, prepared by an interdisciplinary group of academics and practitioners, will provide an overview of the literature in each of the chosen subject areas that is currently unavailable elsewhere, identifying what is known, what has been done, and what are the lacunae in expert knowledge and professional practice.

Mary Ann Beavis
Series Editor

---

*Mary Ann Beavis and Jeffrey Patterson, *A Select, Annotated Bibliography on Sustainable Cities* (Bibliographica 4; Winnipeg: Institute of Urban Studies, 1992). This source has subsequently been called a "'benchmark' for students of urbanization" (Mary Ellen Tyler, Review, *Canadian Journal of Urban Research*, 2:1 (1993): 56.

URBAN DRINKING WATER QUALITY:
A SURVEY OF SELECTED LITERATURE

Eva Pip
Department of Biology
The University of Winnipeg

INTRODUCTION

Water is indispensable for all life on our planet. The quantity of water on earth is finite, amounting to approximately 1500 million cubic kilometres (Morrison, 1984). It is one of the most precious resources that we have, but also one of the most vulnerable and easily tainted. Our present management of it will determine in large part our future as well as the future of our planet.

Throughout human history, settlements have always been located near water. At first, community requirements for water, as well as impacts of human activities on water, were minimal. As social organization and technological capabilities grew, so did both the demand on and the abuse of water. The concentration of people in urban centres throughout the world brings with it today the demand for a safe, dependable, continuous supply of water, not only for individual personal needs, but also for industrial purposes and community uses such as street washing and fire control. The continued growth of the world's human population is unavoidably tied to projected demands for more and more water, yet many cities already find it difficult to meet existing requirements.

The problem of urban water supply and water quality has existed since ancient times. While water supplies have always been mistreated, during earlier periods this impact was less severe because of smaller populations, and few synthetic toxic substances. Abundant archaeological evidence emphasizes the quest for clean water supplies to service early communities in the Middle and Far East. King Sennacherib, for example, was not content with Tigris River water and constructed a canal to convey fresh spring water to Nineveh from several miles away (Brothwell, 1972). In 400 B.C., Hippocrates pointed out the relationship between water quality and health, and recommended the boiling and straining of rainwater (Moore, 1989). Much of the urban population of ancient Egypt drew its water from the Nile, which also served as the disposal site of human waste and garbage, resulting in high frequency of dysentery and other water-borne diseases (Dixon, 1972). In 168 B.C., Athenaeus of Naucratis described how Egyptians purified jars of river water for domestic consumption by exposing the water to sun and air, straining it through cloth, and letting it stand overnight for sediments to settle (Lorch, 1987).

Settling reservoirs were used as early as 250 B.C. in Laodicea. In a system constructed by Antiochus Theos, water was conducted by aqueduct from the Caprus River to a system of sedimentation reservoirs. Clarifying agents were also in use in very early urban centres. Egyptians used crushed almonds as clarifying additives, while alum was used in China (Lorch, 1987). The purifying properties of activated carbon were recognized as well. A 4000 year old Sanskrit manuscript

advises that "it is good to keep water in copper vessels, to expose it to sunlight, and filter it through charcoal" (Moore, 1989).

Ancient Rome had a sophisticated system of aqueducts and distribution pipes. Archaeological evidence indicates that water quality was a significant problem in many cities of antiquity, with epidemics of gastrointestinal illness and intestinal parasites. Improper sanitation practices were rampant (Brothwell, 1972). Unfortunately, many of the same problems are still allowed to exist today, not through lack of knowledge or technology, but through lack of good judgment and political will.

HEALTH AND POLITICS OF WATER

In Canada, consumption of water and water-based beverages is approximately 1.3 litres per day for an average adult, but may exceed four litres in some circumstances (Meranger *et al.*, 1979). Therefore the quality of water is a critical issue in public health and quality of life, since over a lifetime of water consumption, an individual is exposed to a large array of substances that the water contains, and some of these may have long-term effects that can be potentially detrimental to health. A large body of epidemiological evidence indicates that water quality is correlated with mortality rates and a variety of chronic and acute illnesses. Water quality may also have more subtle effects, for example on behaviour, immune response, and reproduction (Hall, 1984).

As water quality continues to deteriorate on a global scale, public concern is increasingly focused on the future of our water supply. Contamination has reached even the most remote areas because of the great distances many pollutants can travel in the atmosphere. Pristine environments no longer exist anywhere on our planet. An examination of annual ice deposits in Greenland, for example, shows increases in metal contamination of 70 percent during the period from A.D. 1200-1870, 210 percent by the 1950s, and 460 percent by the 1960s (Morrison, 1984).

The problem of contamination is not limited to surface waters. Many groundwater aquifers have become unusable because of accidental leaching or chemical spills. Groundwater is easily tainted and the effects are more severe than in surface waters because microbial activity and photochemical degradation, i.e., processes which are important in the breakdown of many contaminants in surface waters, are not available in subsurface regions. In Manitoba, for example, there are many instances of contamination from sources such as landfills, leaking underground fuel storage tanks, leaking sewage lagoons, leaching from industrial sites (e.g., wood preservative plants, aircraft and rocket fuel plants), and pollution from intensive livestock feedlot operations. Pollutants persist in the aquifer for a long time, and subterranean movements of the substances are unpredictable. Pumping of the water from a well tends to attract a stream of the pollutant by generating a net direction of flow towards the well.

Contaminants may travel substantial distances (as much as several kilometres) in an underground aquifer (Exler, 1972).

Where human population is concentrated in urban centres, the problem of water supply becomes a priority issue that must be addressed within a bewildering complex of political, economic, engineering and public health arenas. Raw water sources all too often become a battling ground between political jurisdictions, conflicting users within the watershed, and disagreements with regard to the amount of money that should be spent to safeguard water, and what level of quality it is acceptable to maintain. Because most communities are located reasonably close to their water source, inevitably the water source is affected to some degree by this proximity. In many instances there is no alternative but to draw water from a source of poor quality. Approximately half of the residents of Quebec, for example, take their drinking water from the polluted St. Lawrence River.

A good example of the myriad conflicts that can arise regarding a water source is the Winnipeg water supply. The raw water source is Shoal Lake, the bulk of which is located outside Manitoba's jurisdiction, in Ontario. Demands on Shoal Lake water by Winnipeg affect the Lake of the Woods system, which in turn falls within international jurisdiction. Shoal Lake is subject to a number of uses that are incompatible with its function as a domestic water source, for example recreational use (cottages, power boats, houseboats, roads and hydro rights-of-way maintained by chemical spraying), hunting, commercial fishing, mining, logging, winter roads across the lake surface, contamination by sewage, and garbage disposal. Disagreements among the municipal, provincial, national and international government levels, and lack of appropriate legislation, in this case particularly at the federal level, allows such a situation to continue and the negative impacts to grow, making the problem increasingly harder to resolve as a result of continually failing to address it.

Canada is also faced with the dilemma that many of its communities are located in Arctic regions, where water supply and distribution are subject to a number of unique engineering challenges that are not encountered in Southern areas. Of the many Northern communities, only larger towns have distribution systems. Where permafrost is present, pipes must be installed above ground in covered corridors called utilidors, and the water must be continuously circulated to prevent freeze-up. Utilidors may also be found in more Southern areas, where permafrost is absent, but soil depth is insufficient for pipe installation, for example in Flin Flon, Manitoba, where the town is built on naked bedrock.

The primitive water supplies in many Northern communities account for the frequent epidemics of gastroenteritis, hepatitis and other illnesses (MacLeod, 1977; Pip, unpublished data). Often the same lake or stream from which water is drawn receives the community's waste.

3

WATER QUANTITY

The adequacy of urban water supply is a primary issue as the populations of many cities continue to expand, and *per capita* water usage increases. Many centres are now near the maximum drawing capacity for their water source. The problem of assuring appropriate future water supplies is becoming a greater challenge as more and more regions are expected to experience water shortages in the near future.

The economics of most municipal water supply systems are based on the principle of "least-cost": the water is provided to the consumer for the minimum amount of capital investment and maintenance. The price is established such that the costs of collecting, storing, treating and distributing the water, and the costs of maintenance and administration, are fully recovered by the municipality. Until now, only economic costs have been considered. However, it is becoming increasingly apparent that environmental and social costs of a clean, safe water supply must also be weighed in order to arrive at a truer valuation of this disappearing resource.

Urban water demand depends on a number of factors, for example, population size, distribution of income level, types of land uses in the metropolitan area, type and density of housing, layout, dimensions and landscaping of the streets, type and degree of industrial development, climate and soil conditions. Another significant factor in the amount of water demand is the pricing policy for the commodity. Pricing rate structures may encourage or discourage excessive consumption, and this can be an effective tool in regulating demand.

In all urban centres, there are several classes of water consumers: residential, commercial, industrial and municipal. Any kind of pricing policy generally favours some classes over others (Milliken and Taylor, 1981), and thus inadvertently encourages particular consumption patterns. A number of basic pricing structures exist. In the flat rate system, the water is not metered and a standard fee is charged per unit time regardless of the actual volume consumed. The fee may be set on the basis of criteria such as household size, lot size, *etc*. This system offers no incentives to conserve the resource.

Metered pricing is based on the volume of water used. According to Milliken and Taylor (1981), three main types of metered pricing schedules exist. In the first type, a given unit of water has the same price regardless of the total volume used. In the second type, i.e., regressive rate structure, the cost is reduced for additional volumes that are used above a certain threshold amount. Here the commercial and industrial users benefit. The third type, i.e., progressive rate structure, imposes higher charges for additional volumes above a certain threshold amount. This system favours low volume users. Because of the universal emphasis on economic development and industrial growth, it is not surprising that the second type, the regressive structure, is the most common.

4

Cities that are faced with imminent water shortages can deal with this problem in a variety of ways. Usually the first step is to implement voluntary conservation education programs in which the consumer is made aware of the value of the water resource, and of the benefits of conservation to economy and environment. Municipalities under stress may also opt to restrict the service area, and thus curtail the rise in costs associated with urban sprawl and endless expansion of the distribution system.

During periods of shortfall, many centres may adopt the severe measure of rationing. This is usually a temporary solution, and may be enforced through the application of fines. In other cases, the city may elect to tolerate chronic water shortage and impose restrictions on water supply (Berry and Horton, 1974). In Lviv, Ukraine for example, water supply is routinely shut off for a specified number of hours each day. Such a regime may unfortunately be associated with adverse health effects, as microorganisms can multiply rapidly in the distribution system during the shut-off period. Significant associations have been reported in South Wales between intensity of water supply restrictions and gastrointestinal complaints (Dart and Stretton, 1980).

When the current source can no longer accommodate increased demand, development of new, more distant sources is the usual approach taken by most water utilities (Grima, 1972). In the case of Winnipeg, which already has a distant primary source, supplementary sources that are closer, but of poorer quality than the primary source, are being considered. At present, residential water consumption in Winnipeg is approximately 300 litres *per capita* per day.

Encouraging or even legislating water conservation can delay the need for increased water supply. While water consumption depends on environmental factors such as climatic conditions, social and economic parameters also have a significant effect. Domestic water use can be correlated with economic status of the household (for example disposable household income, market value, size and type of dwelling, size of lot) (Grima, 1972; Ligman *et al*., 1974). More affluent households tend to consume more water not only because they don't worry about the cost for essential uses such as personal consumption, bathing and cleaning, but they also have a greater number of taps and water-using appliances (e.g., humidifiers, dishwashers, garburators, pressurized dental hygiene devices, whirlpools, waterbeds, *etc*.), as well as more servicing demand (e.g., more cars to wash, more lawn to water).

Several approaches can be adopted to conserve water. These include: reduction of non-functional water uses, installation of water-conserving devices, and use of water recycling systems. Reduction of non-functional water uses is self-evident and involves such non-essential uses as in fountains, spas, ornamental and swimming pools, and car washing and lawn sprinkling. Non-functional

water use can be restricted by arbitrary legislation or imposing a premium on water volumes that are in excess of a specified *per capita* amount.

Some municipalities have also advocated reduction of functional water uses, for example taking showers instead of baths, taking briefer showers, reducing the number of toilet flushings, reducing waste during shaving, tooth-brushing, *etc.*, and finding and repairing leaks (Milliken and Taylor, 1981).

An examination of water use within the household shows that some uses account for disproportionately large shares of the total water volume. The following estimates have been provided by Milliken and Taylor (1981) for average household use (excluding external uses):

toilet flushing	45%
bathing	30%
laundry and washing	20%
drinking and cooking	5%

The estimate of five percent for drinking and cooking is very generous and usually is probably even less. Thus more efficient models of washing appliances and plumbing fixtures could have the potential to reduce substantially the total water usage.

Considerable research has been done on water-conserving devices. Many such devices currently available on the market have the advantage of being cheaper and of superior design compared to the older versions. One significant document in this field has been published by the Rocky Mountain Institute (RMI, 1988). Significant savings in water usage can be achieved through the use of faucet regulators and aerators, low-flow showerheads, and high-efficiency toilets. Some comparisons between conventional and efficient designs are given in Table 1:

TABLE 1: COMPARISONS OF AVERAGE WATER USAGE (AS LITRES PER MINUTE) BY CONVENTIONAL AND EFFICIENT FIXTURES. DATA ARE FROM ROCKY MOUNTAIN INSTITUTE (RMI, 1988).		
	Conventional	Efficient
Bathroom and kitchen faucets	13.3	1.9 - 9.5
Showerheads	17.1*	6.8 - 9.5
Toilets (volumes per flush)	13.3 - 19.0	<1.0 - 5.7

* may exceed 30

As an outcome of the 1989 drought conditions that caused widespread water shortages in the United States, that country has adopted legislation requiring installation of water-conserving toilets in all new

constructions and in renovated bathrooms. Conventional toilets are estimated to consume at least 30-40 percent of the daily household water budget (Hanley, 1989).

Water recycling is applicable primarily to commercial and industrial consumers who can reuse process and cooling water a number of times before drawing on a fresh supply. Systems available for commercial and public facilities include wastewater treatment and recycling processes that divert treated water for use in toilets. Such systems may reduce wastewater discharge up to 95 percent (RMI, 1988). Appropriate designs are available for specific situations, for example recycling systems for car washes (RMI, 1988).

Municipalities may also reduce water waste by monitoring for leakage from mains and connections, regulating overflow and dumping from storage reservoirs, and reviewing uses such as water used for flushing mains and storm sewers, street washing, and watering parks and boulevards.

WATER QUALITY

While every community needs to be assured of an adequate quantity of water supply, that water must also meet a number of aesthetic and public health standards. The level of these standards, however, has historically been the subject of much debate. How pure must our water be in order to be acceptable, and how much money are we prepared to spend to bring that water within the chosen level of acceptability? Water supply systems require capital expenditures for installation, maintenance, repair and replacement. The latter, particularly, consumes a large part of the operations budget. It has been estimated that all pipe 70 or more years old has to be replaced (Reeves, 1984), and this becomes costly given the age of most cities. In addition, the water quality has to be monitored, and appropriate treatment applied. Often it is difficult for the systems to pay for themselves, as most urban centres must maintain rate structures that do not put this essential commodity out of reach of consumers (Reeves, 1984), in view of the basic role of an adequate water supply not only for a good personal standard of living, but also for maintenance of urban sanitation, fire control, and industrial uses.

A major dilemma faced by all urban water supply systems is the escalating cost of treating greater and greater volumes of raw water that is of poorer and poorer initial quality, to standards that become more and more stringent with time. The treatment of water to a level that is acceptable for drinking accounts for a major portion of the municipal budget. However, less than five percent of this water is actually used in drinking and cooking. The remainder is not utilized for purposes which require the water to be of drinking water standard. While simple economics would advocate two separate water systems, with the savings to be had on treatment in the long-term, such a design has not been implemented in practice. The reason for this is that public health risks would be too great, as many

7

consumers would by accident or ignorance use the wrong water for drinking, or ingest it accidentally while using it for other purposes.

The standards of purity that society is willing to accept for its drinking water are closely tied to scientific knowledge of the health effects of various contaminants, and the ability of technology to measure them. We have progressed enormously from 1798, when Dr. Joseph Browne set out his standards for water in New York: water "that is clear and from a running source, that boils leguminous vegetables tender, in which soap readily dissolves, and has no bad flavour, may be pronounced good water" (see Blake, 1956). In Canada at present, domestic water supply and quality monitoring is primarily a responsibility of the provinces and municipalities. However, national drinking water quality guidelines were first put forward in Canada in 1968 as a result of joint efforts of the federal and provincial governments and the Canadian Public Health Association (Morrison, 1984). Current water quality standards are compiled in the Canadian Water Quality Guidelines prepared by the Task Force on Water Quality Guidelines, and the Guidelines for Canadian Drinking Water Quality prepared by the Federal-Provincial Subcommittee on Drinking Water. The guidelines are periodically revised and updated, and additional substances catalogued, as new scientific information comes to light. The World Health Organization has published broader and in many cases more stringent standards than those set out in the Canadian guidelines.

A number of weaknesses are associated with most water quality guidelines. "Safe" limits are based on available information. Such information may be inadequate because it is drawn from epidemiological data that are muddied by spurious statistical outcomes and confounding factors. A large proportion of urban populations is highly mobile and it is difficult to trace individual exposures. According to Schneiderman (1978), "migration dilutes (or disperses) the effects of pollutants." Toxicological data may often be based on experimental data for animals. Many effects require a long time before they become measurable. The latency period for human cancer may be 30 years or more (Schneiderman, 1978), while animal tests use relatively short-lived species. Usually no test is continued beyond two years' duration. Other effects may be very subtle, operating at the reproductive or behavioural level for example. In many cases, the same agent may have different effects at different dose levels, showing abortifacient, teratogenic and carcinogenic properties at various concentration ranges (Miller, 1983). However, epidemiological and experimental studies are often restricted only to specific effects and thus the information gained may be incomplete. For these reasons, many limits have been repeatedly revised downwards as new effects have become apparent.

Inevitably, each parameter has a different amount of scientific and practical data to support the standards that are set out (Robeck, 1974). The effects of many, indeed most, chemicals are not yet

known and therefore any guidelines can only reflect the extent of information available at a given time. Mercury, for example, was not included in the U.S. Drinking Water Standards in 1962, because it was not viewed as a contaminant likely to be of widespread significance (Robeck, 1974), but understanding of this element has since changed drastically.

Another difficulty in estimating the effect of a given agent derives from the fact that each parameter is usually considered in isolation. The presence of other, potentially hazardous substances and possible additive, synergistic, or antagonistic interactions are not often taken into account, because in most instances little is known about such interactions.

Human exposure to a particular agent may come from a combination of sources in addition to the exposure from water; such sources may include contact with air, food, soil, drugs and consumer products in a whole range of baffling relative proportions and pathways (e.g., McKone, 1991). Thus acceptable limits in water should ideally be set to accommodate the whole exposure, but in practical terms this is very difficult to estimate, and varies tremendously from individual to individual.

For substances that are known to be carcinogenic in animals, an "acceptable" threshold cannot be established, since any exposure carries some risk, and subgroups exist in any population that are more susceptible because of other predisposing factors (Rohlich, 1978).

In the setting of standards for individual chemicals, analytical capability is often an indirect factor (Robeck, 1974). The concentration that is "acceptable" must be measurable. As technology improves, the threshold concentration which can be reliably measured decreases, and this may have an impact on the standards for trace substances, such as many organics.

Attainability of a prescribed standard is also a consideration. The standard must be achievable with accessible technology within a reasonable cost. Thus the cost of maintaining a particular standard must be weighed ethically against the health costs if the standard is not met.

WATER QUALITY PARAMETERS

Drinking water quality is assessed in terms of physical, chemical and biological parameters which are deemed to be important because of health or aesthetic reasons. While virtually thousands of different chemicals can be found in water, because of practical considerations only certain parameters can be included in general assessments of drinking water quality. According to Robeck (1974), "a certain abundance and general widespread occurrence are necessary before a specific constituent is considered for inclusion in the Drinking Water Standards." Theoretically, a given water sample may fall within the drinking water standards, yet can possibly contain toxic concentrations of a rare substance that is not included in the standards.

PHYSICAL PARAMETERS

Physical parameters include colour, odour, turbidity, and presence of floating materials such as oil and grease or debris. Because these parameters may each reflect a large array of substances, they are difficult to quantify.

Colour

Colour may originate from colloidal forms of iron and manganese, or more commonly it may be the result of dissolved organic compounds in the water. Natural sources of dissolved organic substances include materials excreted by living organisms, and the products of decomposition. Organic materials are also leached from soils and may enter the water source with runoff. Most commonly, colour in surface waters is due to humic substances, particularly fulvic acids (CWQG, 1987). Additional organic substances may be contributed from industrial effluents and sewage. Municipal treatment plants may use coagulation, sedimentation and filtration to reduce colour to acceptable standards.

Taste and Odour

No instruments exist to quantify taste and odour in water, and therefore monitoring is subjective. Guidelines usually stipulate that there shall be "no objectionable taste or odour." However, taste and odour thresholds vary greatly from individual to individual (Holden, 1970). Undesirable odours in water are due primarily to the presence of organic compounds. These may be produced by organisms such as actinomycetes and algae, or be the result of decomposition processes of organic matter. Industrial contaminants, and pollutants such as oil and gasoline may taint the water supply. Occasionally the municipal water treatment process may result in objectionable odours and tastes where such did not exist in the raw water. For example, chlorination may convert some dissolved organic compounds such as phenols and amines to chlorinated entities that have very low threshold values.

Taste can be affected by a number of factors, for example, temperature, pH, presence of certain microorganisms (e.g., iron bacteria), chlorine residuals, the dominant cations and anions, and presence of iron and sulphur compounds (CWQG, 1987).

Oil and Grease

Most standards stipulate that domestic water supplies should be free from oil and grease. This material may be composed of any combinations of thousands of volatile or nonvolatile compounds. They may originate from natural plant and animal lipids, or they may be the result of contamination with petroleum products or industrial effluents containing synthetic compounds. In domestic water supplies, oils commonly gain entry from leaky boat motors, spills and leaching from fuel storage tanks, and lubricants used within the distribution system. Some oils may degrade readily, while others are highly persistent. Toxicity varies with the specific substances present. Many groups, such as the polycyclic

aromatics, are known carcinogens. Oils of plant or animal origin are generally considered nontoxic to humans (USEPA, 1976). The taste threshold for some compounds can be extremely low.

Turbidity

Turbidity and suspended solids reflect the inorganic and organic particles that are suspended in water. Turbidity is objectionable in municipal water not only from an aesthetic standpoint, but in terms of health concerns. Particles may contain microorganisms that are shielded from chlorine disinfectant (USEPA, 1976) or ultraviolet radiation. Some particles, such as asbestos, may pose direct health hazards (Rohlich, 1978). Many particles may carry high concentrations of adsorbed metals or toxic organics.

Total Dissolved Solids

Total dissolved solids consist of all inorganic and organic compounds dissolved in the water. High concentrations of dissolved solids may affect taste, and precipitates may form on the walls of distribution systems and in hot water tanks. Specific health effects depend on the nature of the substances present.

Hardness and Alkalinity

Water hardness is a reflection of the cations present in water. Primarily these are the divalent cations calcium and magnesium, although other elements such as barium, iron, aluminum, manganese and strontium may contribute to the hardness value when they are present. Total hardness is expressed as the equivalent concentration of calcium carbonate. In Canada, the hardest waters are found in Saskatchewan, Manitoba and Southern Ontario (Meranger *et al.*, 1979).

A number of studies have shown that hard water may be associated with reduced incidence of cardiovascular diseases and reduced death rates from related causes such as cerebral haemorrhage (see Andelman, 1974; Twort *et al.*, 1974; Morton *et al.*, 1976; Morrison, 1984). However, hardness in itself may not be a direct protective agent in this regard, but rather, it is typically correlated with concentrations of various trace elements (Andelman, 1974). Many deleterious trace element compounds may become more soluble and/or be more easily absorbed in waters of reduced hardness. An abundance of calcium and magnesium also reduces leaching of metals and corrosion within the distribution system. The hardness affects the amount of chemicals that must be added for coagulation and softening during treatment.

Alkalinity is a measure of the ability of water to neutralize acid, and thus reflects its buffering capacity. It is estimated by titrating with acid until a set pH is reached. Substances which may affect alkalinity include the various forms of carbonate, phosphate, silicate, sulphide and ammonia; metals

such as iron, manganese and magnesium; and organic acids, gases, and suspended particulates (CWQG, 1987).

Precambrian Shield waters typically have low alkalinities because of the low amounts of dissolved substances. In the absence of contaminants, such water sources require very little treatment. Winnipeg's water source, for example, is treated only by coarse screening, chlorination and fluoridation. Waters with low alkalinites have a high aggressive index, i.e., they easily leach out materials from substances with which they come into contact.

INORGANIC PARAMETERS

A.   *Macroscopic Substances*

■   Chloride

Chloride standards are set primarily with respect to taste considerations. Many surface and ground water sources, particularly on the Prairies, may have significant concentrations of chloride. Precambrian Shield waters, on the other hand, have very little chloride. At higher concentrations, chlorides may be very corrosive, and can react with steel in the distribution system (Denholm and Potter, 1971; Lorch, 1987).

■   Nitrogen and phosphorus

The presence of phosphorus and nitrogen in surface waters results in growth of algae (e.g., Zdanowski, 1982). The main sources of nitrogen and phosphorus are runoff from agricultural lands (from chemical fertilizers and livestock and poultry waste), contamination from upstream communities or recreational use (cottage developments, houseboats, bathing) and atmospheric deposition. Contamination of groundwater is primarily the result of leaching of fertilizers and livestock waste.

Inorganic nitrogen may be present in water as ammonia, nitrate and nitrite. Ammonia is very soluble and readily enters the water source from runoff and soil percolation. Ammonia is excreted by aquatic fauna, and is a natural product of decomposition. Additional inputs may originate from wastewater, fertilizers, and industrial activity. Ammonia is toxic, corrosive, and promotes bacterial growth (Lorch, 1987). The fate of ammonia in the water depends to some extent on the characteristics of the latter. In well-aerated surface waters, ammonia does not accumulate but is converted by nitrifying bacteria (i.e., nitrite and nitrate bacteria) into nitrate. Under anaerobic conditions, however, ammonia tends to persist. Concentrations above 0.1 mg/L usually indicate pollution.

Nitrate is the predominant form of inorganic nitrogen in most natural waters. Inputs from human activities may create significant nitrate loadings, for example, from wastewaters, fertilizers, feedlots, and leaching from landfills. Some groundwaters may achieve high nitrate levels, since, unlike

12

in surface waters, algal and aquatic macrophyte growth is not present to remove it. Significant numbers of groundwater wells in Manitoba and Ontario have been reported to contain high nitrate levels (see Holden, 1970).

Nitrite is normally present in very low concentrations, since it is rapidly converted to nitrate by microorganisms when dissolved oxygen is present. Presence of higher concentrations of nitrite indicates pollution and oxygen depletion. Nitrite in drinking water has been associated with methaemoglobinaemia in infants. Occasionally fatal poisonings have been reported in infants at concentrations of more than 10 mg/L in some groundwaters (USEPA, 1976). However, individual sensitivity is highly variable.

Nitrates have been investigated for possible links with gastric cancer, although outcomes have been inconclusive (see RCEP, 1992). In Australia, nitrate concentrations of 5-15 mg/L in drinking water have been linked to increased rates of birth defects such as spina bifida (GPP, 1988). In the acidic conditions of the gastrointestinal tract, nitrites may form nitrous acid, which can react with secondary and tertiary amines that may be present in food or as contaminants in the water, to produce carcinogenic nitrosamines (Atkinson, 1978; APHA, 1985).

Nitrogen may be also be present in water in a wide variety of organic compounds, for example, amino acids and amides, as the result of secretion and decomposition of biota.

In surface waters, phosphorus is a very important indicator of water quality because it is generally the chief limiting factor for algal growth. Phosphorus in groundwater sources originates primarily from agricultural fertilizers and livestock operations. In surface waters, fertilizers and domestic wastewater may provide significant phosphorus loadings to the water source. Human excretion alone has been estimated at 0.55 kg phosphorus *per capita* per year (see Vollenweider, 1968). While the amount of phosphorus in soaps, laundry detergents and dishwashing detergents has been restricted in Canada (Wall and Webber, 1970), cleaning agents such as TSP (trisodium phosphate) may contain a great deal of phosphorus. Much of the phosphorus in septic tank effluent is in the form of orthophosphate (Otis *et al.*, 1977), the form most readily assimilated by algae.

Aside from the nutrient contributions of detergents, these substances may also be a problem in water supplies by causing frothing, and hampering flocculation by coagulants during water treatment (Lorch, 1987).

■   Sulphur compounds

Sulphur may occur in water as inorganic sulphate or sulphide, or in organic compounds. Sulphur dioxide emissions from the burning of coal, from smelters, and from pulp and paper mills may create significant problems with acid rain. Acidification of natural waters leads to a deterioration of water

quality because of the resulting increases in heavy metal availability, corrosion of distribution systems, and impoverishment of the biota that live in the water source.

Hydrogen sulphide is a toxic, highly soluble gas which results from anaerobic decomposition of organic matter and microbial conversion of inorganic sulphates. The taste and odour threshold is very low, and thus very small amounts are sufficient to generate consumer complaints. Industrial wastes may also contribute sulphides.

Sulphate concentrations in Canadian waters vary from almost undetectable levels in some Precambrian Shield areas to more than three grams per litre in some Prairie groundwaters. Sodium sulphate brines in Saskatchewan and Southern Alberta are the sources for commercial sulphate production (CWQG, 1987). Sulphate can occur as a number of different salts, for example in combination with calcium, magnesium, sodium, potassium and others. Most sulphate salts are highly soluble. At higher concentrations, sulphate salts affect taste of the water, but the taste threshold depends on the type of sulphate salt present; for sodium sulphate this value is in the range of 200-500 mg/L, but is higher for other types (CWQG, 1987).

Potassium sulphate is used as fertilizer. Sulphate may also enter the water supply as a result of aluminum sulphate coagulants added during water treatment, or use of copper sulphate in reservoirs to control algae.

Drinking water with high sulphate concentrations may cause abdominal cramps and diarrhoea, particularly in children (CWQG, 1987). Where coagulants such as aluminum or iron sulphate are added to the water during the treatment process, this may cause significant increases in sulphate content of the finished water.

B.   Trace Inorganics

While any chemical element may be present in natural water as a result of the soil and bedrock composition in the watershed, or from anthropogenic sources, the rarer elements are usually not detectable, and thus are not routinely monitored. Health risk data are poor or unavailable for many such elements. Some of the more common trace elements are considered here.

■   Aluminum

Aluminum may enter the raw water source from leaching of aluminosilicate minerals, atmospheric deposition from smelters and burning of coal, and mining activities. Aluminum levels may become significant in acidic waters. Corrosion of aluminum surfaces is of concern if the water contains copper (Twort *et al.*, 1974), and thus all water supplies associated with copper plumbing, for example, will be subject to this problem when aluminum cookware is used. The problem is more severe in hard

waters (Holden, 1970). Aluminum may be present as a residual in the finished water when aluminum sulphate is used as a coagulant during water treatment (Twort *et al.*, 1974).

Aluminum is very poorly absorbed in the gastrointestinal tract (Beliles, 1979). No guidelines currently exist with respect to aluminum in Canada or the United States because of insufficient information regarding the health effects and risks posed by this metal in drinking water. Morton *et al.* (1976) found a positive correlation between aluminum concentrations in water and incidence of human central nervous system malformation rates. At massive doses, gastrointestinal irritation and rickets are produced (Beliles, 1979). The possible role of this metal in Alzheimer's Disease is being scrutinized.

■   Antimony

Sources of antimony in natural waters include leaching of minerals, mining and industrial effluents, smelters, and burning of fossil fuels. Antimony may occur in organic and inorganic complexes of varying solubility and toxicity. No guidelines at present exist for antimony in the Canadian Water Quality Guidelines due to insufficient data regarding its toxicity. The taste threshold for antimony in water has been reported to be 0.6 mg/L (CWQG, 1987). High concentrations cause gastrointestinal distress, and cardiac and liver toxicity (Beliles, 1979).

■   Arsenic

Arsenic may exist in water in a number of forms, the most common being the trivalent or pentavalent inorganic forms, or in organic compounds. While all forms are toxic, the trivalent form is of greatest concern (USEPA, 1976). Arsenic can gain entry to a water source through a number of routes. Processing of arsenopyrite ores for metals such as gold can result in contamination with leachate from tailings. Both ground and surface waters can be tainted with leachate from landfills where arsenical pesticides are used by municipalities to control rat populations. Some paints and metal alloys may contain arsenic.

Inorganic arsenic is readily absorbed in the gastrointestinal tract, and to some extent through the skin (USEPA, 1976). Chronic exposure to trivalent arsenic results in accumulation in bone, muscle and skin. Toxic levels cause nervous disorders, gastrointestinal disturbance, and damage to kidneys and respiratory tract (Moore and Ramamoorthy, 1984). Increased intake of arsenic has been linked to heart attack (Gillies, 1978). Epidemiological studies have demonstrated a relationship between arsenic in drinking water and elevated rates of skin cancer (e.g., Berg and Burbank, 1972; Robeck, 1974; USEPA, 1976).

■   Barium

Barium compounds vary in terms of their solubility. If sulphate is present, barium concentrations are relatively low because of the low solubility of barium sulphate (Gillies, 1978). In

general, the more soluble forms are more easily absorbed in the intestine and are more toxic. The threshold toxic dose in humans has been reported to be 200-500 mg of absorbed barium (Proctor *et al.*, 1989), and water supplies generally show several hundred-fold lower levels per litre. Barium is found primarily in the skeleton, with lesser concentrations in other tissues (Beliles, 1979). Barium affects heart muscle, showing digitalis-like toxicity symptoms at high concentrations (Beliles, 1979), and may elevate blood pressure by constricting blood vessels (USEPA, 1976). At high concentrations, barium ions are physical antagonists of potassium, and act as a muscle poison (Proctor *et al.*, 1989). Barium is readily excreted and does not appear to reach high concentrations in tissue (USEPA, 1976). Few data are available regarding barium concentrations in Canadian drinking water (CWQG, 1987).

■   Beryllium

Aside from leaching of minerals, the major source of beryllium in the environment is the burning of fossil fuels (CWQG, 1987). Canadian Water Quality guidelines do not exist for this element in drinking water, because available data indicate that it is very rarely a problem. Berg and Burbank (1972) found correlations between cancer mortality and concentrations of beryllium in water supplies.

■   Boron

While boron is normally found in very small concentrations in raw waters, groundwater may on occasion contain significant amounts, for example in some areas of the southwestern U.S., and in some hot springs. Boron may occur in water in both inorganic and organic forms. Boron contamination may occur from wastewater, where boron compounds are used as water softeners, cleansers, or antiseptics (e.g., borax, boracic acid). Some pesticides contain boron. Some of the higher boron concentrations in Canada have been reported in Prairie regions of Manitoba and Saskatchewan (CWQG, 1987).

■   Cadmium

Cadmium may enter the environment from mineral leaching, mining and smelting activities, metal and plastic industries, burning of fossil fuels, and use of some pesticides. Sewage lagoon sludge contains significant amounts of this metal, and disposal of the sludge or application to fields as fertilizer may cause surface and groundwater contamination.

Cadmium is of concern because even exposures that are very low are associated with long retention times in the body (Lauwerys, 1979), particularly in the liver and kidneys (Kjellstrom and Nordberg, 1978; Hodgson and Guthrie, 1980). The half-life in human organs has been reported to vary from 10 to 30 years (see Moore and Ramamoorthy, 1984). Cadmium can be transferred across the placenta (USEPA, 1976). Chronic ingestion of cadmium in drinking water and food has been associated with itai-itai disease, characterized by back and joint pain, bone softening and renal problems (Proctor *et al.*, 1989). Cadmium has been linked to hypertension (Gillies, 1978).

Evidence exists for carcinogenic properties of this metal, with the kidneys generally being the site of the initial lesion (Heath *et al.*, 1962; Lauwerys, 1979). Berg and Burbank (1972) found correlations between cancer mortality and concentrations of cadmium in water supplies. Cadmium levels are significantly higher in smokers, as tobacco is rich in cadmium (Piscator, 1979). Zinc and calcium may reduce the effects of cadmium (Gillies, 1978).

■   Chromium

Chromium is a necessary trace element in human nutrition, and deficiency is associated with glucose intolerance and reduced insulin response (USEPA, 1976), mimicking diabetes mellitus. Chromium deficiency has also been linked to atherosclerosis (Gillies, 1978; Beliles, 1979). Only 0.5-1 percent of ingested chromium III is absorbed from the gastrointestinal tract (Rindia, 1979). The total amount of chromium in the body decreases with age (Rondia, 1979). This element is transported across the placenta (Beliles, 1979).

At higher concentrations, the health effects and toxicity of chromium depend on its valence state: divalent (Cr II), trivalent (Cr III) or hexavelant (Cr VI). Cr II and III are believed to be comparatively nontoxic (Proctor *et al.*, 1989). Cr VI has been associated with kidney damage and discolouration of the teeth. Cr VI is more readily absorbed in the gastrointestinal tract than the other forms (Rondia, 1979). Because Cr VI is also absorbed through the skin and is a skin sensitizer, concerns have been raised regarding bathing in water which contains high chromium levels (USEPA, 1976). Some carcinogenic properties have been demonstrated for this metal (Norseth, 1979; Moore and Ramamoorthy, 1984).

Leaching of minerals, industrial activities such as metal plating and cement manufacturing, and burning of fossil fuels are major sources of chromium in water. This element can also gain entry into the water supply from contact with lead chromate and zinc chromate pigments. In surface water, the ratio of Cr III to Cr VI is affected by amount of dissolved oxygen and organic matter present; organic matter increases the proportion of Cr III (see CWQG, 1987).

■   Cobalt

At low concentrations, cobalt is an essential element in human nutrition, because vitamin B12 contains 4.35 percent cobalt by weight. This metal accumulates primarily in muscle and fat (Beliles, 1979). At toxic concentrations, the red blood cell count is elevated, and gastrointestinal disturbances, slowed respiration, and loss of hearing may be evident (Beliles, 1979). High levels of cobalt in drinking water are associated with higher incidence of goitre (Beliles, 1979). Cobalt may enhance the cardiotoxic properties of other compounds (Balazs and Ferrans, 1978).

Cobalt may enter water from weathering of a great variety of rock types. Other sources include atmospheric fallout from smelters (e.g., Flin Flon, Manitoba), and mine drainage. Ontario and Manitoba are the largest producers of cobalt in Canada (CWQG, 1987).

It is interesting to note that, since coffee has been reported to contain high levels of cobalt (see Beliles, 1979), ingestion of coffee made with cobalt-containing water might yield a significant chronic intake.

■   Copper

Copper is essential in human nutrition, and is generally considered to be nontoxic to humans at the concentrations encountered in municipal water supplies. Deficiency of copper results in anaemia (Shamberger, 1979). This element is also necessary for structural integrity of bone collagen.

Copper is more soluble in acidic waters. The standards that are set are based on aesthetic considerations of taste (detectable in excess of 1 mg/L), and staining of laundry and plumbing fixtures (USEPA, 1976; CWQG, 1987). The concentrations normally found in natural waters have not been demonstrated to have adverse effects on human health, although excessive doses of copper may cause liver damage (USEPA, 1976).

Copper levels may be elevated in raw water sources and reservoirs where copper sulphate has been used to control algae, and increases in the distribution system as a result of contact with copper plumbing. Presence of even small amounts of copper in water may cause accelerated leaching of other metals within the distribution system (Twort *et al.*, 1974).

■   Cyanide

Cyanide is found in low concentrations in many natural surface waters as a result of decomposition of plant matter and activity of microorganisms. Additional amounts may originate from gold mining activities and industrial effluents. Cyanide may be present as free ions in water, as salts, or as organic complexes (e.g., nitriles and other organics). Cyanide may combine with metals to form complex metallocyanides, the stability of which varies, depending on the specific metal and oxidation state involved. Cyanide reactions, and thus toxicity, in surface waters may fluctuate on a diurnal basis because during daytime some forms, for example iron cyanide, may undergo photodecomposition, releasing free cyanide ions (USEPA, 1976).

Persistence of cyanide in water is highly unpredictable and depends on a large array of factors. Cyanide ingested by humans at total amounts of less than 10 mg per day is not considered toxic, since at these levels the body is able to transform it to thiocyanate, which can be slowly eliminated by the kidneys (USEPA, 1976).

■   Iron

Iron is essential for proper human nutrition. It can exist in aquatic environments as either the divalent or trivalent inorganic form, as well as in organometallic substances. The divalent (ferrous) form is soluble and exists in anoxic environments, such as groundwater or in deeper strata of poorly aerated impoundments. The trivalent (ferric) form is found where dissolved oxygen is present and is largely insoluble. In this state, it may form colloids of ferric hydroxide that are suspended in water and settle as flocs on the bottom.

A commonly encountered form of iron in deoxygenated waters is ferrous carbonate. Water which contains this form appears clear when first drawn, but on exposure to air becomes reddish due to the formation of ferric hydroxide. If hydrogen sulphide is present, combination with iron may yield ferrous sulphide, which forms a black sediment.

Iron is undesirable in domestic water supplies because it affects taste, forms scale on pipes and tanks, and stains laundry and plumbing fixtures (Lorch, 1987). Standards are thus set primarily because of aesthetic considerations. At extremely high concentrations iron may be toxic to livestock and interferes with phosphorus metabolism (USEPA, 1976).

■   Lead

While some lead gains entry into the environment from leaching of lead-containing minerals, most of the lead originates from human activities, for example wastewater discharges, mining and smelting, and burning of fossil fuels (CWQG, 1987). Reduction in the use of leaded gasoline has contributed to a decrease in lead emissions during the last decade. Lead may exist in water in a number of valency states, and may also complex with organic substances. Significant amounts of lead may be contributed through the municipal distribution system.

The health effects of lead have been reviewed by Ewing and Pearson (1974) and Ferm and Carpenter (1967). Lead is considered to be a neurotoxin (Miller, 1983). Chronic absorption of lead may be manifested in such nonspecific complaints as weight loss, insomnia, weakness, anaemia and gastrointestinal problems and abdominal pain (Proctor *et al.*, 1989). Heme synthesis is disrupted (Gillies, 1978). In children, lead poisoning is associated with brain and renal damage (USEPA, 1976). Hyperactivity has also been linked to elevated lead exposure (see Weiss, 1979). In animals, high levels of lead have been implicated in defects of the skeletal and central nervous systems of embryos, renal tumours, and reduced viability (Ferm and Carpenter, 1967; Mao and Molnar, 1967). Lead is transported across the placenta to the fetus (Di Ferrante, 1979). Lead accumulates primarily in bone, liver and kidney tissue, and the primary route of excretion is through the bile and intestinal mucosa (Hodgson and Guthrie, 1980). However, excretion is very slow (Proctor *et al.*, 1989), and thus

absorption rates often exceed elimination rates, leading to accumulation in the body. Berg and Burbank (1972) found correlations between cancer mortality and lead concentrations in water supplies.

According to Kehoe (1961), approximately 10 percent of lead dissolved in water is absorbed in the intestinal tract in adults. However, gastrointestinal absorption may be as high as 50 percent in children (Hodgson and Guthrie, 1980). Women and children are also relatively more sensitive to lead (Di Ferrante, 1979).

■ Manganese

Manganese is an essential trace element in human nutrition. It is a co-factor for many important enzymes. Manganese is necessary for proper bone and cartilage development. It accumulates in liver, kidneys, intestine and pancreas (Beliles, 1979). While manganese has been linked with liver damage at extremely high doses (USEPA, 1976), it is not normally a health concern in municipal water supplies. However, high levels of both manganese and zinc in drinking water have been linked to an outbreak of an encephalitis-like illness in a town near Tokyo (Holden, 1970). At concentrations greater than 150 ug/L, taste is affected and consumers complain of brownish staining of laundry. The presence of iron may intensify these effects.

Some fertilizers, antiknock compounds in gasoline additives, and burning of diesel fuel are common sources of contamination of water (Beliles, 1979).

■ Mercury

Mercury may exist in a variety of inorganic and organic forms. Approximately 5-15 percent of inorganic mercury ions ingested is absorbed in the gastrointestinal tract, but for organic forms 80-100 percent may be absorbed (Gatti *et al.*, 1979). Mercury accumulates primarily in the kidney, but appreciable amounts also enter the brain and kidneys (Gatti *et al.*, 1979). Excretion rate and toxicity depend on the chemical form of the mercury ingested (Hodgson and Guthrie, 1980). The half-life of methylmercury in the body has been reported to range from 35 to 189 days (see Moore and Ramamoorthy, 1984).

Minamata disease results from organic mercury poisoning. Methyl and ethyl mercury affect central nervous system functions, and have been implicated in effects such as sensory and motor disturbances, behaviour disturbances, and mental retardation (Weiss, 1979). Cerebral palsy has also been reported (Weiss and Doherty, 1975). Chronic exposure is associated with numbness and tingling of extremities, constriction of the visual field, and hearing impairment. Mercury easily crosses the placental barrier (Butler, 1979). In the fetus, which is twice as sensitive to methyl mercury as the adult, this compound causes neurologic damage (Proctor *et al.*, 1989). Elimination of mercury from the body is slow and unpredictable.

20

In Canada, mercury contamination of drinking water has been associated with flooding of lands for hydro dams, and, in the past, fungicides used by pulp and paper mills. Nitrite exerts a synergistic toxic effect in combination with organic mercury. This is of concern since nitrite may be present in the water, or be ingested in food, where it is a frequently used preservative (Gatti *et al.*, 1979). Selenium, on the other hand, is antagonistic and counteracts the toxic effects of mercury. Cadmium and zinc may also suppress mercury effects. Oestrogenic hormones may protect the kidney against toxic action of mercury, and thus females may possibly be less susceptible to mercury effects at this site (Gatti *et al.*, 1979).

■   Molybdenum

While some molybdenum input to the environment comes from leaching of minerals, significant amounts originate from fertilizers, mining and burning of fossil fuels. In water it occurs in a number of valency states, and also in organometallic compounds. Molybdenum is an essential element in human nutrition, where it is required in certain metalloproteins (Shamberger, 1979). It enhances the effect of fluoride in reducing dental caries. Deficiency is associated with anaemia. Canadian guidelines for molybdenum do not exist and few data are available concerning this element in municipal water supplies. Elevated molybdenum intake has been reportedly linked with gout and bone disease (Gillies, 1978).

■   Nickel

Nickel in water originates from leaching, mining and smelting activities, burning of fossil fuels, and industrial operations. Even though this element is very common in Canadian municipal water supplies (see Rondia, 1979), it is generally present in low concentrations. Most groundwaters contain very little nickel (CWQG, 1987).

Sensitization to nickel can occur readily in some individuals. Nickel accumulates primarily in the kidneys, although high levels are also found in the heart, liver and testes (Beliles, 1979). Chronic exposure has been associated with kidney damage (Norseth, 1979). Berg and Burbank (1972) found correlations between cancer mortality and concentrations of nickel in water supplies. Manganese antagonizes the toxic effects of nickel (Norseth, 1979).

■   Selenium

Selenium may be of concern in areas where leaching occurs from seleniferous soils. Selenium contamination may also result from glass, ceramics and photocell industries, and mining and smelting activities. Domestic wastewater may contain selenium from some shampoos (Proctor *et al.*, 1989). It has been reported that selenium concentrations are greater in water bodies near urban centres (see

CWQG, 1987). Selenium may exist in water as a variety of inorganic forms, and can be methylated by microorganisms to yield organic forms.

It is uncertain whether selenium is required in human nutrition (CWQG, 1987). It is readily absorbed from the gastrointestinal tract (Gillies, 1978). High doses are toxic, with symptoms in humans that resemble arsenic poisoning (USEPA, 1976), with gastrointestinal disturbance, and heart, kidney and liver damage (Gillies, 1978). However, some studies have suggested that at lower levels, selenium compounds may retard the action of carcinogens in animals (Shamberger, 1985). It reduces the toxicity of cadmium and mercury (Shamberger, 1979). Selenium compounds may be absorbed through unbroken skin (Proctor *et al.*, 1989). Most Canadian drinking water has low concentrations of this element (CWQG, 1987).

■   Silicon

Silicon is the second most abundant element in the earth's crust, and thus is ubiquitous in natural waters. Most of the silicon originates from leaching of minerals, and contributions from human activities are limited to sources such as aerosols (CWQG, 1987). This element may achieve high concentrations in groundwater, hot springs, and brackish and saline waters. It is found in water as dissolved and particulate forms. At alkaline pH, silicate combines with iron and aluminum oxides to form precipitates. However the presence of humic compounds enhances solubility, and concentrations often increase at higher temperatures (CWQG, 1987). Silicon is an important nutrient for diatom growth, and the seasonal cycles of these algae influence silicon concentration in the water. Silicon may be added to the municipal water supply in the course of fluoridation, when hydrofluosilicic acid is used.

It has been suggested that silicon may be associated with aging processes in the body, as the aorta, skin and thymus contain less silicon the older the tissue (Shamberger, 1979). Abundance of this element can also result in scale formation on pipes and tanks (Lorch, 1987).

■   Silver

Silver is used in a variety of industrial and medical applications, for example photography, metal ware, electronic products, mirrors, and disinfectants, and is also produced during the processing of crude oil (CWQG, 1987). Some is contributed to the environment through cloud seeding with silver iodide crystals. Silver may be added to drinking water from silver oxide coatings on charcoal in water purifiers.

A guideline is set for silver in Canadian drinking water because excessive intake results in argyria in humans, characterized by blue-grey discolouration of the skin, eye and mucous membranes. This element is very poorly excreted, and tends to accumulate in the body, particularly the skin. Silver deposited in the eyes may affect vision (Beliles, 1979). While the concentrations of silver in most

water sources in Canada are believed to be low, silver may be concentrated by some vegetables during cooking (CWQG, 1987).

■   Sodium

Sodium is present in all natural waters, but can achieve high concentrations in groundwater from underground salt deposits (for example in Saskatchewan and Southern Alberta), and saline waters. In coastal areas, seawater may intrude into a freshwater aquifer (Gillies, 1978). A major additional source of sodium is the use of salt on roadways and streets to control ice and snow accumulation, and to prevent the particles in sand and gravel stockpiles from freezing together. Where sodium fluoride is used for fluoridation, this can be another source of sodium in the water supply.

Elevated concentrations of sodium in drinking water may contribute to hypertension and cardiovascular problems.

■   Tin

Tin is considered to be an essential element in human nutrition. It is found at very low concentrations in most natural waters. Sources in the environment include natural leaching, mining activities, and canning plants. Municipal wastewater may contain tin from sources such as stannous fluoride in toothpaste.

Tin accumulates primarily in the lungs and gastrointestinal tract (Beliles, 1979). Large doses of inorganic tin compounds cause neurological, renal and liver toxicity (Beliles, 1979). Organic compounds of tin (organotin) are very toxic. These substances are used in some marine boat paints to deter fouling organisms, and may gain entry to a water source from this route. Organotin has been reported in the St. Lawrence River.

■   Vanadium

Vanadium is found in minerals and fossil fuels. It is considered an essential trace element in human nutrition. It accelerates bone mineralization and inhibits cholesterol synthesis, reducing aortic cholesterol accumulation (Beliles, 1979). This element accumulates primarily in fat tissue. At higher concentrations, vanadium produces gastrointestinal distress and green discolouration of the tongue.

■   Zinc

Zinc in natural waters may be found in both organic and inorganic forms. This element is essential in human nutrition because it is present in a number of metalloenzymes. Zinc deficiency is associated with slow growth, poor appetite, impaired sense of smell, and slow wound healing (Beliles, 1979). Only a small proportion of ingested zinc is absorbed, but vitamin D enhances absorption (Beliles, 1979). Most zinc is contained in muscle and bone. It is interesting that total body content of zinc increases to a peak at approximately age 45, followed by a decline (see Beliles, 1979).

At higher levels, gastrointestinal distress and anaemia may be evident (Beliles, 1979). Zinc poisoning has been reported from the use of galvanized containers for collecting rainwater for drinking (see Holden, 1970). Cadmium is antagonistic to zinc (Beliles, 1979).

■   Radionuclides

Radionuclides may enter the raw water from a variety of sources. Substances such as uranium may be naturally present in the watershed or basin. Some areas of the Precambrian Shield are associated with unacceptably high radioactivity levels. Groundwater in the vicinity of Lac du Bonnet, Manitoba, for example, has exceeded acceptable levels in a number of local wells, which have been closed as a result. Some wells in Southeastern Ontario and Southwestern Saskatchewan have shown elevated uranium levels (CWQG, 1987).

Contamination of waters with radionuclides may also occur because of mining and processing of ores, processing and storage of nuclear fuel, and tainting by release of nuclear reactor coolants. The most widespread type of contamination, however, is fallout from nuclear weapons testing (Hamilton, 1978). More recently, nuclear reactor disasters such as that at Chernobyl, Ukraine have also contaminated water on a global scale.

Radionuclides pose a dual hazard in that they have both chemical toxicity and radioactivity. Uranium (as uranyl ions) is rapidly absorbed in the gastrointestinal tract (Beliles, 1979). The primary target organ for uranium toxicity is the kidney, which sustains damage, and deposition also occurs in bone (Proctor *et al.*, 1989). Radionuclides have carcinogenic properties, but it is not possible to distinguish between chemical and radio-carcinogenicity (Proctor *et al.*, 1989). Disintegration products of radionuclides may be other radioactive elements, for example thorium-230 from uranium.

Canadian Water Quality Guidelines (1987) list maximum acceptable limits for radium-226, tritium, strontium-90, cesium-137 and iodine-131 radionuclides as becquerels per litre. Additive effects have been given some consideration in that radionuclides which affect the same organ or tissue must not exceed acceptable totals.

■   Radon

Radon gas is often present in drinking water. In homes and buildings, it volatilizes from the water supply to increase the indoor concentrations of this gas (Moore, 1989). Volatilization of radon may be increased when the water is used for showers and in humidifiers (Gillies, 1978). According to Moore (1989), public water supplies in the United States average 240 pCi/L of radon gas, and a significant number of drinking water supplies are affected. The same author has made the startling statement that reduction of radon in drinking water supplies could decrease by about 50 percent the

2000-40,000 estimated excess cases of lung cancer, i.e., cases that are not accounted for by causes such as smoking and occupational exposures.

ORGANIC PARAMETERS

Many thousands of organic compounds may occur in water. Some are natural byproducts of metabolism of living organisms. Such compounds are relatively easily degraded. Human activities, on the other hand, have been associated with the introduction of a wide variety of synthetic organic compounds into much of the world's surface and ground water supply. As early as 1976, more than 600 organic substances of industrial origin had been *identified* in drinking waters in the U.S. (Shackelford and Keith, 1976). The environmental and health effects of most of these substances are not known, for many are too new for impacts to have yet become evident.

Several gross measures are used to estimate the amount of organic matter present in water. Biochemical oxygen demand (BOD) represents the amount of oxygen that is needed for microorganisms to oxidize matter from the organic to the inorganic form. This value may also include other oxygen-consuming processes, such as oxidation of inorganic material and reduced forms of nitrogen. Generally the value is reported as the amount of oxygen consumed during five days at 20°C (CWQG, 1987). Disadvantages of this measure are that it includes only those compounds that can be degraded by microorganisms (many synthetic and refractory compounds cannot), and no account is taken of the presence of contaminants which may inhibit microbial activity.

A similar measure is the chemical oxygen demand (COD), which measures the oxygen equivalent of the organic matter which can be oxidized by a strong chemical oxidant, e.g., dichromate (CWQG, 1987). Again, this method may include oxidizable inorganic substances, and has the disadvantage that some organic materials, particularly volatile compounds, may not be oxidized.

Among the organic substances which have been detected in waters, the Canadian Water Quality Guidelines (1987) provide discussion on diphenylhydrazine, chlorinated ethane, ethylene, propane and propene, halogenated methane and ethers, hexachlorobutadiene, hexachlorocyclopentadiene, benzene, chlorinated benzene, nitrobenzene, phenolic substances, chlorinated phenols, nitrophenols, toluene, dinitrotoluenes, ethylbenzene, styrene, nitriloacetic acid, nitrosamines, organotin substances, phthalate esters, polycyclic aromatic hydrocarbons, polychlorinated biphenyl, resin acids and selected pesticides. Some of these groups are examined below.

■   Phenolic Compounds

Phenolic compounds span a large array of substances, all of which have the benzene ring as the basic structural unit. Some phenolic compounds are naturally produced by aquatic plants (e.g., Pip,

25

1992), and may enter the water as a result of decomposition processes, while others result from industrial activities such as pulp and paper mills, and manufacture of pesticides, medications and plastics. Many phenolic compounds are highly resistant to degradation in water. They may affect taste and odour of water.

■   Benzene

Benzene is present in gasoline, and is used in the manufacture of detergents, pesticides and other synthetic organics (Gillies, 1978). It may be used as a solvent or lighter fluid. It is slightly soluble in water. Chronic exposure to benzene has been linked with anaemia and leukaemia (Gillies, 1978). Benzene may contaminate underground aquifers from leaking gasoline storage tanks.

■   Phthalate Esters

Phthalate esters are used as plasticizers in the plastics industry, especially polyvinyl chloride plastics (USEPA, 1976). Certain phthalates may also be used as pesticides. These compounds have been identified in the Great Lakes (CWQG, 1987). Human health effects of these compounds are poorly documented.

■   Pentachlorophenol

Pentachlorophenol is a widely used wood preservative. It may gain entry to the water source from runoff or leaching from outdoor decks, docks, hydro poles and railway ties. This chemical affects the central nervous system, and may be carcinogenic (Gillies, 1978).

■   Polychlorinated Biphenyl (PCBs) and Chlorinated Dibenzofurans

These compounds are utilized primarily in electrical applications such as capacitors and transformers, although they may be found in trace quantities in many common household items. They are resistant to microbial degradation. Concentrations in Canadian drinking water are generally below detectable levels (CWQG, 1987). Toxicity of these compounds varies with degree of chlorination, solubility, and other factors. Exposure to these compounds affects liver function, and reproductive effects have been reported (USEPA, 1976). Their role in cancer induction has been noted (Gillies, 1978).

■   Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbons now have an ubiquitous distribution in surface waters. These compounds arise primarily from the combustion of fossil fuels. Additional sources may include tobacco smoking, and smoking and frying of foods (CWQG, 1987). Surface waters are contaminated through atmospheric deposition and from urban and industrial effluent. Many of these compounds (for example, benzo[a]pyrene) are very persistent in water and are carcinogens (Gillies, 1978).

■   Pesticides

Pesticides are now universally distributed in ground and surface water supplies. Pesticides may gain entry to the water supply source from agricultural runoff, runoff from chemical vegetation control on hydro lines, railway and road rights-of-way, leaching from landfills and effluent from upstream urban centres. Cottage developments and recreational use of the water source or its upstream reaches may contribute organic herbicides used to control aquatic and shoreline vegetation, insecticides, wood preservatives, and agents such as copper sulphate, which cottagers may apply to control algae and swimmer's itch. A municipality may contaminate its own water supply by spraying and fogging for insects upwind of its reservoir or holding cells, or applying herbicides where they can drain into such basins. Atmospheric deposition from drifting of aerial spraying may also be a factor; aerial transport distances as great as 1500 km have been reported (RCEP, 1992).

Many pesticides can persist for a long time in the aquatic environment. Water treated with simazine, for example, cannot be used for human or animal consumption for a year after application (Riemer, 1984). In some cases breakdown products may be even more toxic than the original compound. Persistence is often much greater in underground aquifers than in surface waters because of low microbiological activity and absence of ultraviolet radiation, both of these factors being important mechanisms in the degradation of many pesticides. Persistence is also greater in cold climates, and therefore much available U.S. environmental degradation data is not applicable for many Canadian situations.

Very little is known about toxicity and persistence for a large number of pesticides. Many of these compounds pose a cancer hazard, and the liver is often the primary organ affected (e.g., aldrin/dieldrin)(USEPA, 1976).

At present, hundreds of pesticides have been introduced into the environment. Since all chemicals in the environment that do not break down promptly eventually find their way into water (Heckman, 1982), they all have a potential impact on public health. Unfortunately, the latter data are often inadequate or unavailable. Many health effects may become apparent only after decades of, or after, exposure. The difficulty of obtaining information is complicated by the enormous array of chemical structures and composition of these compounds. Examples of some common pesticide groups are given in Table 2.

TABLE 2: COMMON PESTICIDE GROUPS AND EXAMPLES
Inorganic
Arsenical Cyanide Metallic and rare earth group (e.g., mercury, copper, zinc, cadmium, boron, antimony compounds
Organic
Amides (e.g., alachlor) Botanical (e.g., allethrin, rotenone) Carbamate (e.g., carbaryl, methiocarb) Chlorophenoxy compounds (e.g., dichlorprop, Silvex, MCPA, 2,4-D) Organochlorines Organophosphorus compounds (e.g., parathion, malathion, diazinon) Dinitrophenols (e.g., trifluralin) Phthalimides Propionic compounds Pyridylium compounds (e.g., diquat, paraquat) Thiocyanate (e.g., lethane 384) Triazine (e.g., atrazine, simazine) Trichloroacetate compounds Trichloropicolinic compounds

Of all of these compounds, botanicals are the most innocuous because they occur naturally in certain plants, and therefore can be readily degraded in the environment (Clapham, 1981).

In Canada, pesticides are regulated primarily by the Pest Control Products Act. The provinces issue licenses for larger scale applications. However, licensing applies only to agencies, not to individuals. Thus considerable potential exists for misuse and negligence on the part of private parties.

Urban usage of pesticides is a major contributor to contamination of surface and ground waters, and may have significant impacts on downstream communities which utilize that water. On a per unit land area basis, the average home owner probably applies greater concentrations of pesticides than farmers do (e.g., Hurtig and Harris, 1970). High concentrations of 2,4-D, for example, are found downstream from urban centres. One study (Gummer, 1979) found levels of 2,4-D in the Red River downstream from Winnipeg near the town of Selkirk that were at least 30 times higher than the average concentration for agricultural areas in Western Canada.

Testing of pesticide toxicity is the responsibility of the company that wishes to register the product in Canada. Toxicological studies that are carried out involve administration of the chemical to a test organism for a period of up to two years. However, the effects of many compounds may take

a much longer time to become apparent. Thus trials involved in licensing of a chemical cannot identify long-term effects. For example, in the 1950s the public in New Brunswick was assured by the chemical company that their product, Brushkill, was "safe enough to drink." Almost 30 years later, this product was implicated in illness and death of workers who had been exposed decades earlier (Volgenau, 1987).

In Canada, in many instances the laboratory studies that are used in the licensing process are unpublished and unavailable to the scientific communities and the public because they are properties of the company and are considered trade secrets. Thus there is no mechanism for independent review and assessment of data by independent means. Furthermore, the chemicals are of course tested on non-human organisms, and thus very little relevant information is available for most compounds regarding effects on humans.

A major flaw of the present licensing system is that most of the pesticides in use today were registered during or prior to the 1960s, when standards and analytical technology were much less rigorous than at present. Licensing requirements now in place apply only to new products that are presented for registration. Thus many of the products released into the environment do not conform to current safety standards. Re-evaluation and setting of new standards is a painfully slow process. Because of the effort involved, lack of priority in government spending in the public health area, and the scarcity of data, only a few new chemicals can be added to the Canadian Water Quality Guidelines each year.

Many products are blends of several different chemicals, some of which may be more toxic than the primary pesticide in the formulation. For example, polychlorinated biphenyl (PCBs) may be present as pesticide extenders (CWQG, 1987). Pesticide products are not required to have all of the ingredients listed. Thus materials such as benzene, carbon tetrachloride, asbestos, xylene, formaldehyde, hexachlorophene and various surfactants may be present.

Many chlorinated pesticides tend to persist unaltered for a long time in water (Sunshine, 1969), and the breakdown or conversion products, many of which are still chlorinated, may be biologically active as well. For example, heptachlor may give rise to heptachlor epoxide, which is more persistent than the original compound (Hurtig and Harris, 1970). Studies on the persistence times of a given compound show widely differing results, indicating that a large number of factors affect how quickly a compound will be degraded in a given situation (CWQG, 1987).

When ingested by mammals, chlorinated compounds may be metabolically transformed into a variety of other materials, the health effects of which are little known. Chlordane, for example, is

29

converted to oxychlordane in mammals; this product is toxic and is not degraded further in animal tissues (Barnett and Dorough, 1974).

There is a mistaken belief among the general public that herbicides such as 2,4-D are harmful only to plants. However, 2,4-D has been implicated in a variety of human health effects (NRCC, 1983). It can persist in the environment for several months (Southwick, 1972). The degradation products are also toxic: 2,4-dichlorophenol, 4-chlorocatechol, 2-hydroxy-4-chlorophenoxyacetic acid and 1,2,4-benzene triol (SDWC, 1977).

Compounds such as toxaphene and benzene hexachloride can pass through municipal water treatment plants without reduction in concentration (McAndrews and Kerr, 1970).

A study of the LaSalle and Assiniboine Rivers in Manitoba by Williamson (1984) revealed a variety of compounds including triallate, trifluralin, dicamba, MCPA, diclofop-methyl, 2,4-D and azinphos-methyl. More such studies on a much wider scale are urgently needed.

BIOLOGICAL PARAMETERS

Natural waters, and particularly surface waters, may harbour a large variety of organisms that may have potentially pathogenic effects. These may include bacteria, viruses, protozoa, fungi, as well as eggs of larger parasites such as tapeworms and certain nematodes. Standards for organisms in water vary a great deal in different jurisdictions. Epidemiological data are often inadequate or misleading, as many cases are not reported or are misdiagnosed. Limits for many pathogenic organisms, for example viruses and protozoa, even some pathogenic bacteria, are very tentative or do not exist in the Guidelines for Canada, or countries such as those of the United Kingdom (RCEP, 1992). The primary reason is that routine examinations of water for individual pathogens is laborious and impractical, and may be beyond the technical and economic capabilities of many municipalities. Pathogenic organisms may have a patchy distribution in the water supply, or be present at very low densities. Furthermore, a given pathogenic group may show a large degree of variation in terms of specificity and response to isolation and identification procedures. *Salmonella*, for example, may show more than 1700 serotypes (APHA, 1985). Thus negative findings in the samples may not necessarily guarantee absence of a problem.

■ Bacteria

Virtually all surface waters contain bacteria. Most of these organisms are of no consequence for public health. Some types of bacterial growths may affect aesthetic quality of the water. Musty odours are often the result of metabolites produced by actinomycete organisms (previously classified as fungi, but now viewed as bacteria which grow as branching filamentous colonies). Compounds

30

which have been identified in this regard include geosmin, 2-methylisoborneol, 2-isopropyl-3-methoxypyrazine, and mucidone (Gerber, 1983). Some bluegreen algae also produce these compounds. The odours of these substances can be detected at extremely low threshold concentrations (APHA, 1985), as low as 10-200 nanograms per litre for geosmin and methylisoborneol (Slater and Blok, 1983). These compounds are not destroyed by chlorination (Popovska, 1983). The genus *Streptomyces* is the most common actinomycete which has been associated with production of these compounds in municipal water supplies. This organism may also persist in the sediments of water storage reservoirs, where significant amounts of geosmin may be produced (Wood *et al.*, 1983).

Iron and sulphur bacteria may perceptibly affect water quality, causing, for example, reddish or rusty discolouration, foaming, turbidity and unpleasant odours and tastes. These bacteria subsist on inorganic substrates of ferrous iron or sulphur compounds, which they utilize for their energy supply. The ferric iron may originate from metal in pipes, or iron present in the water, and is converted to insoluble ferric hydroxide, which is precipitated and deposited around the organism. In water distribution systems, such bacteria may proliferate to form mucilaginous slimes that can interfere with water flow and plug filters, including sand filter beds. They result in an increase in organic matter, and provide a substrate for the growth of actinomycetes and fungi (Holden, 1970).

Sulphate-reducing bacteria (e.g., *Thiobacillus*) may produce sulphuric acid, which corrodes metals and concrete pipe within the distribution system. *Desulphovibrio desulphuricans* can convert sulphate to noxious hydrogen sulphide gas.

Unfortunately, a large variety of pathogenic bacteria may survive in water for substantial periods of time (Brandes, 1976), and many serious outbreaks of illness can stem from a contaminated water supply. Historically, for example, many epidemics of typhoid and paratyphoid fever (caused by specific members of the *Salmonella* group) and cholera (*Vibrio cholerae*) have been associated with tainted water supplies. In recent times, cholera outbreaks associated with drinking water occurred in cities in Iran and Iraq in 1964, and in Odessa, Ukraine in 1970 (Hutchinson, 1972). The numbers of organisms that must be ingested in order to result in illness may vary from a single cell for *Salmonella* to several thousand cells for some other bacteria (USEPA, 1976). Whether illness will be produced also depends on a variety of individual predisposing factors, such as health, age, and chemical characteristics of the water and any other food ingested.

A problem which has been reported with respect to bacteria in raw water sources is the transfer of R-factors which alter the resistance of pathogenic bacteria to antibiotics, heavy metals and ultraviolet light (USEPA, 1976). Outbreaks of illness involving antibiotic-resistant strains have been of increasing concern.

31

Unfortunately, many of the pathogenic bacterial strains found in water contain transferable drug resistance factors. This was found, for example for *Salmonella* and faecal coliforms in the water supply for the town of Selkirk, Manitoba, which draws some of its water from the Red River, downstream of the City of Winnipeg (Dr. Ian Reid, personal communication).

Distribution and concentration of pathogenic organisms in a water body vary tremendously with location and time, since there are innumerable opportunities for contamination from runoff, human activities, wildlife and waterfowl. Most pathogens are unable to multiply in water, but many can remain viable for long periods of time. Guidelines for drinking water quality reflect this natural variability by specifying a number of conditions which must be met in order for the water to be of acceptable microbiological quality. According to the existing Canadian guidelines (CWQG, 1987): no 100 mL sample should contain more than 10 total coliform organisms, not more than 10 percent of samples spanning a 30-day period should show the presence of coliform organisms, not more than two consecutive samples from the same site should show the presence of coliform organisms, and none of the coliform organisms present should be faecal coliforms. Since surface water sources generally do not meet these requirements, the water must be disinfected before it is distributed to the consumer.

Bacterial densities in water are difficult to measure accurately because a large number of factors may influence the result. For example, environmental stress may incapacitate many bacteria (including coliforms) to the extent that, even though they are present in water, they may not grow and produce colonies when incubated in the laboratory. In such cases, bacterial counts of a water sample may be seriously underestimated. Environmental stress could include: chlorination, high salinity, presence of heavy metals (for example, copper), presence of toxic organics, shortage of nutrients in unpolluted waters, extremes in temperature, pH, and presence of antagonistic organisms. Some handling practices of the sample may also induce stress (Holden, 1970; APHA, 1985).

Coliform organisms include a very broad range of bacteria and are defined as all aerobic or facultative anaerobic, gram-negative, non-spore-forming, rod-shaped bacteria which can ferment lactose with gas formation within 48 hours at 35°C (APHA, 1985). Most of these organisms are nonpathogenic, although a large variety of coliform species may be encountered in feces. Coliform organisms include the genera: *Escherichia, Shigella, Edwardsiella, Salmonella, Arizona, Citrobacter, Klebsiella, Enterobacter, Serratia, Hafnia, Proteus, Providencia, Morganella, Erwinia, Pectobacterium* and *Yersinia*. Coliforms are monitored because they indicate the general level of pollution. Elevated total coliform counts suggest that pathogenic organisms are likely to be present. Routinely, faecal coliform counts are made as well in order to distinguish between coliform organisms that are innocuous and those that are of concern. Innocuous coliforms are those free-living forms which grow on organic

materials in the water supply. Occasionally they may be numerous enough to produce slimes on filters and the walls of distribution pipes.

Faecal coliform organisms are those coliform bacteria which originate from the faeces of warm-blooded animals and birds, and presence of such organisms in the water is direct evidence of faecal contamination. These coliforms are differentiated analytically from those of other environmental origin by being able to produce gas from lactose when incubated at 44.5°C (APHA, 1985).

The most common faecal coliform organism encountered in Canadian waters is *Escherichia coli* (APHA, 1985). Most strains of *E. coli* are not virulent and are normal, dominant (comprising up to 97% [APHA, 1985]) components of the human intestinal flora, although they are present in other mammals and birds as well. *E. coli* gastroenteritis (turista, Montezuma's revenge) is produced by certain strains which can invade the intestinal epithelium, or which produce enterotoxins that result in diarrhoea. Nausea and dehydration are common, but usually the illness is not accompanied by fever (Dart and Stretton, 1980). The infection can be much more serious in children. Chronic exposure to local virulent strains in the water supply is associated with production of antibodies in the exposed population, but visitors to the region may develop acute symptoms.

Shigellosis or bacillary dysentery is a diarrhoeal disease caused by four species of *Shigella* which vary in their degree of virulence. Infection can occur at a very low exposure (10-100 bacteria), and is most serious in children and debilitated persons (McKane and Kandel, 1985). Urban outbreaks of shigellosis are usually associated with accidental contamination of water pipes with sewage during construction and repair, or chronic seepage. *Shigella* may survive for more than a month in water (Hutchinson, 1972). It interesting that this organism survives longer in cold water, and longer in sterile or unpolluted water than in polluted water (Holden, 1970).

Klebsiella is a coliform that is often encountered in water supply systems. Approximately four percent of bacterial pneumonia and 18 percent of urinary tract infections can be ascribed to pathogenic *Klebsiella* strains (APHA, 1985). It is capable of causing infections of the nasal sinuses and middle ear as well (Brooks, 1958). Although it is a common component of faeces, *Klebsiella* may also have non-faecal origins, for example in pulp and paper mill, dairy and other industrial wastes.

Yersiniosis (caused by *Yersinia enterocolitica*) produces diarrhoea that is often accompanied by fever and severe abdominal pain. This organism is responsible for frequent false diagnoses of appendicitis, and up to 10 percent of yersiniosis victims in the United States needlessly undergo appendectomies (McKane and Kandel, 1985). Approximately 20 percent of yersiniosis patients develop autoimmune disorders. A large variety of animals form the natural reservoir of this organism, including beavers, muskrats, otters, raccoons and farm animals. In the environment, if organic nitrogen is

present, the organism can grow even at temperatures of 4° (APHA, 1985). Total and faecal coliform counts are not correlated with *Yersinia* densities present, and the organism may still be found in water treated by chlorination (APHA, 1985).

Besides faecal coliforms, faecal *Streptococci* may also be used as indicators of faecal contamination. These coccoid bacteria are found primarily in the intestines of warm-blooded animals and birds. Ratios of faecal coliforms to faecal *Streptococci* have been used to differentiate between human and nonhuman sources of pollution. A ratio greater than 4.1 is considered to be indicative of human waste, while ratios of less than 0.7 suggest nonhuman sources (APHA, 1985). *Enterococci* have similarly been used to indicate recent faecal pollution from warm-blooded animals (USEPA, 1976).

Some forms of water-borne gastroenteritis may be caused by *Campylobacter jejuni* and *C. coli*, which occur in many animals, including domestic livestock, and birds, as well as humans. The illness generally lasts for one to four days, and is accompanied by diarrhoea. These organisms can survive in water, particularly at cool temperatures, up to five weeks (APHA, 1985; McKane and Kandel, 1985). Outbreaks have been reported from water supplies that were chlorinated, but not filtered (Dart and Stretton, 1980).

Pseudomonas aeruginosa can grow in a very wide range of aquatic environments, including distilled and deionized water. It is present in the gastrointestinal tract of approximately five percent of the healthy population (McKane and Kandel, 1985). Contact with water containing the organism may cause respiratory, eye, ear, skin and other infections.

Staphylococcus aureus can also be responsible for a large array of infections, ranging from skin infections to pneumonia, toxic shock and meningitis (McKane and Kandel, 1985).

Icteric leptospirosis (or Weil's disease) (caused by *Leptospira interrogans* and other similar organisms) can be transmitted to human hosts through water contaminated with the urine of infected rats, wildlife and farm animals. Water supplies may be tainted when pig and cattle manure is used as fertilizer (Dart and Stretton, 1980). The organism is a spirochaete (i.e., spiral motile bacterium) (Holden, 1970) and can survive up to 30 days in lakes (Alperin, 1984). Leptospirosis has been documented in Europe, the Middle East, Far East and the Americas (Dart and Stretton, 1980). Infection occurs through contact of the organisms with mucous membranes and breaks in the skin. The illness usually has a sudden onset, with headache and fever. Often this is followed by jaundice, as the liver, kidneys and central nervous system become involved.

Water-borne outbreaks of leptospirosis have occurred in many countries, particularly Europe, for example Ukraine (Alperin, 1984) and England and Wales (RCEP, 1992). In Hermapolis, Greece, an outbreak occurred as a result of contamination of a reservoir by rats (Holden, 1970).

Legionellosis (caused primarily by *Legionella pneumophila*) can be manifested as the severe Legionnaires' Disease or the milder Pontiac Fever (RCEP, 1992). Infection appears to be through inhalation of contaminated droplets, as for example from water-cooled air conditioners and humidifiers. The organisms cause respiratory infection and fever. They appear to be widely distributed in aquatic environments and are able to survive for extended periods of time (APHA, 1985). *Legionella* may colonize the hot water systems of institutions and residences, and multiplication of this organism can be enhanced by the presence of materials such as fibre seals and rubber in the distribution system (see Schoenen and Scholer, 1985). Often the organism may find refugia in niches in shower heads and faucets (Moore, 1989).

Water sources which are subject to contamination from livestock waste may harbour a number of pathogens that are potentially capable of infecting humans. *Clostridium tetani*, the causative agent of tetanus for example, is extremely common in horse manure. *Clostridium perfringens*, which causes gas gangrene, and several *Salmonella* species, may originate from livestock (McKane and Kandel, 1985). Some strains of *Clostridium perfringens* produce spores that can survive one to three hours of boiling (Holden, 1970).

Salmonellae are frequently harboured by healthy cattle, sheep and pigs, but other animals and also birds may distribute these organisms (Dart and Stretton, 1980). At least 500 serotypes of *Salmonella* have been reported to be pathogenic to humans (Hutchinson, 1972). Water-borne *Salmonella* infection is manifested as acute gastroenteritis, with fever, headache and abdominal pain (Dart and Stretton, 1980). According to material reviewed by Hutchinson (1972), *Salmonella* may in some instances survive for more than one year in water. As has been also observed for *Shigella*, *Salmonella* survives longer in cold water, and longer in unpolluted water (Holden, 1970). *Salmonellae* have been isolated up to 73 miles downstream from sewage outfalls in winter (Dart and Stretton, 1980).

Brucella species, responsible for brucellosis or undulant fever, are common in cattle and this illness can be contracted by humans (Brooks, 1958). *Brucella tularensis*, the organism responsible for tularemia, has been reported in Russia, where river water used as a community supply was contaminated by rats; this organism has been responsible as well for outbreaks of water-borne illness in the Middle East, and Montana (Holden, 1970). The pathogen may also enter through abrasions in the skin or mucous membranes. Infection is accompanied by fever, which may progress to delirium and coma (Dart and Stretton, 1980). Rabbits and various rodents can contaminate a water supply through their excrement and carcasses. Survival times of this pathogen are extended in cold water (Dart and Stretton, 1980).

35

Mycobacterium tuberculosis can in some instances be transmitted by water. Since the latency period may be several years before tuberculosis becomes evident, it is difficult to trace the source of infection and implicate a particular water supply. The organisms may survive in water for several weeks (Dart and Stretton, 1980).

Treponema hyodysenterae, which causes swine dysentery, may contaminate water sources (Turner and Fraser, 1986). Some contagious bacterial fowl diseases, for example, psittacosis and ornithosis (caused by rickettsiae), can be transmitted to man (Pelczar and Reid, 1972).

■   Viruses

Viruses cannot multiply outside the body of their host. Unlike many intestinal bacteria, viruses are not part of normal human microflora, and are shed only by infected or recently vaccinated individuals. Many types of viruses can be found in municipal water supplies. These include polioviruses, coxsackieviruses, echoviruses, adenoviruses, reoviruses, rotaviruses and others, for example, the infectious hepatitis virus. Payment and Trudel (1985) found that 79 percent of raw water samples collected in Quebec contained viruses. As a general rule, the numbers of viruses present bear no relation to the faecal coliform count (APHA, 1985). Many viruses that can infect humans may be carried by warm blooded animals or birds which can contaminate a water supply.

Viruses may remain viable in water for extended periods of time. Survival times of more than 270 days have been reported for coxsackieviruses, and more than 180 days for polioviruses (see Hutchinson, 1972). Coxsackie B5 virus causes a fairly mild illness in adults, but may be fatal to infants (Holden, 1970). An outbreak of polio in Edmonton during 1952-53 has been attributed to a contaminated water supply (Holden, 1970). According to literature reviewed by the latter author, viruses tend to remain viable for longer periods of time in "cleaner" water.

As with bacteria, the number of units needed to produce an infection varies greatly according to the type of virus, the composition of the water and food that are ingested, and a large array of personal predisposing factors. The infective dose of Poliovirus I may be as little as 2 viral units (see Taylor and Johnson, 1974). According to the latter workers, water is an important medium in the spread of infectious viral agents within and among communities. Both surface and groundwaters may acquire viruses as a result of contamination from domestic wastewater (CWQG, 1987).

Enteric viruses, for example hepatitis A and Norwalk agents (APHA, 1985), can easily contaminate a water supply, and many outbreaks of illness have been traced to a municipal source (Dart and Stretton, 1980). Norwalk agents cause gastrointestinal illnesses of brief duration that are often erroneously diagnosed as "stomach flu." More serious gastroenteritis is produced by rotaviruses, which are associated with severe diarrhoea in children (Moore, 1989).

Vaccine strains of enteric viruses may be shed by the body for several weeks after vaccination. Shedding periods of up to 120 days have been reported after administration of oral polio vaccine (Holden, 1970). Presence of these strains in water indicates contamination by human waste. In the finished, chlorinated water supply in the town of Selkirk, Manitoba, a total of 15 vaccine strains of polioviruses were found on a number of occasions (Dr. Ian Reid, personal communication).

Because of the large numbers of pathogenic viruses, data are at present inadequate to provide an accurate assessment of the degree of hazard posed by viruses in water supplies. According to Dart and Stretton (1980), any human virus that is excreted can theoretically be transmitted through contaminated water supplies. Concern has been expressed, for example, with regard to viruses that are implicated in certain cancers, such as the reovirus which causes Burkitt's lymphoma (Holden, 1970). According to material reviewed by the latter author, there has been suggestion that some chemical carcinogens and tumorigenic viruses may interact synergistically; this may be significant since both of these elements occur together in some water supplies. The human HIV virus presents another interesting question for which adequate information is at present unavailable. Sewage containing discarded condoms may potentially present a source of contamination.

Because of the cost of isolating and identifying viruses, and the limitations inherent in concentrating viruses from water, municipal water supplies are not routinely examined for these agents.

■   Protozoa

Protozoans which parasitize the intestinal tract may create a problem in a municipal water supply because they produce cysts that not only are not affected by disinfection, but are resistant enough to pass through the acid stomach environment undamaged (McKane and Kandel, 1985). These organisms are of great concern, because a single cyst may cause infection (Moore, 1989). Where municipal water treatment also involves filtration, a large proportion of cysts may be removed by this step.

Giardiasis (beaver fever, hiker's diarrhoea) is a cosmopolitan illness caused by the flagellate *Giardia lamblia*. In the last two decades, this pathogen has been the organism most commonly responsible for waterborne diarrhoea in the United States (McKane and Kandel, 1985; Moore, 1989), and has also been a problem in water supplies in Russian cities (Brodsky *et al.*, 1974). Urban populations are particularly susceptible to outbreaks of this disease. During the 1960s, for example, an estimated 50,000 cases of giardiasis resulted from a contaminated water supply in Portland, Oregon (Meyer and Raduvescu, 1979). Indeed, giardiasis is probably much more common than available statistics indicate, for, according to Brodsky *et al.* (1974), physicians have been generally unaware of this disease and many cases are not properly diagnosed or treated promptly, contributing to the spread

of this illness. Most outbreaks originate from relatively clear and wholesome-appearing stream and river water (Moore, 1989), but groundwater may also be contaminated (Dart and Stretton, 1980).

Beavers are often the natural reservoir for *Giardia* (infection rates as high as 18% have been reported [Wallis *et al.*, 1984]), and beaver colonies within the drainage system may contaminate a water supply. Other hosts include various small rodents (e.g., muskrats, in which infection rates may be even higher than in beavers), and dogs and cats (Grant and Woo, 1978). In a survey in Alberta, 25 percent of domestic cats in the Kananaskis Valley were found to be infected (Wallis *et al.*, 1984). The source of contamination is also often human waste. Beaver faeces infected with *Giardia* show a seasonal pattern, with increases in autumn (Monzingo and Hibler, 1987).

The organisms survive in the aquatic environment as resistant cysts, which may remain infective up to two months at 8°C. Ingestion of only a few cysts can lead to infection (APHA, 1985). Symptoms appear 10-15 days after exposure (CWQG, 1987), and diarrhoea may recur intermittently over an extended period of time (Dart and Stretton, 1980). The organisms adhere to the wall of the small intestine, where they interfere with nutrient absorption and cause lesions at the attachment sites, which in turn provide opportunities for infection by bacteria and fungi (Meyer and Raduvescu, 1979). If reinfection does not occur, the illness generally resolves after six to seven weeks (Erlandsen and Meyer, 1984). Some evidence exists that urban populations which are chronically exposed to this pathogen may acquire a degree of immunity (Brodsky *et al.*, 1974).

Cryptosporidiosis is caused by *Cryptosporidium parvum*, which inhabits the intestinal tract of humans and other mammals. Often the sources are infected livestock (RCEP, 1992). The organisms are transmitted via cysts in contaminated water or food. The organisms cause gastroenteritis, and effects may be severe in infants or immunologically stressed individuals. Outbreaks have been reported in the United Kingdom as recently as 1989 (RCEP, 1992).

Amoebic dysentery is caused by *Entamoeba histolytica*. According to Moore (1989), the carrier frequency for this protozoan may often exceed 50 percent in human populations in the tropics. A 1977 estimate asserted that at least 10 percent of the world's total population was affected at that time by *Entamoeba* (Evison and James, 1977). A serious outbreak of amoebic dysentery occurred in Chicago during the 1933 World's Fair (Holden, 1970).

Entamoeba damages the intestinal wall, and can spread to other organs. Humans are the only hosts of this pathogen (McKane and Kandel, 1985). Many infected hosts are asymptomatic for years, but in certain individuals diarrhoea can develop, and occasionally may be fatal. The cysts have been reported to remain viable for more than 150 days at 12°-22°, but cyst persistence is extended at cold temperatures (Dart and Stretton, 1980).

Pathogenic strains of the amoeba *Naegleria gruberi* cause amoebic meningoencephalitis, which is generally fatal. Contact of the water with the upper respiratory tract may allow the organism to enter the body. It invades the bloodstream and brain. Illness becomes evident four to seven days after water contact, and death occurs four to five days later (Dart and Stretton, 1980). According to the latter authors, this disease has been reported from Florida, Australia and Europe. Apparently the cysts of this organism can be destroyed by chlorination.

A pathogenic ciliate, *Balantidium coli*, may cause balantidiasis, an intestinal infection. Few data are available regarding the frequency of this disease.

■   Helminthic parasites

Contamination of water by sewage always presents the potential for infection by parasitic worms. Furthermore, since surface waters and storage reservoirs are accessible to wildlife and waterfowl, the potential for faecal contamination and distribution of helminth parasites may be significant. Additional sources of helminths may be livestock, and domestic pets. Hundreds of different helminth species may originate from animals (e.g., Smith *et al.*, 1974) and some of these are capable of infecting humans.

In warmer climates, water-borne parasite eggs can have serious impacts on public health, resulting for example in debilitating illnesses such as hookworm infection (ankylostomiasis) and strongyloidiasis. Dracontiasis (caused by *Dracunculus medinensis*) is often acquired in the tropics through drinking water (Holden, 1970). Travellers can bring the parasites to temperate areas, where environmental conditions may be seasonally adequate to allow local spread through contaminated water. An outbreak of hookworm, for example, has been reported in Britain (Holden, 1970). In temperate areas, eggs of the intestinal roundworms *Oxyuris vermicularis* and *Trichuris trichiura* may contaminate water.

Ascariasis (caused by the large roundworm *Ascaris suum*) is normally encountered in swine intestines but human infections easily occur. A single female worm may produce 200,000 eggs per day (Dart and Stretton, 1980). The eggs are common in sewage sludge and can remain viable in the environment for several months. While surface water sources are the most likely to be contaminated, an outbreak of ascariasis has been documented from a groundwater supply (Hutchinson, 1972).

Tapeworm eggs may persist for extended periods of time after they are shed in faeces. Eggs of the pork tapeworm, *Taenia solium*, may be present in water. Once ingested, the eggs hatch and the larvae encyst at various sites in the body (Holden, 1970). Eggs of the beef tapeworm, *Taenia saginata*, have been reported to persist in cool, moist conditions for more than 330 days (see Dart and Stretton, 1980). An outbreak of fish tapeworm disease (caused by *Diphyllobothrium*) has been reported in Russia

after contamination of a reservoir with sewage (Dart and Stretton, 1980). According to the latter authors, the dog tapeworm (*Echinococcus granulosus*) may in some instances also be transmitted by water.

In summer, many temperate surface waters can harbour trematode cercariae (i.e., larval stages of flukes), which on contact and penetration of the skin result in cercarial dermatitis (swimmer's itch). In tropical areas, schistomiasis is a serious public health problem. This is caused by worms of the genus *Schistosoma* which live in the blood. In temperate regions, most cercariae are nonspecific for humans (although some fasciolids, for example, have the potential of infecting humans), but are species that parasitize waterfowl and other wildlife. This means that the larvae cannot develop to maturity in human hosts, but die after penetrating the skin, causing inflammation and allergic reaction. The intensity of the reaction depends on previous exposures and sensitivity of the individual.

Some concern has been expressed about non-parasitic aquatic nematodes which may carry live pathogenic bacteria in their intestines (Holden, 1970). Such bacteria could be shielded from the chlorination process.

■   Fungi

A number of fungi occur naturally in surface waters, and are of ecological interest in that the genera present may reflect the water quality. Some aquatic fungi may parasitize algae.

Aquatic fungi attract notice in municipal water supplies when they grow as slimes on the walls of pipes. The water supply may contain yeasts that can be potential pathogens in susceptible individuals. Candidiasis, caused by *Candida albicans*, can result from proliferation of the yeast at various sites, particularly on moist mucous surfaces. Other pathogenic fungi may occur in the water supply, although their association with water-borne disease has been poorly documented. Some of these include *Aspergillus fumigatus* (which causes pulmonary aspergillosis, otomycosis, and skin and nasal sinus infections), *Exophiala mansonii* (tropical chromomycosis), *Petriellodium boydii* (eumycotic mycetoma), and *Endomyces candidus*.

■   Algae

Algae often reach nuisance proportions in surface waters that form a municipal water source. Algal blooms proliferate when inorganic phosphorus and nitrogen are present and temperatures are warm. Besides clogging filters and pipes, and generating unpleasant tastes and odours, some algae associated with bloom conditions are toxic if ingested by people or animals (Aziz, 1974). In Manitoba, bluegreen algal species which have been linked to gastrointestinal illness are *Anabaena flos-aquae*, *Microcystis aeruginosa* and *Aphanizomenon flos-aquae* (McLeod and Bondar, 1952; Senior, 1960). In some instances, livestock and pets have died within hours of drinking from algae-laden ditches or ponds

(see CWQG, 1987; Pip, unpublished data). Illness has also been recorded from swimming in waters containing blooms of toxic algae (CWQG, 1987). Algal toxins have been implicated in some outbreaks of illness from municipal water supplies (Lippy and Erb, 1976).

Anabaena flos-aquae has been linked with production of at least four anatoxins. Anatoxin-a is an alkaloid which causes death by respiratory arrest; the other anatoxins differ in properties and toxicity. The toxins of *Microcystis* are small polypeptides which produce gastrointestinal distress, and affect the central nervous system and liver. Gastroenteritis has also been reported as a result of bluegreen algal lipopolysaccharide endotoxin. Available information indicates that bluegreen algal toxins show a wide array of chemical structures and toxicological mechanisms (see CWQG, 1987).

The objectionable odours attributable to bluegreen algae are due to many of the same compounds that are produced by actinomycetes (see above), although a wide variety of metabolites and degradation products of these algae can taint water (Slater and Blok, 1983). The odours persist even after cell disintegration and chlorination (Popovska, 1983). While bluegreen algae are often the most obvious problem, other algal groups (diatoms, green algae, yellow algae) may also produce various compounds that result in objectionable odours (Juttner, 1983).

Some bluegreen algae fix atmospheric nitrogen, incorporating it into organic compounds. A proportion of this organic nitrogen may be excreted into the water by the living cells, while the remainder is released on death and decomposition of the organisms, adding to the nitrogen pool originally present. Death and decay of large algal mats following a bloom may deplete the water of oxygen to the extent that fish and other aquatic animals die, and the organic compounds resulting from decomposition can seriously taint a water supply. Bluegreen algae also form good substrates for growth of actinomycetes (Popovska, 1983).

Problems with an algal bloom in the water supply, whether at the source or in the storage reservoirs, can be compounded when the municipality attempts to control the bloom using chemicals. Winnipeg, for example, has controlled excessive algal growth in its water storage cells with copper sulphate, which is a toxic agent. While most of this chemical precipitates to the sediments, some may remain in the water supply (Holden, 1970). Copper sulphate also kills fauna that may be in the reservoir, for example zooplankton, benthic organisms and fish. The resultant decay may affect water quality.

In tropical areas, the nonphotosynthetic alga *Prototheca* may cause skin ulcers (protothecosis), or inhabit the human gastrointestinal tract (McKane and Kandel, 1985).

MUNICIPAL WATER TREATMENT AND DISTRIBUTION

While protection of the raw water source is critical in ensuring that the initial water quality is the best possible given the environmental circumstances, values for water quality parameters that exceed the water quality guidelines necessitate that the water be treated for aesthetic and/or public health reasons. In 1990, 84 percent of Canadians were reported to drink municipally treated water (Ohlendorf-Moffat, 1990). In the United Kingdom, 99 percent of the population is served by distributed water (RCEP, 1992). While water treatment may improve the specific problem it is designed to address, at the same time, there may be undesirable reactions with various substances present in the water. Residual effects from chemicals added to the water during the treatment process are of concern, as they may be subtle and long-term, with physical as well as behavioural impacts (Rotton *et al.*, 1982). It was estimated in 1984 that approximately one million tons of chemicals were used annually in Canada for water treatment purposes (Morrison, 1984). Besides the effects from the chemicals themselves, various impurities in these chemicals (e.g., metals) may have further impacts on health. Strangely, there are no purity standards for chemicals used in water treatment in Canada (Morrison, 1984).

The efficacy of water treatment depends a great deal on the characteristics of the raw water. Factors such as pH, temperature, and the kinds of dissolved and suspended materials present may affect chlorination, decolorization, coagulation and aeration (CWQG, 1987). Since most natural waters show seasonal variation, treatment procedures must be adjusted according to need.

STORAGE

Municipalities often store water in a reservoir or impoundment after it has been collected from the natural water source. Storage is usually undertaken as a "stockpile" measure to guard against seasonal uncertainties of the water source, and to exert greater control over potential contamination. In cases where the water source is some distance from the community, the stored water provides a ready supply that is close at hand.

Regardless of the design of the storage basin, changes in water quality during storage are inevitable. If the basin is steep-sided and deep, stratification may develop with depletion of dissolved oxygen in the lower layers. This may give rise to odour problems, particularly in autumn (Popovska, 1983). Geosmin production may be significant in the sediments of the storage cell (Wood *et al.*, 1983). Algae may multiply in the reservoir, particularly if the water is warm, in which case the water may be treated with copper sulphate. If the walls of the reservoir have coatings or liners, the water may leach out various chemicals.

In general, storage of water in reservoirs is associated with a number of dynamic processes. Suspended particles are reduced as sedimentation occurs. Numbers of viruses, *Salmonella*, *Vibrio cholerae*, *Shigella* and *Escherichia coli* often become reduced, provided new sources of contamination, such as resting waterfowl, are absent. However *Pseudomonas* often multiplies during storage (Holden, 1970). Since the reservoir is close to the urban centre, the water is especially susceptible to atmospheric deposition of pollutants.

DISINFECTION

■   Chlorination

Chlorination has become a common practice in many urban centres after New Jersey pioneered its use in 1908. The addition of free chlorine to water is effective for inactivation of most enteric pathogenic bacteria and viruses (EHD, 1992). The widespread chlorination of water supplies during this century has been credited with the dramatic reductions in incidence of such diseases as typhoid (McKane and Kandel, 1985). In Toronto, for example, where water was filtered and chlorinated after 1912, typhoid mortality was 0.41 per 1000 population in 1910, 0.073 in 1921, and 0.007 in 1940 (see Grima, 1972).

Chlorine destroys algae, oxidizes organic compounds and removes some tastes and odours. Noxious sulphides, for example, are converted into less objectionable sulphate and elemental sulphur during chlorination (Chen, 1974). A residual level of chlorine can remain in the distribution system so that water remains disinfected until its delivery at the tap.

Chlorination is a relatively economical and easily managed way to disinfect water supplies. However, the effectiveness of chlorination depends on temperature, and takes longer when the water is cold (Holden, 1970). Disinfection efficiency varies for different bacteria. While it is relatively effective for *Escherichia*, results are less satisfactory for *Yersinia*, *Streptococcus* and *Staphylococcus* (APHA, 1985). Despite the presence of free chlorine residuals, significant numbers of coliform bacteria can often be recovered from water treatment systems (Moore, 1989). Chlorine does not destroy spores of *Clostridium perfringens* (Holden, 1970). *Legionella* is also relatively resistant to chlorine (Moore, 1989). Chlorination is not very effective against protozoan cysts, nematodes, or polioviruses and coxsackieviruses (Lorch, 1987; Moore, 1989). Payment and Trudel (1985) reported that viral incidence after chlorination in Quebec water samples fell only to 64 percent from an initial 79 percent. Chlorine also has no effect on musty and earthy odours produced by actinomycetes and bluegreen algae; indeed, chlorination can make these problems worse (Montiel, 1983). According to the latter worker, the same is true for objectionable tastes due to phenolic compounds.

43

Unfortunately, free chlorine reacts with dissolved organic compounds to yield a large variety of chlorinated organic substances spanning a wide range of molecular weights (McClanahan, 1975; EHD, 1979). That chlorination of municipal water supplies results in chlorinated organics such as trihalomethanes was not discovered until 1974 (EHD, 1992). Prior to this, chlorination was viewed as essentially harmless to health, and many municipalities used it liberally and indiscriminately to maximize disinfection. While trihalomethanes have received the most attention, these compounds account for only 10-20 percent of the total products of chlorination of water (Harris, 1984). Little is known of the health effects or even the identity of most of the other products, which may include such diverse compounds as: trichloroacetic and dichloroacetic acids, chloral hydrate, halogenated acetonitriles, halogenated ethylene, and halogenated humic acids and lignins (Moore, 1989).

The problem is compounded in that chlorinated organics may already be present in the raw water as a result of contamination by effluent from pulp and paper mills, industrial operations and agricultural runoff. Chlorinated organics are poorly metabolized and tend to concentrate in fatty tissues (Morris, 1975; Hodgson and Guthrie, 1980). For many of these compounds, insufficient data are available for water quality guidelines to be established (EHD, 1989a; CWQG, 1992).

Chlorophenols are formed from naturally occurring phenolic acids in surface and ground water. These compounds may contribute to undesirable tastes and odours in the finished water (Lee, 1967; EHD, 1989a). They are fetotoxic agents and may be carcinogenic or promote tumour formation by other carcinogens (EHD, 1989a).

Trihalomethanes (THMs) (e.g., chloroform) arise from reaction of chlorine (or other halogen) with organic precursors such as humic or fulvic acid (CWQG, 1987), or substances generated by some algae (EHD, 1992). THMs are known carcinogens (EHD, 1977c; Highland *et al.*, 1979; EPA, 1990) and perinatal behavioural toxins (Miller, 1983). Toxicity data for THMs and correlation studies between cancer rates and chlorinated water have been reviewed by EHD (1992). THM concentrations in untreated, uncontaminated water are generally low, and these compounds arise in drinking water primarily through the process of chlorination (EPA, 1978; CWQG, 1992). The level of chlorination of a given water is directly related to the concentration of THMs in the finished water (Symons *et al.*, 1982). Chloroform levels in treated water may be two to three orders of magnitude higher than in raw water (CWQG, 1987).

Seasonal variability in THM concentration occurs as a result of varying amounts of organic precursors in the raw water (EHD, 1977c), different levels of chlorination as adjustments are made in response to fluctuating microbial counts during the year, and factors such as contact time, temperature, pH and presence of other halogen ions (EPA, 1978). Generally THM levels are lower in winter (EHD,

1992).   Treated water from surface sources (rivers and lakes) contains significantly greater concentrations of THMs than water from underground aquifers (EHD, 1977a) because of the smaller amounts of precursor organic compounds in most groundwaters. In a survey of Canadian municipal water supplies (EHD, 1977a), THM concentrations were found to be greater in water collected from the municipal distribution systems than in water sampled immediately after treatment. In Winnipeg, both treated and distributed samples collected on the same day in 1991 at various locations within the system showed a wide range of THM values (unpublished data, Manitoba Environment Department), suggesting that THM concentration in water supplied to a particular location cannot be predicted.

A 1978 document by the EPA estimated that 23-97 percent of the total annual human chloroform uptake in urban areas in the United States was contributed by drinking water, with food and air constituting the other primary sources. Furthermore, chloroform in water may also be inhaled and absorbed even when the water is not ingested directly (EHD, 1992).

Reduction of the concentrations of chlorinated organics in treated water may be achieved through removal of organic materials in the raw water prior to chlorination, or removal of the chlorinated substances after chlorination. Removal of precursor organics requires addition of other chemicals, for example, aluminum coagulants, which may persist in the finished water and may affect its aesthetic characteristics (e.g., increased turbidity) (EHD, 1992). Reduction of levels of chlorinated substances after they have formed can be achieved using air stripping or activated carbon adsorption; however, the effectiveness of these methods varies with the type of chlorinated compound, the carbon adsorbent must be replenished frequently, and chlorinated organics continue to form after treatment as long as residual free chlorine remains in the water (EHD, 1992).

Chlorination may also have other effects on water quality. This process tends to increase copper concentration in the distributed water (Andelman, 1974). If cyanide is present in the raw water, chlorination may give rise to a series of reactions that result in highly toxic cyanogen chloride (Singleton, 1986).

Chlorination may convert chromium from the III valence state to chromium VI, which is not as easily removed as chromium III by conventional treatment processes (CWQG, 1987) and is much more toxic. Certain pesticide contaminants may give rise to highly toxic products on chlorination. For example, while chlorine destroys the pesticide parathion, paraoxon may be formed (CWQG, 1987). Nitrogen trichloride may be generated under some conditions, resulting in objectionable odour (AWWA, 1971).

Other forms of chlorine which may be used for disinfection of drinking water are chlorine dioxide, chlorite ion and chloramine. These methods are not associated with THM production. However

toxic effects reported for these substances have included oxidative changes in haemoglobin, haemolysis of red blood cells, and gastrointestinal disturbances (see Gillies, 1978; McKane and Kandel, 1985). Chloramine may also affect taste and odour of the treated water (Gillies, 1978).

■   Ozonation

Ozone has been used as an alternative means of disinfection in many urban centres in Europe and North America; for example it has been in use in Paris for almost a century. In Canada, it is in use at a number of treatment plants in Quebec. Ozonation is not associated with the formation of chlorinated organic compounds. Besides destroying bacteria (e.g., coliforms and *Salmonella*), it inactivates pathogens that are not affected by chlorine, such as many viruses, spores, fungi and protozoan cysts (e.g., *Entamoeba*) (Diaper, 1975; CWQG, 1987). It is also effective for trematodes (Venosa, 1972). Payment and Trudel (1985) reported that viral incidence in Quebec water samples fell to 8 percent after ozonation from an initial 79 percent. Furthermore, its effects on bacteria and poliovirus have been reported to be much more rapid than those of chlorine, smaller concentrations and shorter contact times are required, and effectiveness appears to be independent of pH, unlike the case for chlorine (see Diaper, 1975). Indeed, doses of less than 0.1 mg/L are adequate to maintain low bacterial levels (Lorch, 1987). The decay product of ozone is oxygen.

Ozone also eliminates colour from organic sources, and objectionable odour and taste. Colour of organic origin is generally due to conjugated unsaturated moieties (i.e., chromophores) which are disrupted by ozone (Rice, 1984). It oxidizes nitrite to nitrate (Diaper, 1975), and oxidizes sulphides almost instantaneously to sulphate and elemental sulphur (Chen, 1974; Rice, 1984). It effectively removes iron, manganese, and many heavy metal ions (Chen, 1974; Lorch, 1987). Ozone also decomposes organically bound heavy metal complexes (Rice, 1984). It partially oxidizes some detergents and pesticides (Rice, 1984), and can be used to remove cyanide and phenols (Diaper, 1975; Rice *et al.*, 1981). Ozone is very efficient at decreasing concentrations of polycyclic aromatic hydrocarbons (EHD, 1979). Ozone can accomplish significant destruction of nitrilotriacetic acid, whereas chlorine and chlorine dioxide are only slightly effective (Hrubec *et al.*, 1984). Ozone does not, however, oxidize trihalomethanes that are already present in the raw water (Rice, 1984). It also has little effect on actinomycete and bluegreen algal odours (Montiel, 1983).

Ozonation has not universally replaced chlorination, however, primarily because of its greater cost, and because residuals in the distribution system are of relatively short duration. Thus, water quality tends to decline more rapidly in the distribution system than when chlorine is used. Ozonation can also cause conversion of nonbiodegradable organics to biodegradable forms which provide substrate for additional bacterial growth within the distribution system (EHD, 1992). For these reasons,

46

many European installations post-chlorinate the water after it has been disinfected with ozone in order to maintain a residual disinfectant in the distribution system (EHD, 1979). Post-chlorination does not result in levels of chlorinated organics that are as high as is the case when chlorination is used as the primary disinfection treatment (EHD, 1979), perhaps because concentrations of dissolved organic materials are lower in the water by the time it is exposed to chlorine, and because much smaller amounts of chlorine are required.

The chemistry of the interactions between ozone and organics in the raw water is poorly understood, and it is not known whether some of the organic products would be objectionable (EHD, 1992). Compounds which have been reported as a result of partial oxidation by ozone include oxalic and formic acids, and formaldehyde (Moore, 1989).

■   Other Disinfection Practices

A number of other disinfection methods are used by a few installations. Potassium permanganate has disinfection properties and can reduce some, but not all, of the odours generated by actinomycetes and bluegreen algae, but a high dosage is required (Gerber, 1983; Montiel, 1983).

Irradiation with ultraviolet light is effective for destruction of bacteria, viruses and many organic substances. Ultraviolet light can inactivate polioviruses (Holden, 1970). It also provides decolouration, clarification, flocculation, deodorization, dehalogenation of carbon and nitrogen halogenated compounds, and decomposition of ozone-resistant heavy metal complexes. Detoxification of a number of carcinogens and neurotoxins has also been documented (see Lorch, 1987).

The optimal germicidal wavelength is approximately 265 nm (EHD, 1977b). The light is usually generated by mercury or antimony gas discharge lamps. Low pressure mercury lamps emit the bulk of the radiation at 253.7 nm (EHD, 1977b). The water must have relatively low turbidity in order that pathogens are not shielded by particles suspended in the water. Humic materials and iron in the water may interfere with effectiveness of this method (EHD, 1977b), and it may be necessary to pretreat the water to remove the offending substances.

Bromine and iodine have received some limited application. Since these are halogens, the problem of halogenation of organic compounds exists with a mechanism that is analogous to that seen for chlorine. However, the resistance of microorganisms varies with the different halogens. Some chlorine-resistant algae, such as *Cosmarium*, succumb readily to bromine, and bromine may be superior to chlorine in inactivating some amoebic cysts (see Taylor and Johnson, 1974). The disinfecting capability of iodine, on the other hand, is less affected than chlorine by elevated pH or organic matter (EHD, 1977b). However, iodine is less effective than chlorine in oxidizing capacity.

OTHER TREATMENTS

■   Fluoridation

Fluoride does not appear to be required in human nutrition, but it is added in the form of sodium fluoride, sodium silicofluoride or hydrofluorosilicic acid to the water supplies of 57 percent of the North American population in order to reduce the incidence of dental caries (Fillmore, 1992). According to the latter author, 263 communities in Canada fluoridated their water supply as of January 1992.

Considerable controversy exists regarding the benefits and risks of fluoridation. At low concentrations, fluoride ions improve bone and tooth mineralization (Shupe *et al.*, 1979). Approximately 98 percent of the total body content of fluoride is accumulated in the bones, and fluoride readily crosses the placental barrier (Shupe *et al.*, 1979).

However, fluoride ions are inhibitors of many enzymes (Cantarow and Schepartz, 1967), and thus are toxic at higher concentrations, hence their use in some rodenticides, and to control the intestinal roundworm *Ascaris* in pigs (Shupe *et al.*, 1979). Elevated levels of naturally occurring fluorides in drinking water (most often from deep wells) may result in dental fluorosis, characterized by mottling and brittleness of the enamel (Cantarow and Schepartz, 1967). Along the coastal plains of North Africa, a painful deterioration of the teeth, called darmous, is caused by excessive fluoride intake (Shupe *et al.*, 1979). Fluoride has been implicated in reports of a number of other health effects (e.g., Newbrun, 1972). At toxic concentrations, fluoride causes gastrointestinal disturbances, depression, restlessness and neurologic and cardiac problems (Shupe *et al.*, 1979).

Since most dentists now apply fluoride directly to the teeth as a preventative measure, and fluoride-containing dentifrices are in wide usage, there is some question whether the water supply should be fluoridated. This practice has been debated in the public arena as an ethical issue with regard to using the public water supply as a vehicle for compulsory mass medication (Wolman, 1969). Furthermore, fluoride in water is most effective while the teeth are still developing, and is of less benefit in adults once the teeth have calcified (Holden, 1970).

Since only a small proportion of municipal water (usually less than 5%) is actually ingested, fluoridation of an entire water supply is wasteful. There is no need to flush toilets, water lawns or fight fires with fluoridated water. The fluoride is eventually released to the environment, where its long-term consequences are not well understood.

■   Aeration and Flotation

Aeration may be used to improve the quality of drinking water, particularly from a ground water source. It may be used to oxidize iron and manganese and cause these to precipitate from the water. The process known as "air stripping" may release dissolved gases such as carbon dioxide from ground

48

water. Aeration reduces problems associated with undesirable tastes and odours of drinking water, and is useful in the control of some trace organic compounds (Turner and Fraser, 1986).

Flotation is the process whereby air bubbles are passed through the water. As they rise, solid particles become attached to them, and these complexes form agglomerates which float on the surface, where they can be skimmed off (Lorch, 1987).

■   Sedimentation and Filtration

Sedimentation occurs in water-storage reservoirs and holding cells, where organic and inorganic particulate matter settles passively to the bottom. Sedimentation may be enhanced by addition of aluminum sulphate, which flocculates and precipitates fine suspended particles and many microorganisms.

Filtration is achieved by passing the water through a series of sand filter beds. This step can remove many of the bacteria, algae, protozoan cysts and parasite eggs. Microfiltration may be achieved by passing the water through filters with mesh sizes that may range from 100 to 0.04 micrometers (Lorch, 1987).

■   Water Softening and Conditioning

Water of objectionable hardness may be softened through removal of calcium and magnesium salts by precipitation, or conversion of these salts into the corresponding sodium salts through ion exchange (see below). Municipal treatment plants generally utilize the former because of economy and the volumes involved. Generally precipitation is achieved by adding lime (calcium oxide), or soda (sodium carbonate) (Holden, 1970). Treatment for hardness may achieve significant reductions in calcium and magnesium content. Meranger *et al.* (1979) reported that Portage la Prairie, Manitoba reduced calcium levels from 90.0 to 26.1 mg/L and magnesium levels from 54.6 to 13.3 mg/L in the treated water.

■   Coagulation and Flocculation

Coagulation and flocculation involves the addition of chemicals to form precipitates and particles which can then be removed by sedimentation and/or filtration. Materials which are removed by this process include organic particles, suspended clay, colloidal particles, some dissolved organic matter, and a portion of the bacteria and viruses (Twort *et al.*, 1974; CWQG, 1987). Most commonly, the chemical added is aluminum sulphate. If the chemical is incorrectly applied, some may persist in the finished water. In some cases activated silica may be added as a coagulant aid (Holden, 1970). Coagulation-flocculation treatment may aggravate earthy-musty odours in water (Montiel, 1983).

■   Ion exchange

In the process of ion exchange, one type of ion in water is removed into an insoluble solid resin, and is replaced by an equal amount of another ion of the same electrical charge. In water softening, for instance, calcium and magnesium ions are removed by a cation exchange resin and sodium ions are substituted instead. Ion exchange can be used where the total dissolved solids concentration does not exceed 700 mg/L (Lorch, 1987). According to the latter author, with a correct choice of ion exchange resin, even many organic materials can be removed. Many types of resins are available, for example cation exchange, macroporous, isoporous, polyacrylic, organic scavenger, *etc.*

■   Electrodialysis

This has been used primarily for brackish waters, of up to 12,000 mg/L total dissolved solids concentration. The product contains about 200 mg/L total dissolved solids. This process may also be used as a pretreatment step for ion exchange (Lorch, 1987).

■   Reverse Osmosis

Osmosis is the process whereby water molecules move across a semipermeable membrane from a solution that contains a lower concentration of dissolved substances to a solution that is more concentrated, in an attempt to establish equal concentrations on both sides of the membrane. This movement of water molecules generates osmotic pressure. In reverse osmosis, the water containing dissolved substances is subjected to hydrostatic pressure that is greater than the osmotic pressure. A cellulose acetate membrane is commonly used (Fair *et al.*, 1971). This process results in water that is of greater purity than the original solution.

Reverse osmosis is used on a large scale for waters above 700 mg/L total dissolved solids, and also in situations where the total dissolved solids concentration is low, but concentrations of organics are high (Lorch, 1983). The product contains, on average, five to ten percent of the original total dissolved solids, but very high organic removals may be achieved.

■   Treatment with Activated Carbon

Activated carbon adsorbs a wide variety of organic compounds from water, and thus is highly effective for improving taste and odour, as well as reducing levels of potentially toxic organics (EHD, 1979; Dyksen and Hess, 1982). It works well for the removal of musty and earthy odours associated with actinomycetes and bluegreen algae (Montiel, 1983). It is less effective for contaminants such as cadmium, where reductions of only 10-50 percent are achieved (Sorg *et al.*, 1978).

Another alternative using MCA (macroreticular carbonaceous adsorbents) synthetic resins has recently been applied. These resins adsorb compounds of low molecular weight, but allow higher

50

weight organics to pass through. The advantage of MCA resins is that they can remove some volatile non-polar compounds that are not effectively handled by activated carbon (Turner and Fraser, 1986).

■   Distillation

Distillation is employed in cases where the water source is seawater or brackish water, i.e., where the dissolved solids exceed 5000 mg/L (Lorch, 1987). Since this process is very expensive, it is feasible for a municipal supply only where local energy supplies are cheap and readily available, or where solar power can be used. The finished product is of high quality, being free from organics and with very low total dissolved solids concentrations.

■   Freezing

While freezing is an effective way to separate salts from water, it is not economically feasible in most municipal applications. This method is potentially more useful in Northern areas.

INCIDENTAL EFFECTS OF DISTRIBUTION

Given the physical system requirements for collecting, pumping, storing, treating and distributing the water, it is inevitable that the water should come in contact with a variety of substances that can adversely affect its final quality. Besides the main substances used in the mechanical construction of the system itself, such as concrete, metal and plastic pipe, *etc.*, there are numerous other materials that may be used for specific applications within the distribution system. These can include bitumen, which is a mixture of hydrocarbon compounds used to line reservoirs and pipelines. Chlorinated rubber may be used in coatings to protect pipes against corrosion; these coatings may contain additives such as plasticizers and fillers. Epoxy resins are also often used as protective surface treatments. Resins generally contain many additives such as hardeners, accelerators, solvents, fillers and pigments (Schoenen and Scholer, 1985). The pigments may contain cadmium, titanium or phthalocyanines. Sealants may be various organic resins, polysulphide or silicones.

Even concrete is not innocuous, as an enormous variety of additives may be present, as the following list demonstrates: setting and hardening accelerators, liquidizers and inhibitors, additives for packing and mould injection, additives to confer porosity, additives to assist release of air, gas-forming additives, swelling agents, mineral additives, additives for reduction of permeability, bonding agents, additives to protect against alkalis, corrosion retardants, fungicidal, bactericidal and insecticidal additives, antiflaking additives and colouring materials (Schoenen and Scholer, 1985).

■   Asbestos

Asbestos is a group of fibrous silicate minerals which occur as amphibole or chrysotile varieties. The latter are more difficult to remove from water, and are unfortunately the type that is most

frequently found in Canadian drinking waters (Chatfield and Dillon, 1979). Asbestos fibre concentrations are usually quantified by electron microscopy, and although these tests are laborious and expensive, the results are only approximate because of the large numbers involved (counts are reported in millions of fibres per litre).

While asbestos-containing mining wastes may contaminate some drinking water sources (as was shown for Duluth, Minnesota in 1973 [Robson, 1987]), most asbestos originates in water distribution systems primarily as a result of erosion of asbestos cement pipe. This type of pipe is composed of a mixture of Portland cement and asbestos fibre. In Winnipeg, for example, asbestos composes approximately 17 percent by weight of such pipe (MacBride, 1986). Asbestos cement pipe has been widely utilized in Europe, and has been manufactured in Great Britain since 1928 (Steel, 1960). Water with a high aggressive index, i.e., with acidic properties, or water containing various dissolved materials, tends to corrode the pipe (ACI, 1966; Camp and Meserve, 1974). Asbestos fibres are thus released into the water supply at a faster rate when the aggressive index is high. Fibres also enter the water supply when the pipe is drilled or cut.

Exposure to asbestos fibres in drinking water is in addition to that in air and dietary sources (Rowe, 1983). Asbestos fibres in the water supply may pose hazards to lungs through inhalation via agencies such as vaporizers, humidifiers and showers (Robson, 1987). While it is yet unclear to what extent and under what conditions asbestos in drinking water poses a hazard to health, some evidence does exist for neoplasms arising as a result of ingested asbestos (e.g., Marsh, 1983). Ingested fibres have been reported to cross the gastrointestinal wall and to migrate to other organs (Patel-Mandlik and Millette, 1983), although the percentage of fibres involved in gut penetration in the absence of breaks in the mucosa are probably low (Cook, 1983). Asbestos fibres have been shown to be toxic to human fibroblast cells in cell culture (Chang *et al.*, 1983) and produce chromosomal aberrations in several cell types in rodents (Daniel, 1983).

Unfortunately the establishment of a "safe" level in drinking water is difficult since, like many other environmental hazards, human response to asbestos exposure appears to be a long-term effect which cannot be evaluated adequately using animal models where the lifespan is comparatively short (Condie, 1983). Available studies of human populations exposed to water supplies with different asbestos concentrations are limited, and have yielded variable, conflicting results (e.g., Meigs, 1983; Millette *et al.*, 1983; Toft and Meek, 1983). Such discrepancies are associated with a large number of complicating factors inherent in such studies, for example, variable residence time of individuals within a specific jurisdiction, fluctuating levels of asbestos fibres in the water supply, consumption rates of municipal water as compared to other sources such as bottled or additionally treated water, and

confounding exposures to other environmental hazards (Nicholson, 1983). The last factor is of particular interest, as some evidence exists that certain chemicals may enhance asbestos effects. Polynuclear aromatic hydrocarbons, for example, are thought to be cocarcinogens with asbestos (Kandaswami and O'Brien, 1983). According to these authors, it is unclear whether asbestos is in itself carcinogenic, or whether it acts to impair detoxification of these organic carcinogens, and thus the hydrocarbons have longer residence times in the body before they are inactivated.

Another complicating factor which adds to the difficulty of establishing a standard is associated with the variability in asbestos fibre length. Tilkes and Beck (1983) reported that toxicity of fibres to rat cells increases with fibre length and thinness.

Whatever the difficulties in quantifying the risk, according to Erdreich (1983): "Due to the large number of individuals with potential lifetime exposure to asbestos, even small increases in relative risks are important; therefore, measures to reduce exposure are still indicated." Accordingly, everything possible should be done to reduce the sources of asbestos in distribution systems by replacement of existing asbestos cement pipes with other, less hazardous types. Water-conditioning processes which reduce the aggressive index of the water may also be implemented where problems are known to exist.

At the same time, mitigating measures to reduce asbestos levels must be reviewed carefully in order not to introduce additional problems. For example, before 1980 asbestos cement water pipe with a vinyl liner was installed extensively in New England and New York. The liner was subsequently found to release tetrachloroethylene into the water supply (Robson, 1987) and further installation of the pipe was halted.

Plastics are often perceived as being relatively inert, but mechanically weak, with a short lifespan and vulnerability to the damaging effects of ultraviolet light. However use of some types of plastic pipes and plastic and synthetic resin coatings may promote bacterial growth because of low molecular weight hydrocarbons present in the material (Schoenen and Scholer, 1985). A major problem with plastics is the plasticizer and moulding agent content which is subsequently leached into the water (Lorch, 1987). Polyvinylchloride plastic pipe may release vinyl chloride monomers, and some plastic pipes have been shown to release chloroform and carbon tetrachloride (Schoenen and Scholer, 1985). Metal contamination in polyvinyl chloride plastics can also occur from the use of stabilizers such as cadmium stearate, and addition of barium or zinc salts to the polymer to protect it from excess chlorine during manufacture (Moore and Ramamoorthy, 1984).

■   Metals

Metal contaminants in drinking water have been the subject of increased attention as the presence of these substances in natural waters has become inevitable as the result of atmospheric

fallout and pollution with effluents and runoff. Metals such as cadmium and lead in water supplies have been investigated with respect to the incidence of particular forms of cancer and some cardiovascular illnesses (see Meranger *et al.*, 1979). Some metals are toxic in very small amounts and have cumulative effects. Even those metals which are regarded as essential micronutrients in human nutrition (e.g., zinc, copper, chromium, vanadium) may have adverse effects on health when they are present in drinking water at higher concentrations.

Most urban raw water sources in Canada contain relatively small amounts of metals. In general, concentrations of cadmium, chromium, copper, lead and zinc do not differ significantly among lake, river and ground water sources (Meranger *et al.*, 1979). However the treatment and distribution processes may greatly alter the metal levels. Concentrations of metals to which the consumer is exposed at the tap cannot be predicted from a knowledge of metal concentrations in the raw water.

Any exposed metal within the distribution system may contribute towards metal levels in drinking water. A number of metals often show higher concentrations in post-treatment than in raw water (Andelman, 1974). Chlorination, for example, increases copper levels. Copper concentrations also increase through contact of water with copper pipes, and brass and bronze fittings. Lee and Kjartanson (1990) found that leaching levels of copper into water increased with standing time of the water in the pipes, but age of the copper plumbing did not appear to have a significant effect. Presence of manganese in the water may also accelerate corrosion of copper within the system (Holden, 1970).

Acidic water brings metals into solution much more readily than does alkaline or hard water. Thus communities which draw their water from sources on the Precambrian Shield, or areas subject to acid rain, as for example near smelters, have a corrosion problem. Where lime is added to the water during the treatment process, for instance in Edmonton, alkalinity is increased and leaching of metals is reduced. While water sources of low pH and alkalinity are generally considered to be of high quality, such water acquires high levels of copper and lead once it is in the distribution system. Vancouver, for example, as well as Portland, Oregon, are faced with this dilemma (JMCE, 1983).

Presence of chloride accelerates corrosion of metals within the distribution system as this ion readily forms soluble salts with most metals (Holden, 1970). Dissolved organic substances, particularly organic acids, can also form complexes with metals.

Zinc may increase in concentration within the distribution system from contact with galvanized pipes, brass fittings and some anti-corrosion preparations. Zinc and copper are not normally toxic at the concentrations found in distributed water, and guidelines are set for these metals primarily with regard to taste and aesthetic considerations.

Lead has been in use in water distribution systems since at least the time of ancient Rome, where this metal was used for water pipes (Brothwell, 1972). Paradoxically, in supposedly enlightened times, lead is still of major concern where lead service connections exist or pipes in buildings have been joined using lead solder. A survey of Canadian drinking water (Meranger et al., 1979) found that treated and distributed water in a number of municipalities contained more lead than was present in the raw water.

Under a Manitoba Plumbing Code regulation which came into effect in 1989, new installations of lead solders and fluxes for use in potable water supply systems cannot exceed a lead content of 0.2 percent. However, lead installations made prior to this time are in widespread service. In a study of Winnipeg tapwater, levels of lead could be correlated with presence of lead service connections and newness of lead solder joints, although homes more than 10 years old showed unexpectedly high values of lead (Lee and Kjartanson, 1990). The National Building Code has been expected to ban the use of lead in solder, but this has not yet occurred.

While lead pipes and solder are obvious sources of contamination, other materials within the distribution system may also contribute lead. Some polyvinylchloride (PVC) plastic pipes contain lead-based stabilizers, which may contaminate the water with lead compounds (Schoenen and Scholer, 1985). The amount of lead contamination depends on the type of lead stabilizer and the physical and chemical conditions of the water.

Morning tapwater samples often show significantly greater concentrations of iron, lead, copper and zinc than samples collected in the evening (e.g., Morton et al., 1976) because of stagnation and leaching of water in pipes during the night. Surveys of drinking water in Toronto (Gibson et al., 1989 in Lee and Kjartanson, 1990) and Winnipeg (Lee and Kjartanson, 1990) showed that morning samples contained greater levels of lead, copper and zinc than samples collected after five minutes of flushing. An example of such differences is given in Table 3 for tapwater samples collected at the University of Winnipeg daycare center, and at a home on a nearby street.

TABLE 3: CADMIUM, LEAD AND COPPER LEVELS (AS ug/L) FOR TAPWATER SAMPLES COLLECTED IN THE MORNING BEFORE RUNNING AND AFTER 5 MINUTES OF RUNNING. TESTING WAS CARRIED OUT AT THE UNIVERSITY OF WINNIPEG			
LOCATION	CADMIUM	LEAD	COPPER
University of Winnipeg Infant Daycare - February 19, 1993			
Before running	5.4	18.6	937
After running	4.6	1.8	98
University of Winnipeg preschool Daycare - February 19, 1993			
Before running	0.4	17.6	949
After running	4.8	4.0	119
Agnes Street, Winnipeg (private home in old core area) - January 20, 1993			
Before running	0.4	15.8	783
After running	<0.1	6.2	51.5

Water from the hot tap normally contains higher amounts of metals than that from the cold tap because leaching rates are greater at higher temperatures and water is subjected to additional metal exposure in the hot water tank.

Cadmium may gain entry into the distribution system from certain pigments and corrosion-resistant metal fittings (Friberg *et al.*, 1974), or from stabilizers in plastic pipe. Cadmium levels have been reported to be greater in the distributed than in the raw water in a number of cases (e.g. Andelman, 1974; Meranger *et al.*, 1979).

Lee and Kjartanson (1990) found that contact of water with pipes and fittings had little effect on aluminum concentrations. Other elements such as chromium and antimony may be leached from the distribution system (CWQG, 1987). Some PVC plastic pipe may contain organotin compounds as stabilizing agents (Schoenen and Scholer, 1985); these are highly toxic.

■   Post-delivery Treatment

For a variety of reasons, real or perceived, consumers are often dissatisfied with the quality of their water at the tap. Such consumers may elect to install an additional water treatment system at their tap. Many types of point-of-use systems, ranging from primitive low-priced canisters that screw on to a single tap, to expensive multifunction units that service the entire residence, are commercially available. In some cases, these may be of little benefit, or may even reduce the water quality if they

are defective or have been in operation for an extended period of time. The consumer should be informed about the purposes for which these units are intended, what type of water treatment is required, and how the units should be properly maintained.

Types of units commonly available include carbon filtration, adsorption, ion exchange and reverse osmosis systems. A single unit may combine two or more processes for greater effectiveness. For example, a reverse osmosis system may be combined with carbon filtration.

Mechanical filtration removes suspended materials, and often some type of ceramic, fibrous or membrane filter is used. Filters are rated according to size of the smallest particles removed.

Adsorption usually involves the use of activated carbon. This form of treatment is very common in municipalities where the water supply is a problem. In Regina, it was reported in 1984 that approximately one in six houses used activated carbon filters (Morrison, 1984). This procedure is effective in reducing concentrations of many organic substances. However, the efficiency depends on the length of time the carbon cartridge has been in service; it is most effective when the carbon is new. Carbon filters are susceptible to bacterial contamination over time (EHD, 1977b) and must be changed frequently. Since residual chlorine in the water is also adsorbed, the potential exists for bacteria, for example, *Pseudomonas aeruginosa*, to multiply in the unit (Baumann and Dworkin, 1978; Morrison, 1984). To reduce this problem, the activated carbon may be impregnated with silver, which inhibits growth of bacteria. However, silver concentrations in the water are increased. The antimicrobial action of silver may be adversely affected by presence of chlorides, phosphates, and sulphides in the water, elevated hardness and low dissolved oxygen concentration (EHD, 1977b).

Ion exchange involves displacement of calcium and magnesium ions with sodium ions, reducing hardness (Baumann and Dworkin, 1978). This process can add significantly to the sodium concentrations. Decreases of calcium and magnesium, and increases in sodium have been implicated in hypertension and cardiovascular disease (Baumann and Dworkin, 1978).

Reverse osmosis utilizes a membrane filtering system that removes many salts and organics (particularly those with higher molecular weights), but it may also remove viruses and bacteria. Since many reverse osmosis units operate at water recovery rates that can be as low as 10 percent, much water is wasted (EHD, 1977b). The effectiveness of reverse osmosis systems depends on water pressure in the system, temperature, pH, chemical composition of the dissolved substances in the water, and degree of interference from colloidal particles and oils (EHD, 1977b). Concentrations of chlorine in excess of 1 mg/L may adversely affect the cellulose acetate membrane (EHD, 1977b).

For more specialized needs, electrodialysis units can be used to remove particular ions. In extreme cases, distillation may be used. While distillation is effective in eliminating most of the

dissolved materials, nonetheless some volatile organics such as phenolic compounds may be distilled along with the condensate. Indeed, some volatile organics may actually be concentrated into the finished product, particularly if the volume of the latter is small (EHD, 1977b). Distilled water is highly aggressive, and thus the composition of the walls of the containers and tubing with which it comes into contact may affect the resultant water quality.

Occasionally, other types of units may be found. For example, the water may be superchlorinated with high concentrations of chlorine, followed by a short period of chlorine contact, and subsequent removal of the chlorine residual by dechlorination using activated carbon (EHD, 1977b). Home units which utilize iodine, ozone or ultraviolet light for disinfection have also been marketed (EHD, 1977b).

Considerable confusion exists among consumers with respect to the efficiency of the various types of units on the market. The claims of the manufacturer are often inflated or unrealistic. A large turnover of companies exists in the business of home water purification. Since tests of the efficiency of a unit are expensive, the consumer has little tangible evidence to decide whether the unit is satisfying the needs for which it was purchased. For example, many consumers are concerned about metal levels in water. Table 4 shows a comparison of metal levels in distributed (at tap) and home treated water for three randomly tested types of units, the manufacturers of all of which claim that metals (including cadmium) are removed to a significant extent by their product. In this instance, the cheapest system actually added metals to the water, while the reverse osmosis system was the most effective.

TABLE 4: COMPARISON OF CADMIUM, LEAD AND COPPER IN DISTRIBUTED (AT TAP) AND HOME TREATED WATER FOR 3 WATER TREATMENT UNITS IN SELKIRK, MANITOBA, SAMPLED ON FEBRUARY 23, 1993. THE UNITS WERE FLUSHED IN ACCORDANCE WITH EACH MANUFACTURER'S INSTRUCTIONS BEFORE THE SAMPLES WERE COLLECTED. VALUES ARE ug/L. TESTING WAS CARRIED OUT AT THE UNIVERSITY OF WINNIPEG.

TYPE OF UNIT	CADMIUM	LEAD	COPPER
Screw-on to tap (after 1 week in operation)			
At connection into unit	2.8	7.0	1.0
Outlet from unit	3.0	8.4	3.8
Carbon Filtration			
At connection into unit	1.0	7.8	4.8
Outlet from unit	3.2	6.2	< 1.0
Reverse Osmosis			
At connection into unit	4.0	7.2	53
Outlet from unit	2.2	2.4	< 1.0

Some consumers may elect to add water softeners to their tapwater. Caution should be exercised in adding softeners to water that will be used for drinking or cooking, as many of these products contain borax, which is toxic.

Another choice available for consumers is to purchase bottled water for personal consumption, while utilizing distributed municipal water for washing and watering. Water for drinking and cooking often amounts to less than one percent of the total water use in a community. Essentially two types of bottled water are on the market: (a) municipal water treated by reverse osmosis, distillation, *etc.*; and (b) disinfected spring or well water. Commercially prepared bottled water is generally disinfected by ozone (Baumann and Dworkin, 1978). Again, however, caution must be exercized as bottled water is not stringently regulated in Canada.

APPENDIX I. SUMMARY OF EXISTING CANADIAN DRINKING WATER QUALITY GUIDELINES (CWQG, 1987, AND 1989, 1990, 1991, 1992 UPDATES)		
PARAMETER	MAXIMUM ACCEPTABLE LEVEL	TREATMENT
A. Gross Measures		
Colour	15 true colour units (TCU)	Coagulation and filtration, ozonation
Odour	"inoffensive"	Dependent on substance causing odour
pH	8.5 (maximum 6.5)	
Total dissolved solids	500 mg/L	
Turbidity	5 nephelometric turbidity units (NTU)	Coagulation and filtration
B. Organics		
Antimony	I.D.	C-F-CA
Arsenic	0.05 mg/L	Coagulation, lime softening
Asbestos	I.D.	C-F-F
Barium	1.0 mg/L	Lime softening, ion exchange
Boron	5.0 mg/L	CA, ion exchange
Cadmium	0.005 mg/L	Coagulation, lime softening
Chloride	250 mg/L	Ion exchange
Chromium	0.05 mg/L	Coagulation, lime softening
Copper	1.0 mg/L	Coagulation, aeration
Cyanide	0.2 mg/L	Ozonation
Fluoride	1.5 mg/L	Ion exchange
Iron	0.3 mg/L	Precipitation and filtration, ion exchange
Lead	0.01 mg/L	Coagulation, lime softening
Manganese	0.05 mg/L	Coagulation, lime softening
Mercury	0.001 mg/L	C-F-F, CA
Nitrate	10 mg/L	Oxidation
Radium	1 Bq/L	Precipitation, ion exchange

APPENDIX I. SUMMARY OF EXISTING CANADIAN DRINKING WATER QUALITY GUIDELINES (CWQG, 1987, AND 1989, 1990, 1991, 1992 UPDATES) - 2 -		
PARAMETER	MAXIMUM ACCEPTABLE LEVEL	TREATMENT
Selenium	0.01 mg/L	Coagulation, lime softening
Silver	0.05 mg/L	Coagulation, lime softening
Sulphate	500 mg/L	Ion exchange
Sulphide	0.05 mg/L	Aeration, oxidation
Tritium	40,000 Bq/L	I.D.
Uranium	0.02 mg/L	Carbonate addition, ion exchange
Zinc	5.0 mg/L	Lime softening
C. Organics		
Aldrin/dieldrin	0.0007 mg/L	Ozonation, CA
Atrazine	0.060 mg/L	CA
Carbofuran	0.090 mg/L	I.D.
Chlordane	0.0007 mg/L	CA
Cyanazine	0.010 mg/L	CA
2,4-D	0.1 mg/L	CA
DDT	0.03 mg/L	CA
Diazinon	0.014 mg/L	I.D.
Dichloroethane	0.005 mg/L	CA
Endrin	0.0002 mg/L	CA
Glyphosate	0.280 mg/L	I.D.
Heptachlor/heptachlor epoxide	0.003 mg/L	CA
Lindane	0.004 mg/L	CA
Methoxychlor	0.1 mg/L	CA
Methyl parathion	0.007 mg/L	I.D.
Metribuzin	0.080 mg/L	CA, chlorination

APPENDIX I. SUMMARY OF EXISTING CANADIAN DRINKING WATER QUALITY GUIDELINES (CWQG, 1987, AND 1989, 1990, 1991, 1992 UPDATES) - 3 -		
PARAMETER	MAXIMUM ACCEPTABLE LEVEL	TREATMENT
Nitrilotriacetic acid	0.05 mg/L	Ozonation, CA
Parathion	0.035 mg/L	CA
Phenols	0.002 mg/L	Oxidation, CA
Picloram	0.190 mg/L	I.D.
Simazine	0.010 mg/L	CA
Toxaphene	0.0088 mg/L	CA
Triallate	0.230 mg/L	I.D.
Trichloroethylene	0.05 mg/L	I.D.
Trifluralin	0.045 mg/L	CA
Trihalomethanes	0.350 mg/L[*]	Air stripping, CA

*   new proposed guideline 0.050 mg/L, as annual average of quarterly samples (EHD, 1992)

CA = activated carbon adsorption

C-F-CA = coagulation-flocculation-activated carbon adsorption

C-F-F = coagulation-flocculation-filtration

I.D. = insufficient data

REFERENCES

ACI. "Guide for the Protection of Concrete against Chemical Attack by Means of Coatings and Other Corrosion-Resistant Materials." *American Concrete Institute Proceedings*, 63 (1966): 1305-91.

Alperin, A. "Caution: Leptospires!" *Rad'ianska Zhinka (Kiev)* (July 1984): 16A.

Andelman, J.B. "The Effect of Water Treatment and Distribution on Trace Element Concentrations." In A.J. Rubin, ed., *Chemistry of Water Supply, Treatment and Distribution*, pp. 423-40. Ann Arbor: *Ann Arbor Science Publishers Inc.*, 1974.

APHA. *Standard Methods for the Examination of Water and Wastewater*. Washington, DC: American Public Health Association, 1985.

Atkinson, J.W. "British Experiences on Problems of Drinking Water Quality." In C.S. Russell, ed., *Safe Drinking Water: Current and Future Problems*, pp. 225-42. Washington, DC: Resources for the Future, 1978.

AWWA. *Water Treatment Plant Design*. New York: American Water Works Association, 1971.

Aziz, K.M.S. "Diarrhoea Toxin Obtained from a Waterbloom-producing Species, *Microcystis aeruginosa* Kutzing." *Science*, 183 (1974): 1206-1207.

Balazs, T. and V.J. Ferrans. "Cardiac Lesions Induced by Chemicals." *Environmental Health Perspectives*, 26 (1978): 181-91.

Barnett, J.R. and H.W. Dorough. "Metabolism of Chlordane in Rats." *Journal of Agricultural and Food Chemistry*, 22 (1974): 612-19.

Baumann, D.D. and D.M. Dworkin. "Consumer Perception and Choice of Drinking Water Quality." In C.S. Russell, ed., *Safe Drinking Water: Current and Future Problems*, pp. 355-88. Washington, DC: Resources for the Future, 1978.

Beliles, R.P. "The Lesser Metals." In F.W. Oehme, ed., *Toxicity of Heavy Metals in the Environment, Part 2*, pp. 547-615. New York: Marcel Dekker, Inc., 1979.

Berg, J.W. and F. Burbank. In H.C. Hopps and H.L. Cannon, eds., *Geochemical Environment in Relation to Health and Disease*. Annals of the New York Academy of Sciences 199 (1972).

Berry, B.J.L. and F.E. Horton. *Urban Environmental Management*. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1974.

Blake, N.M. *Water for the Cities*. New York: Syracuse University Press, 1956.

Brandes, M. "Efficiency of Subsurface Sewage Disposal Systems in Removal of Contaminants from Domestic Sewage." *Proceedings of the 11th Canadian Symposium on Water Pollution Research*, pp. 1-18, 1976.

Brodsky, R.E., H.C. Spencer Jr. and M.G. Schultz. "Giardiasis in American Travellers to the Soviet Union." *The Journal of Infectious Diseases*, 130 (1974): 319-23.

Brooks, S.M. *Basic Facts of Medical Microbiology*. Philadelphia: W.B. Saunders Co., 1958.

Brothwell, D. "The Question of Pollution in Earlier and Less Developed Societies." In P.R. Cox and J. Peel, eds., *Population and Pollution*, pp. 15-27. London: Academic Press, 1972.

Butler, G.C. "Exposure to Mercury." In E. Di Ferrante, ed., *Trace Metals Exposure and Health Effects*, pp. 65-72. Oxford: Pergamon Press, 1979.

Camp, T.R. and R.L. Meserve. *Water and Its Impurities*. Stroudsburg, PA: Dowden, Hutchinson & Ross, Inc., 1974.

Cantarow, A. and B. Schepartz. *Biochemistry*. Philadelphia: W.B. Saunders Company, 1967.

Chang, M.J.W., N.P. Singh, A. Turturro and R.W. Hart. "Characterization of Cytotoxic Effect of Asbestos on Normal Human Fibroblasts." *Environmental Health Perspectives*, 51 (1983): 237-39.

Chatfield, E.J. and M.J. Dillon. *A National Survey for Asbestos Fibres in Canadian Drinking Water Supplies*. Ottawa: Department of National Health and Welfare, 1979.

Chen, K.Y. "Chemistry of Sulphur Species and their Removal from Water Supply." In A.J. Rubin, ed., *Chemistry of Water Supply, Treatment, and Distribution*, pp. 109-35. Ann Arbor, MI: Ann Arbor Science Publishers Inc., 1974.

Clapham, W.B. Jr. *Human Ecosystems*. New York: MacMillan Publishing Co., 1981.

Condie, L.W. "Review of Published Studies of Orally Administered Asbestos." *Environmental Health Perspectives*, 53 (1983): 3-9.

Cook, P.M. "Review of Published Studies on Gut Penetration by Ingested Asbestos Fibres." *Environmental Health Perspectives*, 53 (1983): 121-30.

CWQG. *Canadian Water Quality Guidelines*. Ottawa: Task Force on Water Quality Guidelines of the Canadian Council of Resource and Environment Ministers, 1987.

CWQG. *Canadian Water Quality Guidelines Updates (March 1992)*. Ottawa: Task Force on Water Quality Guidelines of the Canadian Council of Resource and Environment Ministers, 1992.

Daniel, F.B. "In Vitro Assessment of Asbestos Genotoxicity." *Environmental Health Perspectives*, 53 (1983): 163-67.

Dart, R.K. and R.J. Stretton. *Microbiological Aspects of Pollution Control.* Amsterdam: Elsevier Scientific Publishing Company, 1980.

Denholm, W.T. and E.C. Potter. "A Survey of the Principles of Metallic Corrosion and its Control in Saline Waters." In T. Talsma and J.R. Philip, eds., *Salinity and Water Use.* London: Macmillan, 1971.

Diaper, E.W.J. "Disinfection of Water and Wastewater Using Ozone." In J.D. Johnson, ed., *Disinfection, Water and Wastewater*, pp. 211-31. Ann Arbor, MI: Ann Arbor Science Publishers Inc., 1975.

Di Ferrante, E. "Lead: Exposure and Health Effects." In E. Di Ferrante, ed., *Trace Metals Exposure and Health Effects*, pp. 5-11. Oxford: Pergamon Press, 1979.

Dixon, D.M. "Population, Pollution, and Health in Ancient Egypt." In P.R. Cox and J. Peel, eds., *Population and Pollution*, pp. 29-36. London: Academic Press, 1972.

Dyksen, J.E. and A.F. Hess III. "Alternatives for Controlling Organics in Groundwater Supplies." *American Water Works Association Journal*, 74 (1982): 394-403.

EHD. *National Survey for Halomethanes in Drinking Water.* Ottawa: Environmental Health Directorate, Health Protection Branch, 1977a.

EHD. *Survey and Test Protocols for Point-of-Use Water Purifiers.* Ottawa: Environmental Health Directorate, Health Protection Branch, 1977b.

EHD. *A Study of the Removal of Synthetic Organics from Drinking Water by Activated Carbon.* Ottawa: Environmental Health Directorate, Health Protection Branch, 1977c.

EHD. *The Removal of Organics from Drinking Water by Ozonation, Biodegradation and Activated Carbon Adsorption.* Ottawa: Environmental Health Directorate, Health Protection Branch, 1979.

EHD. *Chlorophenols and their Impurities: A Health Hazard Evaluation.* Ottawa: Environmental Health Directorate, Health Protection Branch, 1989a.

EHD. *Guidelines for Canadian Drinking Water Quality.* Ottawa: Environmental Health Directorate, Health Protection Branch, 1989b.

EHD. *Consultation Package on Trihalomethanes.* Ottawa: Environmental Health Directorate, Health Protection Branch, 1992.

EPA. *Statement of Basis and Purpose for an Amendment to the National Interim Primary Drinking Water Regulations on Trihalomethanes.* Washington, DC: Office of Water Supply Criteria and Standards Division, U.S. Environmental Protection Agency, 1978.

EPA. *Quality Criteria for Water - 1990.* Washington, DC: Criteria and Standards Division, Office of Water, U.S. Environmental Protection Agency, 1990.

Erdreich, L.S. "Comparing Epidemiologic Studies of Ingested Asbestos for Use in Risk Assessment." *Environmental Health Perspectives*, 53 (1983): 99-104.

Erlandsen, S.L. and E.A. Meyer. *Giardia and Giardiasis: Biology, Pathogenesis, and Epidemiology*. New York: Plenum Press, 1984.

Evison, L.M. and A. James. "Microbiological Criteria for Tropical Water Quality." In R. Feachem, M. McGarry and D. Mara, eds., *Water, Wastes and Health in Hot Climates*. London: John Wiley & Sons, 1977.

Ewing, B.B. and J.E. Pearson. "Lead in the Environment." *Advances in Environmental Science and Technology*, 3 (1974): 1-126.

Exler, H.J. "Defining the Spread of Groundwater Contamination Below a Waste Tip." In J.A. Cole, ed., *Groundwater Pollution in Europe*, pp. 215-41. Port Washington, NY: Water Information Center Inc., 1972.

Fair, G.M.; J.C. Geyer and D.A. Okun. *Elements of Water Supply and Wastewater Disposal*. New York: John Wiley & Sons, Inc., 1971.

Ferm, V.H. and S.J. Carpenter. "Development of Malformations Resulting from the Administration of Lead Salts." *Journal of Experimental Molecular Pathology*, 7 (1967): 208.

Fillmore, C. "Fluoride and Tooth Decay." *Alive*, 115 (January, 1992): 8.

Friberg, L., N. Piscator, G. Nordburg and T. Kyellstrom. *Cadmium in the Environment*. Cleveland: CRC Press, 1974.

Gatti, G.L., A. Macri and V. Silano. "Biological and Health Effects of Mercury." In E. Di Ferrante, ed., *Trace Metals Exposure and Health Effects*, pp. 73-98. Oxford: Pergamon Press, 1979.

Gerber, N.N. "Volatile Substances from Actinomycetes: Their Role in the Odour Pollution of Water." *Water Science and Technology*, 15 (1983): 115-25.

Gillies, M.T. *Drinking Water Detoxification*. Park Ridge, New Jersey: Noyes Data Corporation, 1978.

GPP. *The Groundwater Pollution Primer*. Fredericton: Conservation Council, 1988.

Grant, D.R. and P.T.K. Woo. "Comparative Studies of *Giardia* spp. in Small Mammals in Southern Ontario. I. Prevalence and Identity of the Parasites with a Taxonomic Discussion of the Genus." *Canadian Journal of Zoology*, 56 (1978): 1348-59.

Grima, A.P. *Residential Water Demand*. Toronto: University of Toronto Press, 1972.

Gummer, W.D. *Pesticide Monitoring in the Prairies of Western Canada*. Regina: Water Quality Interpretive Report No. 4, Water Quality Branch, Western and Northern Region, Inland Water Directorate, 1979.

Hall, R. "The Quality of Existing Water Systems and Public Perception." In *National Conference on Critical Issues in Drinking Water Quality*, pp. 45-49. Ottawa: F.A.C.E., 1984.

Hamilton, C.E. *Manual on Water*. Philadelphia: American Society for Testing and Materials, 1978.

Hanley, R. "Redesigned Toilet is New Weapon in Drought." *New York Times*, March 22, 1989, p. A16.

Harris, R. "Public Interest and Water, U.S. Experience." In *National Conference on Critical Issues in Drinking Water Quality*, pp. 78-87. Ottawa: F.A.C.E., 1984.

Highland, J.H., M.E. Fine, R.H. Harris, J.M. Warren, R.J. Rauch and A. Johnson. "Drinking Water and Cancer." In *Malignant Neglect*. New York: Environmental Defense Fund, pp. 82-101, 1979.

Heath, J.C., M.R. Daniel, J.T. Dingle and M. Webb. "Cadmium as a Carcinogen." *Nature*, 193 (1962): 592-93.

Heckman, C.W. "Pesticide Effects on Aquatic Habitats." *Environmental Science and Technology*, 16 (1982): 48A-57A.

Hodgson, E. and F.E. Guthrie. *Introduction to Biochemical Toxicology*. London: Oxford University Press, 1980.

Holden, W.S. *Water Treatment and Examination*. London: J. & A. Churchill, 1970.

Hrubec, J., M.J. Hart, P. Marsman and J.A. Luijten. "Impact of Chlorine, Chlorine Dioxide and Ozone on the Oxidation of NTA During Drinking Water Treatment." *Bulletin of Environmental Contamination and Toxicology*, 33 (1984): 548-55.

Hurtig, H. and C.R. Harris. *Nature and Sources of Pollution by Pesticides*. In A. Devos, N. Pearson, P.L. Silveston and W.R. Drynan, eds., *The Pollution Reader*, pp. 85-94. Montreal: Harvest House, 1970.

Hutchinson, M. "Microbiological Aspects of Groundwater Pollution." In J.A. Cole, ed., *Groundwater Pollution in Europe*, pp. 167-202. Port Washington, NY: Water Information Center Inc., 1972.

Kjellstrom, T. and G.F. Nordberg. "A Kinetic Model of Cadmium Metabolism in the Human Being." *Environmental Research*, 16 (1978): 248-69.

JMCE. *Internal Corrosion Mitigation Study, Addendum Report*. Portland: James M. Montgomery Consulting Engineers, Inc., Bureau of Water Works, 1983.

Juttner, F. "Volatile Odorous Excretion Products of Algae and their Occurrence in the Natural Aquatic Environment." *Water Science and Technology*, 15 (1983): 247-57.

Kandaswami, C. and P.J. O'Brien. "Effect of Chrysotile Asbestos and Silica on the Microsomal Metabolism of Benzo(a)pyrene." *Environmental Health Perspectives*, 51 (1983): 311-14.

Kehoe, R.A. "The Metabolism of Lead in Man in Health and Disease. The Harben Lectures 1960, Lecture No. 1: The Normal Metabolism of Lead." *Journal of the Royal Institute of Public Health*, 1961.

Lauwerys, R.R. "Health Effects of Cadmium." In E. Di Ferrante, ed., *Trace Metals Exposure and Health Effects*, pp. 43-64. Oxford: Pergamon Press, 1979.

Lee, C.F. "Kinetics of Reactions Between Chlorine and Phenolic Compounds." In S.D. Faust and J.V. Hunter, eds., *Principles and Applications of Water Chemistry*, pp. 54-74. New York: John Wiley & Sons, Inc., 1967.

Lee, P.S. and K.J.T. Kjartanson. *A Water Quality Study: Lead in Winnipeg Drinking Water*. Winnipeg: Waterworks, Waste & Disposal Department, 1990.

Ligman, K.; N. Hutzler and W.C. Boyle. "Household Wastewater Characterization." *Journal of the Environmental Engineering Division*, 100 (1974): 201-13.

Lippy, E.C. and J. Erb. "Gastrointestinal Illness at Sewickley, PA." *Journal of the American Water Works Association*, 68 (1976): 606-10.

Lorch, W. *Handbook of Water Purification*. Chichester, UK: Ellis Horwood Limited, 1987.

MacBride, B. "Asbestos in Drinking Water—No Cause for Concern." *Western Canada Water and Sewage Association*, 1986, pp. 11-12.

MacLeod, W. *Water Management in the Canadian North*. Ottawa: Canadian Arctic Resources Committee, 1977.

Mao, P. and J.J. Molnar. "The Fine Structure and Histochemistry of Lead-induced Renal Tumours in Rats." *American Journal of Pathology*, 50 (1967): 571-81.

Marsh, G.M. "Critical Review of Epidemiological Studies Related to Ingested Asbestos." *Environmental Health Perspectives*, 53 (1983): 49-56.

McAndrews, C.J. and H.A. Kerr. *Water Pollution and Agriculture*. In A. Devos, N. Pearson, P.L. Silveston and W.R. Drynan, eds., *The Pollution Reader*, pp. 115-21. Montreal: Harvest House, 1970.

McClanahan, M.A. "Recycle—What Disinfectant for Safe Water Then?" In J.D. Johnson, ed., *Disinfection—Water and Wastewater*, pp. 49-66. Ann Arbor: Ann Arbor Science Publishers Inc., 1975.

McLeod, J.A. and G.S. Bondar. "A Case of Suspected Algal Poisoning in Manitoba." *Canadian Journal of Public Health*, 43 (1952): 347-50.

McKane, L. and J. Kandel. *Microbiology: Essentials and Applications*. New York: McGraw-Hill, Inc. 1985.

McKone, T.E. *Environmental Transport and Human Exposure: A Multimedia Approach to Health-risk Policy*. Toronto: Proceedings, Environmental Research: 1991 Technology Transfer Conference, pp. 3-6.

Meigs, J.W. "Assessment of Studies on Cancer Risks from Asbestos in Connecticut Drinking Water." *Environmental Health Perspectives*, 53 (1983): 107-108.

Meranger, J.C., K.S. Subramanian and C. Chalifoux. "A National Survey for Cadmium, Chromium, Copper, Lead, Zinc, Calcium and Magnesium in Canadian Drinking Water Supplies." *American Chemical Society*, 13 (1979): 707-11.

Meyer, E.A. and S. Raduvescu. "*Giardia* and Giardiasis." *Advances in Parasitology*, 17 (1979): 1-47.

Miller, R.K. "Perinatal Toxicology: Its Recognition and Fundamentals." *American Journal of Industrial Medicine*, 4 (1983): 205-44.

Millette, J.R., G.F. Craun, J.A. Stober, D.F. Kraemer, H.G. Tousignant, E. Hildago, R.L. Duboise and J. Benedict. "Epidemiology Study of the Use of Asbestos-cement Pipe for the Distribution of Drinking Water in Escambia County, Florida." *Environmental Health Perspectives*, 53 (1983): 91-98.

Milliken, J.G. and G.C. Taylor. *Metropolitan Water Management*. Washington, DC: American Geophysical Union, 1981.

Montiel, A.J. "Municipal Drinking Water Treatment Procedures for Taste and Odour Abatement—A Review." *Water Science and Technology*, 15 (1983): 279-89.

Monzingo, D.L. Jr. and C.P. Hibler. "Prevalence of *Giardia* sp. in a Beaver Colony and the Resulting Environmental Contamination." *Journal of Wildlife Diseases*, 23 (1987): 576-85.

Moore, J.W. *Balancing the Needs of Water Use*. New York: Springer-Verlag, 1989.

Moore, J.W. and S. Ramamoorthy. *Heavy Metals in Natural Waters*. New York: Springer-Verlag, 1984.

Morris, J.C. "Aspects of the Quantitative Assessment of Germicidal Efficiency." In J.D. Johnson, ed., *Disinfection, Water and Wastewater*, pp. 1-10. Ann Arbor, MI: Ann Arbor Science Publishers Inc., 1975.

Morrison, A. "Is Canada's Drinking Water Safe?" In *National Conference on Critical Issues in Drinking Water Quality*, pp. 6-16. Ottawa: F.A.C.E., 1984.

Morton, M.S., P.C. Elwood and M. Abernethy. "Trace Elements in Water and Congenital Malformations of the Central Nervous System in South Wales." *British Journal of Preventive Social Medicine*, 30 (1976): 36-39.

Newbrun, E. *Fluorides and Dental Caries*. Springfield, IL: Charles C. Thomas Publisher, 1972.

Nicholson, W.J.   "Human Cancer Risk from Ingested Asbestos: A Problem of Uncertainty." *Environmental Health Perspectives*, 53 (1983): 111-13.

Norseth, T. "Health Effects of Nickel and Chromium." In E. Di Ferrante, ed., *Trace Metals Exposure and Health Effects*, pp. 135-46. Oxford: Pergamon Press, 1979.

NRCC. *2,4-D: Some Current Issues*. Ottawa: Publication No. NRCC 20647, National Research Council of Canada, 1983.

Ohlendorf-Moffat, P. "Is Your Water Safe to Drink?" *Chatelaine* (November 1990): 54-56.

Otis, R.J., W.C. Boyle, J.C. Converse and E.J. Tyler. *On-site Disposal of Small Wastewater Flows*. Small Scale Waste Management Project. Madison: University of Wisconsin, 1977.

Patel-Mandlik, K. and J. Millette. "Accumulation of Ingested Asbestos Fibres in Rat Tissues Over Time." *Environmental Health Perspectives*, 53 (1983): 197-200.

Payment, P. and M. Trudel. "Detection and Health Risk Associated with Low Virus Concentration in Drinking Water." *Water Science and Technology*, 17 (1985): 97-103.

Pelczar, M.J. and R.D. Reid. *Microbiology*. New York: McGraw-Hill, Inc., 1972.

Pip, E. "Phenolic Compounds in Macrophytes from the Lower Nelson River System, Canada." *Aquatic Botany*, 42 (1992): 273-79.

Piscator, M. "Exposure to Cadmium." In E. Di Ferrante, ed., *Trace Metals Exposure and Health Effects*, pp. 35-41. Oxford: Pergamon Press, 1979.

Popovska, P. "Odour Problems in Two Reservoirs." *Water Science and Technology*, 15 (1983): 25-33.

Proctor, N.H., J.P. Hughes and M.L. Fischman. *Chemical Hazards of the Workplace*. New York: Van Nostrand Reinhold, 1989.

RCEP. *Royal Commission on Environmental Pollution*. 16th Report, Freshwater Quality. London: HMSO Publications, 1992.

Reeves, H.C. *Funding Clean Water*. Lexington, Massachusetts: Lexington Books, 1984.

Rice, R.G. "Ozone Treatment of Drinking Water, Evolution and Current Status." In: *National Conference on Critical Issues in Drinking Water Quality*, pp. 205-40. Ottawa: F.A.C.E., 1984.

Rice, R.G., C.M. Robson, G. Wade Miller and A.G. Hill. 1981. "Uses of Ozone in Drinking Water Treatment." *Journal of the American Water Works Association*, 73 (1981): 44-57.

Riemer, D.N. *Introduction to Freshwater Vegetation*. Westport, Connecticut: Avi Publishing Co., 1984.

RMI. *Water-efficient Technologies for the Urban/Residential Sector*. Snowmass, CO: Rocky Mountain Institute, 1988.

Robeck, G.G. "Criteria Development for National Drinking Water Standards." In A.J. Rubin, ed., *Chemistry of Water Supply, Treatment, and Distribution*, pp. 1-9. Ann Arbor, MI: Ann Arbor Science Publishers, 1974.

Robson, B. "Asbestos in Our Water Supply." *US Magazine* (February 9, 1987): 54-57.

Rohlich, G.A. "Drinking Water and Health." In C.S. Russell, ed., *Safe Drinking Water: Current and Future Problems*, pp. 47-75. Washington, DC: Resources for the Future, 1978.

Rondia, D. "Sources, Modes and Levels of Human Exposure to Chromium and Nickel." In E. Di Ferrante, ed., *Trace Metals Exposure and Health Effects*, pp. 117-34. Oxford: Pergamon Press, 1979.

Rotton, J., R.S. Tikofsky and H.T. Feldman. "Behavioral Effects of Chemicals in Drinking Water." *Journal of Applied Psychology*, 67 (1982): 230-38.

Rowe, J.N. "Relative Source Contributions of Diet and Air to Ingested Asbestos Exposure." *Environmental Health Perspectives*, 53 (1983): 115-20.

Schneiderman, M.A. "Water and Epidemiology." In C.S. Russell, ed., *Safe Drinking Water: Current and Future Problems*, pp. 111-48. Washington, DC: Resources for the Future, 1978.

Schoenen, D. and H.F. Scholer. *Drinking Water Materials*. New York: Ellis Horwood Limited, 1985.

SDWC. *Drinking Water and Health*. Washington, DC: National Academy of Sciences, U.S. Research Council, 1977.

Senior, V.E. "Algal Poisoning in Saskatchewan." *Canadian Journal of Comparative Medicine*, 24 (1960): 26-31.

Shackelford, W.N. and L.H. Keith. *Frequency of Organic Compounds Identified in Water*. Washington, DC: United States Environmental Protection Agency, Report 600/4-76-062, 1976.

Shamberger, R.J. "Beneficial Effects of Trace Elements." In F.W. Oehme, ed., *Toxicity of Heavy Metals in the Environment*, Part 2, pp. 689-796. New York: Marcel Dekker, Inc., 1979.

Shamberger, R.J. "The Genotoxicity of Selenium." Mutation Research, 154 (1985): 29-48.

Shupe, J.L., A.E. Olson and R.P. Sharma. "Effects of Fluorides in Domestic and Wild Animals." In F.W. Oehme, ed. *Toxicity of Heavy Metals in the Environment*, Part 2, pp. 517-40. New York: Marcel Dekker, Inc., 1979.

Singleton, H.J. *Water Quality Criteria for Cyanide, Technical Appendix*. Victoria: Water Management Branch, British Columbia Ministry of Environment, 1986.

Slater, G.P. and V.C. Blok. "Volatile Compounds of the Cyanophyceae—A Review." *Water Science and Technology*, 15 (1983): 181-90.

Smith, H.A., T.C. Jones and R.D. Hunt. *Veterinary Pathology*. Philadelphia: Lea and Febiger, 1974.

Sorg, T.J., M. Csanady and G.S. Logsdon. "Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics: Part 3." *Journal of the American Water Works Association*, 70 (1978): 680-91.

Southwick, C.H. *Ecology and the Quality of Our Environment*. New York: D. Van Nostrand Co., 1976.

Steel, E.W. *Water Supply and Sewerage*. New York: McGraw-Hill Company, 1960.

Sunshine, I. *Handbook of Analytical Toxicology*. Cleveland: Chemical Rubber Co., 1969.

Taylor, D.G. and J.D. Johnson. "Kinetics of Viral Inactivation by Bromine." In A.J. Rubin, ed., *Chemistry of Water Supply, Treatment, and Distribution*. Ann Arbor, MI: Ann Arbor Science Publishers Inc., 1974.

Tilkes, F. and E.G. Beck. "Influence of Well-defined Mineral Fibres on Proliferating Cells." *Environmental Health Perspectives*, 51 (1983): 275-79.

Toft, P. and M.E. Meek. "Asbestos in Drinking Water: A Canadian View." *Environmental Health Perspectives*, 53 (1983): 177-80.

Turner, D. and S. Fraser. *Potential Sources of Groundwater Contamination in Manitoba*. Winnipeg: Manitoba Environmental Council, unpublished manuscript, 1986.

Twort, A.C., R.C. Hoather and F.M. Law. *Water Supply*. New York: American Elsevier Publishing Company, Inc., 1974.

USEPA. *Quality Criteria for Water*. Washington, DC: U.S. Environmental Protection Agency, 1976.

Venosa, A.D. "Ozone as a Water and Wastewater Disinfectant: A Literature Review." In F.L. Evans III, ed., *Ozone in Water and Wastewater Treatment*. Ann Arbor, MI: Ann Arbor Science Publishers Inc., 1972.

Volgenau, G. "High School Victims 30 Years Ago." *Journal of Pesticide Reform*, 7 (1987): 2: 2-3.

Vollenweider, R.A. *The Scientific Basis of Lake and Stream Eutrophication, with Particular Reference to Phosphorus and Nitrogen as Eutrophication Factors*. Technical Report DAS/DSI/68. Paris: OECD, 1968.

Wall, G.J. and L.R. Webber. "Soil Characteristics and Subsurface Sewage Disposal." *Canadian Journal of Public Health*, 61 (1970): 47-54.

Wallis, P.M., J.M. Buchanan-Mappin, G.M. Faubert and M. Belosevic. "Reservoirs of *Giardia* spp. in Southwestern Alberta." *Journal of Wildlife Diseases*, 20 (1984): 279-83.

Weiss, B. "Behaviour as a Sentry of Metal Toxicity." In E. Di Ferrante, ed., *Trace Metals Exposure and Health Effects*, pp. 185-98. Oxford: Pergamon Press, 1979.

Weiss, B. and R.A. Doherty. "Methyl Mercury Poisoning." *Teratology*, 12 (1975): 311-13.

Williamson, D.A. *A Preliminary Investigation into the Presence of Agricultural Pesticides in the LaSalle and Assiniboine Rivers, Manitoba, Canada*. Winnipeg: Water Standards and Studies Report 84-5, Manitoba Department of Environment, 1984.

Wolman, A. "Fluorine and the Public Water Supply." In G.F. White, ed., *Water, Health and Society*. Bloomington: Indiana University Press, 1969.

Wood, S., S.T. Williams, W.R. White and F. Jones. "Factors Influencing Geosmin Production by a Streptomycete and their Relevance to the Occurrence of Earthy Taints in Reservoirs." *Water Science and Technology*, 15 (1983): 191-98.

Zdanowski, B. "Variability of Nitrogen and Phosphorus Contents and Lake Eutrophication." *Polish Archives of Hydrobiology*, 29 (1982): 541-97.