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Abbreviations

AI	adequate intake
CCME	Canadian Council of Ministers of the Environment
CWF	community water fluoridation
HTA	health technology assessment
IQ	intelligence quotient
MAC	maximum acceptable concentration
pH	potential hydrogen
ppm	parts per million
UL	upper limit

Introduction

Dental caries is a common public health problem in Canada,[1] and it affects about 57% of children aged six to 11 years and 59% of adolescents aged 12 to 18 years.[2] It has been estimated that the prevalence of coronal caries and the prevalence of root caries for Canadian adults aged 19 years and older is 96% and 20.3%, respectively.[2] Dental caries can result in pain, infection, premature tooth loss, and misaligned teeth.[3] Untreated dental caries in children are associated with poor overall growth, iron deficiency, behaviour problems, low self-esteem, and a reduction in school attendance and performance.[4-9] In pregnant women, periodontal diseases are risk factors for preterm low birth weight.[10,11] By adulthood, about 96% of Canadians have experienced dental caries.[2] In 2018, the cost of dental services was estimated to be approximately $17 billion in Canada, about $461 per Canadian, based on total national health expenditure estimated from both the private sector ($15.2 billion) and public sector ($1.8 billion).[12] Poor oral health is experienced by Canadians who cannot access regular dental care, including lower income families with no insurance, seniors in long-term care, new immigrants, and Indigenous peoples.[2,13]

Fluoride is a negative ion (F^-) of the element fluorine (F_2).[14] The term fluoride also refers to compounds containing F^-, such as sodium fluoride (NaF), calcium fluoride (CaF_2), fluorosilicic acid (H_2SiF_6), or sodium fluorosilicate (Na_2SiF_6).[14] In water, these compounds dissociate to release F^-.[14] Fluoride compounds exist in soil, air, plants, animals, and water.[15] Epidemiological studies in the 1930s and 1940s found that people living in areas with high naturally occurring fluoride levels in water had lower incidence of dental caries (i.e., cavities and tooth decay), a chronic and progressive disease of the mineralized and soft tissue of the teeth. This finding led to the controlled addition of fluoride to community drinking water with low fluoride levels in order to prevent dental caries.[16,17] In 1945, Brantford, Ontario, was the first city in Canada and the third city in the world to implement drinking water fluoridation.[18,19]

Fluoride helps to prevent dental caries both systemically (pre-eruptive or before the teeth emerge) and topically (post-eruptive or on the tooth surface).[20,21] The systemic effect occurs through the incorporation of ingested fluoride into enamel during tooth formation, which strengthens the teeth, making them more resistant to decay.[21-23] The major sources of systemic fluoride are fluoridated water and foods and beverages prepared in areas with fluoridated water.[24,25] Fluoride from other sources such as toothpaste, mouth rinses, gels, varnishes, or foams provides a topical effect (unless swallowed) through direct contact with exposed tooth surface; this increases tooth resistance to decay against bacterial acid attack by inhibiting tooth de-mineralization, facilitating tooth remineralization, and inhibiting the activity of bacteria in plaque.[26] As well, after being absorbed systemically, a small portion of fluoride is excreted into the saliva where it provides a topical effect from the continuous bathing of saliva over the teeth.[27] Evidence has suggested that CWF is associated with a decrease in dental caries, a decline in numbers of hospital attendances for general anesthesia and tooth extractions, and a reduction in the cost of dental treatment in children.[28-34]

Daily intake levels of fluoride in humans vary depending on many factors, these include sources of fluoride (water, foods or beverages, or dental products), levels of fluoride in water or foods, the amount of water or food consumed, and individual characteristics and habits.[14] About 75% to 90% of ingested fluoride is absorbed through the gastrointestinal tract, and up to 75% of the absorbed fluoride is deposited in calcified tissues (such as bones and teeth) in the form of fluorapatite within 24 hours.[35,36] The rest is excreted primarily in the urine, with small amounts excreted in perspiration, saliva, breast milk, and feces.[35,36] In 2007, a dietary survey of the Canadian population estimated that the average intake of fluoride in children aged one to four years old in fluoridated and non-fluoridated communities was 0.026 mg/kg/day and 0.016 mg/kg/day, respectively.[14] The average dietary intake of fluoride in adults 20 years and older ranged from 0.038 mg/kg/day to 0.048 mg/kg/day in fluoridated communities, and ranged from 0.024 mg/kg/day to 0.033 mg/kg/day in non-fluoridated communities.[14] Based on the average daily dietary fluoride intakes in fluoridated areas (i.e., 0.7 to 1.1 ppm) in Canada and US, the recommended adequate intake (AI) of fluoride from all sources that is sufficient to prevent dental caries is 0.05 mg/kg/day, irrespective of age groups, sex, and pregnancy status.[37,38] The tolerable upper limit (UL) value for infants through children aged eight years is 0.10 mg/kg/day.[37] The UL for children older than eight years and for adults including pregnant women is 10 mg/day.[37]

According to the 2010 Health Canada *Guidelines for Drinking Water Quality*, the maximum acceptable concentration (MAC) of fluoride in drinking water is 1.5 ppm (parts per million or mg/L), while the optimal level of fluoride in drinking water is recommended to be 0.7 ppm (reduced from the previous range of 0.8 ppm to 1.0 ppm) for providing optimal dental health benefits and minimizing dental fluorosis.[15] MAC was determined with moderate dental fluorosis as the end point of concern.[15] Thus, community water fluoridation (CWF) in Canada is the process of controlling fluoride levels (by adding or removing fluoride) in the public water supply to reach the recommended optimal level of 0.7 ppm and to not exceed the maximum acceptable concentration of 1.5 ppm.[15] Most sources of drinking water in Canada have low levels of naturally occurring fluoride.[15] According to a Canadian survey conducted between 1984 and 1989, the average, provincial, naturally occurring fluoride levels in drinking water ranged from less than 0.05 ppm in British Columbia and Prince Edward Island, to 0.21 ppm in Yukon.[15] The provincial and territorial data on drinking water in 2005 provided by the Federal-Provincial-Territorial Committee on Drinking Water showed that the average fluoride concentrations in fluoridated drinking water across Canada ranged between 0.46 ppm and 1.1 ppm.[15] As of 2017, about 38.7% of Canadians were exposed to CWF for the protection of dental caries.[39] The decision to fluoridate drinking water is not regulated at the federal, provincial, or territorial levels, but rather the decision is made at the municipal level and is often taken by means of a community vote (i.e., by referendum or plebiscite).[14]

While public and dental health agencies and organizations, and about 60% of Canadians, view CWF as an effective and equitable means of improving and protecting the dental health of populations, there continues to be opposition, resistance, and skepticism about CWF, especially in terms of human and environmental health.[40-42] There are a variety of different perspectives on CWF, some of which centre on the scientific evidence of dental benefit,[42,43] while others include the availability of alternative oral public health programs or interventions that avoid perceived concerns of CWF.[43,44] Alternative publicly funded oral public health programs, such as school-based topical fluoride varnishes, though available, are not consistent across Canadian jurisdictions.[45-47] Importantly, the available programs are not universal in nature and mainly target high-risk populations.[45,46] Furthermore, public health programming is often targeted toward youth, excluding the adult and elderly populations. CWF, in contrast, is an intervention that reaches a broader population, so long as persons drink from municipal water supplies. Still, others cite potentially harmful side effects of fluoridation, for example, fluorosis, thyroid function, lowered average intelligence quotient (IQ) in populations, and negative environmental impact[14,48] as motivation for water fluoridation cessation. Additional concerns include possible relationships between industry and fluoridation.[14,48] Finally, an unsettled tension exists around the ethics of CWF in terms of distribution of benefits to all persons who consume fluoridated tap water, removing (or making very difficult) the ability to “choose” fluoridation.[43,49-51]

It is within this context that some municipalities are choosing to cease water fluoridation, leading to its decline.[39] Notably, large Canadian cities such as Calgary, Quebec City, Windsor, Moncton, and Saint John have discontinued their water fluoridation programs in recent years.[52-54] Other municipalities have also discontinued CWF across provinces and territories since 2012.[39] Although the total percentage of Canadians with access to CWF has increased from 2012 (37.4%) to 2017 (38.7%), some provinces and territories have shown a significant decline in fluoridated water system coverage.[39] As of 2017, the provinces and territories with the fewest municipalities with CWF systems include British Columbia, Quebec, New Brunswick, Newfoundland and Labrador, and Yukon.[39] The impact of CWF cessation on dental health is unclear.

Policy Question

This Health Technology Assessment (HTA) is intended to provide guidance to policy- and decision-makers at the municipal levels to help orient discussions and decisions about water fluoridation in Canada. This HTA seeks to address the following policy question: Should community water fluoridation be encouraged and maintained in Canada? The analytic framework informing this HTA is presented in Appendix 1.

Objectives

The aim of this HTA is to inform the policy question through an assessment of the effectiveness and safety,[55] economic considerations,[56] implementation issues,[57] environmental impact,[58] and ethical considerations[59] for CWF. An analysis of the evidence related to these considerations comprises different chapters of the HTA, each with specific and different research questions and methodologies. The following report presents the Environmental Assessment. Other sections have been published separately.

Research Question

The HTA addressed the following research questions:

Review of Dental Caries and Other Health Outcomes

1. What is the effectiveness of community water fluoridation (fluoride level between 0.4 ppm and 1.5 ppm) compared with non-fluoridated drinking water (fluoride level < 0.4 ppm) in the prevention of dental caries in children and adults?
2. What are the effects of community water fluoridation cessation (fluoride level < 0.4 ppm) on dental caries in children and adults compared with continued community water fluoridation (fluoride level between 0.4 ppm and 1.5 ppm), the period before cessation of water fluoridation (fluoride level between 0.4 ppm and 1.5 ppm), or non-fluoridated communities (fluoride level < 0.4 ppm)?
3. What are the negative effects of community water fluoridation (at a given fluoride level) compared with non-fluoridated drinking water (fluoride level < 0.4 ppm) or fluoridation at different levels on human health outcomes?

Economic Analysis

4. From a societal perspective, what is the budget impact of introducing water fluoridation in a Canadian municipality without an existing community water fluoridation program?
5. From a societal perspective, what is the budget impact of ceasing water fluoridation in a Canadian municipality that currently has a community water fluoridation program?

Implementation Issues

6. What are the main challenges, considerations, and enablers related to implementing or maintaining community water fluoridation programs in Canada?
7. What are the main challenges, considerations, and enablers related to the cessation of community water fluoridation programs in Canada?

Environmental Assessment

8. What are the potential environmental (toxicological) risks associated with community water fluoridation?

Ethical Considerations

9. What are the major ethical issues raised by the implementation of community water fluoridation?
10. What are the major ethical issues raised by the cessation of community water fluoridation?
11. What are the major ethical issues raised by the legal, social, and cultural considerations to consider for implementation and cessation?

The Environmental Assessment addressed research question 8.

All chemicals (from both anthropogenic and natural sources) have the potential to cause toxicological effects. However, the level of effect depends on the ecological receptor (e.g., non-human mammal, bird, fish, plant) being exposed, the route and duration of exposure (e.g., ingestion or dermal contact for chronic periods of time), and the hazard (i.e., inherent toxicity) of the chemical. The possibility of a toxicological risk exists if all three components are present (Figure 1).

Figure 1: Risk Diagram

Given the ways fluoride can enter the environment from CWF, and the ways ecological receptors can be exposed to fluoride from CWF, this Environmental Assessment evaluated the potential risks associated with exposure of ecological receptors to fluoride from CWF.

Study Design

Literature Search Strategy

A targeted literature search was performed by an information specialist, using a peer-reviewed search strategy. Environmental impact-related information was identified by searching the following bibliographic databases: MEDLINE (1946–) with in-process records and daily updates, ERIC (1965–), and BIOSIS Previews (1989 to 2010) via Ovid; CINAHL (1981–) and GreenFILE via EBSCO; PubMed; Toxline; and Scopus. The search strategy comprised both controlled vocabulary, such as the National Library of Medicine's MeSH (Medical Subject Headings), and the following keywords: community water fluoridation, aquatic, terrestrial, water quality, animals (e.g., invertebrates, fish, birds, mammals, and plants), effect(s), ecosystem(s), toxicology, and ecological risk assessment. The main search concepts were fluoridation and fluoride in water. Regular alerts were established to update the searches until the publication of the final report.

Grey literature (literature that is not published commercially and that is inaccessible via bibliographic databases) were identified by searching the Grey Matters checklist (https://www.cadth.ca/grey-matters). This checklist includes national and international HTA websites, drug and device regulatory agencies, clinical trial registries, health economics resources, Canadian health prevalence or incidence databases, and drug formulary websites. Google and other Internet search engines were used to search for additional Web-based materials. These searches were supplemented by reviewing the bibliographies of key papers.

Only literature relevant to the environmental impact on non-human, ecological receptors was included. Literature retrieval had no date limit, but the search was limited to English- or French-language publications.

Study Selection and Data Analysis

Eligible literature included primary studies of any design (i.e., laboratory and field studies), articles that do not contain original data (i.e., reviews and technical reports), and grey literature (e.g., regulatory agency guidelines). Conference abstracts were excluded from all searches. The search was focused on literature based in relevant comparison countries (Canada, US, Australia, New Zealand, UK, and members of the European Economic Area).

The literature search yielded 1,494 citations. In the first stage, the title and abstracts of citations were screened for relevance by a single reviewer in accordance with the criteria listed in Table 1. Based on this screening, 149 articles were determined to likely provide insights into the potential environmental risks associated with CWF, and the full text of these articles was retrieved. After reviewing the bibliographies of these papers, and through further opportunistic Internet searches, 68 additional articles not captured in the literature search were identified and the full text was retrieved for them. In the second stage, the full text of each article was reviewed in detail, and those determined to provide information pertaining to the variables listed in Table 1 were included in the analysis. This yielded a total of 90 articles that provided the relevant information used to address the research question. The study selection process is presented in Appendix 2.

The bibliographic details (authors, year of publication, and country of origin) were captured from each article. Data pertaining to any of the three key risk assessment criteria (exposure, receptor, and hazard) were extracted from each study. The environmental factors related to possible effects were broken down into variables (as outlined in Table 1).

Table 1: Information Included in the Assessment of Environmental Impact

Exposure	Source media for fluoride exposure (e.g., soil, groundwater, surface water, sediment); fate and transport of fluoride in different environmental media (e.g., groundwater transport, soil leaching, sedimentation, dilution); background environmental fluoride concentrations in soil, groundwater, surface waters, and sediment.
Receptor	Ecological receptors likely exposed to fluoride from CWF (e.g., plants, microbes, invertebrates, birds, mammals, fish, amphibians) based on exposure information.
Hazard	Reported effects of fluoride exposure on ecological receptors (e.g., growth, reproduction, survival); toxicological data for ecological receptors (e.g., no-observed-effect concentration, lethal or inhibitory concentration); environmental quality guidelines.

Findings

This Environmental Assessment focused on each component of the risk diagram: exposure, receptor, hazard, and risk. The findings from the literature search, as they pertain to the research question, are provided in the following section.

Exposure

Fluoride is ubiquitous in the environment. It is released naturally from the weathering of rocks, volcanic emissions, and marine aerosols.[60] Fluoride is also released into the environment from anthropogenic sources, such as fertilizer, pesticide, aluminum, as well as emissions from steel and oil production, coal burning, and some industrial effluent.[3] The controlled fluoridation of drinking water (i.e., CWF) also contributes fluoride to the environment, but this activity does not constitute a substantial source of fluoride in the environment, contributing less than 1% of total fluoride released into Canadian soils and waters.[61,62]

The concentration of fluoride in freshwaters across Canada has been reported to range from 0.01 ppm to 11 ppm, with a mean concentration of 0.05 ppm.[62] Generally, higher concentrations of fluoride are found in waters in the vicinity of industrial activities.[62] The mean global concentration of fluoride in seawater has been reported as 1.3 ppm (Environment Canada and Health Canada, 1993).[62] Fluoride concentrations in groundwater are influenced by the minerals and rock through which the water flows. In Canada, concentrations of fluoride in groundwater typically vary from 0.02 ppm to 1.2 ppm and may reach levels as high as 15 ppm.[63] The concentrations of fluoride in ambient soils in Canada range from 300 ppm to 700 ppm.[62]

The MAC of fluoride in drinking water is 1.5 ppm.[15] In 2005, the Federal-Provincial-Territorial Committee on Drinking Water reported that the average concentrations of fluoride in fluoridated drinking water systems across Canada vary from 0.46 ppm to 1.1 ppm (Health Canada, 2010).[15] Furthermore, based on provincial and territorial data, 75% of the Canadian population are estimated to receive fluoride in their water at concentrations below 0.6 ppm, and less than 2% of the population receive community water at levels more than 1 ppm.[15] Yarmolinski et al. (2009) compared levels of water fluoridation in 14 urban and three rural distribution systems in Ontario and used these data as an indicator of the level of fluoride that the estimated 9.5 million urban dwellers and 1.7 million rural dwellers in Ontario are exposed to in their municipal water supply.[64] Results of this study showed that all 14 urban water suppliers were within the range of 0.5 ppm to 0.8 ppm, while the three rural suppliers were below 0.6 ppm.[64]

Fluoride from community water supplies may enter soil and groundwater directly through surface run-off from, for example, firefighting, washing cars, and watering gardens, and from leakage of water from the municipal distribution system.[65] Soil may leach fluoride into groundwater and groundwater may transport and discharge fluoride into surface waters. The fate and bioavailability of fluorides in soil depends on the soil potential hydrogen (pH), temperature, organic content, clay content, and soil type.[66] Most soils act as a sink for fluoride, retaining it strongly within clay minerals, calcareous, and silicate components.[67,68] The organic fraction of surface soil also contains humic and fulvic acids that can retain fluoride ions; therefore, in surface soils only a small fraction (< 1 ppm) of fluoride is water soluble .[67] Fluoride retention by acidic soils (pH 4 to 6) can be 10 times greater than that of alkaline soils (pH > 7). Leaching generally removes only a small amount of fluoride from soils; for example, laboratory leaching studies have shown that soil columns can retain more than 95 % of added soluble fluorides;[67] Gibson et al. (1992) showed that approximately 75% of fluoride applied to soil was retained by the soil particles;[69] and Oelschlager (1971) reported that about 0.5% to 6% of fluoride added yearly to forest and agricultural soils through fertilizers was lost in the leaching process.[60,70] However, in soils containing mainly sand with little clay, iron and aluminum, up to half the fluoride may leach through the soil. Nevertheless, soils tend to act as a buffer system and soluble fluoride concentrations decline as water travels underground.[67] One study found that 40% to 50% of the fluoride discharged to groundwater is removed as the water travels through the soil and aquifer.[71] Extensive migration of fluoride from groundwater into surface waters will only occur if there is a heavy deposition of water-soluble fluorides onto alkaline soils composed predominantly of coarse sand.[67] Although fluoride from community water supplies can be released into soils, natural and anthropogenic sources also contribute fluoride to these media. As such, it is difficult to attribute an environmental concentration of fluoride in soil to CWF.

Most of the fluoride from community water supplies enters fresh water ecosystems located downstream of drinking- and waste-water treatment plants.[72] Osterman (1990) described the fate of fluoride added to drinking water in a typical municipal water management system as follows: (1) fluoridated water is distributed to the municipality; (2) waste water is transported through the sewer system to the sewage treatment plant; (3) waste water undergoes primary (mechanical and chemical) and secondary (biological) treatment; (4) treated water is discharged into surface waters.[73] The microorganisms present in secondary biological treatment systems are efficient in reducing fluoride concentrations in effluent.[73] For instance, raw sewage from seven fluoridated Ontario communities contained 0.96 ppm of fluoride, and secondary biological treatment reduced the amount of fluoride by 35% to 0.62 ppm. For 56 fluoridated California cities, raw sewage contained an average of 1.80 ppm of fluoride and biological treatment reduced fluoride levels by 56% to approximately 0.8 ppm.[74] When the treated waste water is discharged into a receiving water body, it undergoes rapid dilution. Natural currents may carry the waste water farther downstream, creating a secondary dilution over several miles.[73] In surface waters, fluoride may bind to various elements (e.g., calcium, aluminum, magnesium), forming insoluble complexes that can subsequently settle in the sediment.[60] There is potential for fluoride to be released from sediments and leach into the water column, especially if the sediment is disturbed.[75] However, the extent to which this movement occurs in the environment is unknown and will depend on the mineralogical composition of sediments, as well as the geochemistry of the water.[76]

Osterman (1990) showed that CWF has little impact on the receiving aquatic environment with respect to the increase in the overall fluoride concentration.[73] The city of Montreal was used as an example; there, water fluoridation was estimated to raise average aquatic fluoride levels in the waste-water plume immediately below effluent outfall by 0.05 ppm to 0.09 ppm. Downstream, in the St. Lawrence River, the estimated average daily increase in the fluoride concentration would be 0.02 ppm to 0.05 ppm at 1 km below effluent outfall, and 0.01 ppm to 0.03 ppm at 2 km below effluent outfall. Based on a mathematical model, Osterman (1990) predicted that overall, fluoride concentrations in the St. Lawrence river would be raised by 0.001 ppm to 0.002 ppm as a result of CWF.[73] These predicted increases are below the detectable level of analytical techniques.[73] In Montana, effluent from a waste-water treatment plant containing 0.6 ppm to 2.0 ppm of fluoride was regularly discharged into the East Galletin River. The river contained 0.62 ppm of fluoride at a 0.3 km distance from the effluent outfall and returned to the background level of 0.33 ppm within 5.3 km.[77] Similarly, a sewage disposal plant in Minneapolis–St. Paul regularly discharged effluent with a fluoride concentration of 1.21 ppm into the Mississippi River. Fluoride levels in the river returned to background levels of 0.2 ppm within 19 km of the outfall.[78]

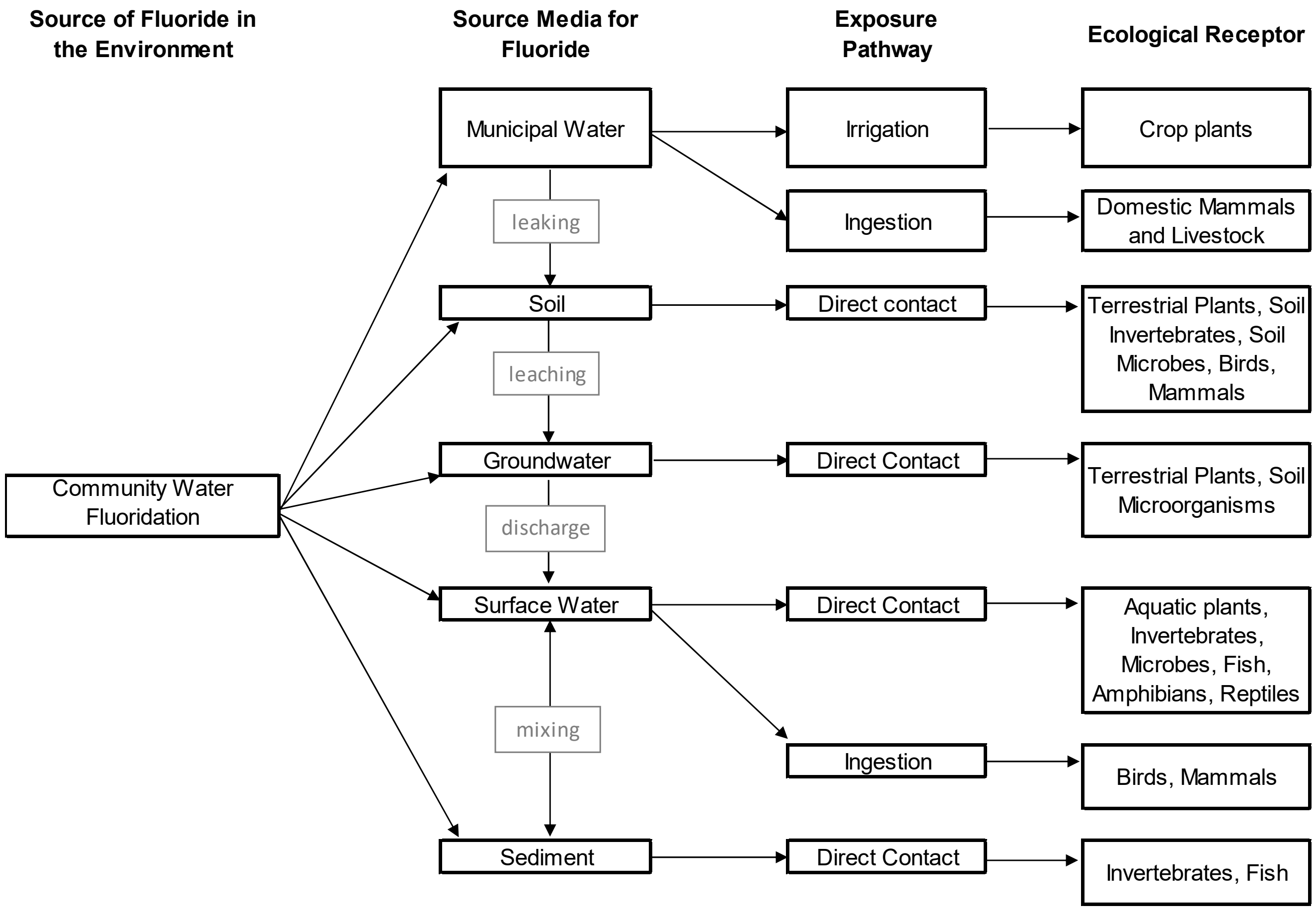
Receptor

The impact of fluoride from CWF on human health was not considered in this Environmental Assessment; rather, the focus was on the impact on ecological receptors. Given that fluoride from CWF can enter soil, groundwater, surface waters, and sediment, the following groups of organisms are likely to be exposed to fluoride:

- terrestrial plants
- terrestrial invertebrates and microbes
- birds
- mammals
- aquatic plants
- aquatic invertebrates and microbes
- fish
- amphibians and reptiles.

Terrestrial plants, invertebrates, and microbes may be exposed to fluoride through direct contact with soil and groundwater. Crop plants may be exposed to fluoride from irrigation water, and domestic mammals and livestock may be exposed through ingestion of municipal water. Birds and mammals may be exposed by ingesting surface water, while aquatic organisms (i.e., aquatic plants, invertebrates, fish, amphibians and reptiles) can be directly exposed to fluoride in surface waters and sediments. The ecological conceptual model provided in Figure 2 depicts the relevant pathways linking fluoride exposure in various environmental media from CWF to the identified receptors.

Figure 2: Ecological Conceptual Model



Hazard

Terrestrial Receptors

Soil Invertebrates and Microbes

Fluoride retained in soil can exert a negative impact on the growth and metabolic activity of invertebrates and microbes that have fundamental roles in nutrient cycling. Rao and Pal (1978) reported that as the concentrations of fluoride in soil and litter (the top, organic layer of soil) progressively increased from 380 ppm to 1,803 ppm, there was a parallel increase in the organic matter content of surface soils.[79] They attributed this to inhibition of growth and activity of the soil microbes responsible for the breakdown of organic matter. Van Wensem and Adema (1991) examined the effects of fluoride on the ability of soil microbes to mineralize nutrients in a terrestrial micro-ecosystem of poplar litter.[80] The no-observed-effect concentration (i.e., the highest concentration of fluoride that has no adverse effect on the exposed organism) for microbial mineralization of nitrate, ammonium, and phosphorus was 100 ppm, 320 ppm, and 1,000 ppm, respectively.[80] The survival and growth of the arthropod

Porcellio scaber was not affected when exposed to 3,200 ppm of fluoride in poplar litter for four weeks.[80] Ropelewska et al. (2016) investigated whether fluoride, at concentrations considerably higher than those typically found in soils, had an effect on the biomass and activity of soil-dwelling microbes.[81] In soil, fluoride doses of 500 ppm to 3,000 ppm led to an increase in microbial biomass relative to control samples, and as a result, glucose biodegradation also increased. However, at the highest dose tested (5,000 ppm), the microbial biomass decreased, nitrification and glucose biodegradation were inhibited, and ammonification was reduced. Other laboratory studies have shown that soil fluoride amendments of less than 200 ppm inhibited microbial respiration and dehydrogenase activity in soil, while amendments over this level and up to 2,000 ppm did not affect respiration, but did inhibit denitrification.[68] In one study, microbial enzymatic activity in soil was decreased substantially when water-extractable fluoride concentrations exceeded 20 ppm in soil.[82] The water-extractable fluoride fraction represents the total amount of easily mobilized and bioavailable fluoride in the soil. Therefore, the extractable fluoride concentration may be one to three orders of magnitude lower than the total soil fluoride concentration.[68]

As Osterman (1990) described, the fate of fluoride added to drinking water in a typical municipal water management system undergoes secondary (biological) treatment and this treated water is subsequently discharged into surface waters.[73] Some data exists on the effects of fluoride on the microbial populations used in biological treatments. Carrera et al. (2003) investigated the effect of fluoride on nitrification by sludge microbes in an activated sludge system for the treatment of industrial waste water.[83] The microbe's capacity for nitrification was reduced by 5% to 15% at fluoride concentrations of less than 50 ppm. Singh and Kar (1989) found that fluoride at concentrations of 100 ppm did not affect the cell growth or degrading capacity of sludge microbes.[84] Ochoa-Herrera et al. (2009) evaluated the inhibitory effect of fluoride toward the microbial populations responsible for the removal of organic constituents and nutrients in waste-water treatment processes.[85] Their results showed that microorganisms involved in anaerobic digestion processes were most sensitive to fluoride. The concentrations of fluoride causing 50% metabolic inhibition of propionate- and butyrate-degrading microorganisms, as well as acetate-utilizing methanogens, ranged from 18 ppm to 43 ppm. Fluoride was also inhibitory to nitrifying bacteria, showing a 50% inhibition in nitrification at 149 ppm.[85] Other microbial populations (i.e., glucose fermenters, aerobic glucose-degrading heterotrophs, denitrifying bacteria, and methanogens) tolerated fluoride doses in excess of 500 ppm.[85] The microbes involved in waste-water treatment have many of the same metabolic activities (e.g., nitrification, ammonification, glucose degradation, etc.) as soil-dwelling microbes; therefore, data on the inhibitory effect of fluoride on these microbial populations may be used to infer effects on microbes in the soil environment.

Terrestrial Plants

Fluoride from CWF may reach soil through surface run-off and then further leach from the soil into groundwater. Although CWF would contribute minimal fluoride to these media, terrestrial plants may be exposed to fluoride through direct contact with soil and groundwater. Soil extraction studies, leaching experiments, and adsorption investigations indicate that the majority of fluoride released into soil becomes fixed by one or more of the soil components.[67] As a result, fluoride bioavailability is limited and plant uptake from soils is generally minimal.[68] Considering that fluoride is naturally present in soil at average concentrations of 300 ppm to 700 ppm,[62] most plants must have evolved some tolerance to it.[86] The potential for fluoride toxicity varies greatly among different plant species, with effects reported at soil fluoride concentration ranging from 55 ppm to 2,500 ppm. For the onion plant, the phytotoxic threshold was found to be 55 ppm in soil, beyond which the biomass yield decreased by 50% relative to the control (unamended media; i.e., 0 ppm fluoride).[87] The nettle plant displayed phytotoxic effects (leaf discoloration and brown spots) at 100 ppm of fluoride.[88] Singh et al. (1995) reported that irrigation water containing up to 120 ppm of fluoride did not produce any visible phytotoxic effects on ladyfinger plants grown in soil or sand over the course of 18 weeks.[89] Szostek and Ciecko (2017) conducted a pot experiment to investigate the response of various crops to soil contamination with fluoride.[90] The results of this study showed that soil fluoride at concentrations of up to 300 ppm enhanced the biomass of maize, yellow lupine, winter oilseed rape, black radish, and phacelia relative to the control treatment (i.e., no fluoride added to the soil). Telesinski et al. (2012) demonstrated that soil fluoride concentrations of 441 ppm and 503 ppm resulted in a 50% decrease in the root biomass of white mustard and common wheat plants, respectively.[91] Spinach plants did not display any visible symptom of phytotoxicity at 800 ppm of fluoride in soil.[92] Kumar and Singh (2015) reported a 73% decline in the root biomass of the upland cotton plant when irrigated with water containing 1,000 ppm of fluoride, relative to the control.[93] Cui et al. (2011) noted an 85% decrease in the biomass of maize in response to 1,500 ppm of fluoride in soil.[94] The toxicity effects of fluoride in olive trees (leaf necrosis and leaf drop) were observed in soil spiked with more than 2,500 ppm of fluoride.[95]

Short-term studies on plants grown in solution (hydroponic studies) indicate much lower fluoride toxicity thresholds.[61] Bale and Hart (1973) found that the roots of barley seedlings exposed to solutions containing 0.04 ppm sodium fluoride had chromosomal abnormalities, although seedling growth was not affected at concentrations up to 4.2 ppm.[96,97] Fluoride levels as low as 0.25 ppm in solution caused leaf necrosis in the ornamental plant *Cordyline terminalis* and damaged gladiolus florets, while 1.5 ppm injured rose petals.[98,99] In the environment, plants are not directly exposed to fluoride in solution; however, this exposure media may be relevant to plants (e.g., crops and ornamental plants) grown commercially in hydroponic systems.

Birds and Mammals

Birds and mammals may be exposed to fluoride from CWF by drinking from surface waters that receive fluoridated municipal effluent. With respect to domesticated birds, Merkley and Sexton (1982) found no negative effects on the reproductive performance (egg production, fertility, duration of fertility, and hatchability of fertile eggs) of chickens exposed to 100 ppm of fluoride in their drinking water over defined growing (0 weeks to 20 weeks) and production periods (from 20 weeks on).[100] In another study, 1,000 hens were given drinking water containing fluoride (0 ppm, 6 ppm, 10 ppm, 14 ppm, and 20 ppm) over a 17-week growth and 57-week laying period. Mortality was not affected by water fluoride concentrations of up to 20 ppm over the 74-week treatment period. Food intake decreased by the same degree at 10 ppm, 14 ppm, and 20 ppm of fluoride; however, the efficiency of food utilization (i.e., food intake: weight gain) was not affected. Body weight decreased at 10 ppm and 14 ppm of fluoride, albeit in a non-linear manner, and was not affected at 6 ppm and 20 ppm. The lack of a clear dose response (i.e., when an increase in the level of exposure does not produce a parallel increase in the effect response) with respect to body weight makes it difficult to discern a threshold effect level. During the laying period, egg production decreased significantly in hens receiving 20 ppm of fluoride, but eggshell breaking strength was not significantly influenced.[101] The British Columbia Ministry of the Environment defines the safe total dietary levels of fluoride for growing and broiler chickens as 300 ppm, and for laying hens and turkeys as 400 ppm. This total dietary exposure includes feed, forage, mineral supplements, and drinking water.[72] Japanese quail exposed to 50 ppm of fluoride in their drinking water for six weeks displayed no adverse effects on body weight, tibia weight, bone ash, or egg shell thickness.[102] With respect to wild birds, European starling nestlings were given daily oral doses of either distilled water or up to 160 mg of the fluoride in distilled water per kilogram of body weight for 16 days. The concentration resulting in 50% mortality (24-hours of acute exposure) in day-old starlings was 50 mg/kg. The 16-day 50% lethal concentration was 17 mg/kg.[103]

Early reports of the effects of fluoride on mammals came from field studies on domestic animals.[61] In these animals, fluoride toxicity presented itself in the form of tooth mottling, loss of appetite, and bone changes. Cattle appear to be the most sensitive livestock to fluoride toxicity because they have high water uptake rates and long lives, which provides maximal opportunity for fluoride to accumulate in their tissues. Some authors report that cattle developed mottled teeth when given water with fluoride at 0.5 ppm to 0.6 ppm, and that teeth eroded at 3.3 ppm. Other studies indicate that tooth mottling does not occur until 1 ppm to 2 ppm fluoride.[72] The safe total dietary levels of fluoride for cattle range from 40 ppm to 100 ppm depending on the type of cattle (e.g., dairy, beef, slaughter, or heifer), while those for sheep, horses, dogs, and swine range from 60 ppm to 150 ppm. This total dietary exposure includes feed, forage, mineral supplements, and drinking water.[72] Experimental populations of three wild species of small mammals (short-tailed field vole, bank vole, and wood mouse) were exposed to 40 ppm or 80 ppm of fluoride in their drinking water for up to 84 days. The wood mouse had no adverse effects at the highest fluoride treatment (80 ppm); however, premature mortalities were observed at 40 ppm and 80 ppm for the two vole species.[104]

Few laboratory studies have evaluated toxicity in mammals at fluoride concentrations relevant to those used in CWF. Rabbits given drinking water containing 1 ppm of sodium fluoride for 10 weeks had no adverse effects on food intake, weight gain, or fluoride deposition in teeth.[105] Similarly, rats receiving fluoridated water (1 ppm) for 4 weeks also showed no effect on food and water consumption, or in weight gain.[106] Auskaps and Shaw (1955) reported that fluoride administered in drinking water to rats (at 1 ppm, 5 ppm, and 20 ppm) had no adverse effects on their growth or reproduction.[107]

Fluoride may affect thyroid function in animals. One study found no thyroid abnormalities in rats given up to 20 ppm of fluoride in their drinking water, while another study found that 1 ppm may influence the thyroid gland indirectly by changing thyroid hormone transportation in the blood.[107,108] Adverse effects at the cellular level have also been reported in the literature studied. Rats receiving fluoridated water (1 ppm) for 4 weeks had elevated 3', 5' cyclic ampicillin concentrations in the liver, tibia, femur, and heart. Study authors postulated that metabolic processes regulated by this messenger molecule could be affected in rats if levels of 3’, 5’ cyclic ampicillin were elevated as a result of drinking fluoridated water.[106] In another study with rats, chronic ingestion (6 months) of 0.8 ppm of fluoride had effects on the electrical conduction in the heart, shown by reduced electrical systole. Water depletion in bone and kidneys, and water retention in liver, atria, thyroid and submandibular glands was also observed at 0.8 ppm of fluoride. The zinc ion content of bone and tooth and the sodium, potassium, magnesium, and calcium ion content in the joint was reduced with chronic ingestion of 1.1 ppm of fluoride in drinking water.[109] One study found that fluoridation of drinking water at 1.5 ppm aggravated renal disease and increased aortic calcification in rats with chronic kidney disease.[110] However, another study evaluated the effects of 1 ppm of sodium fluoride in drinking water over the entire life-span (520 days) of healthy rats and found no effect on kidneys.[111]

Exposure to low levels of fluoride in drinking water has been shown to alter the synthesis and release of certain neurotransmitters in rats. Decreased levels of norepinephrine and dopamine and increased activity of acetylcholine esterase was observed at 1 ppm of fluoride.[112] Another study concluded that the consumption of fluoridated water (1 ppm) reduced the stores of insulin in rats.[113] A two-year study supplied distilled drinking water containing 1 ppm of fluoride to rats and found resorption cavities in the femurs; however, this study used a small number of rats.[114] Gedalia et al. (1960) also investigated rat femurs histologically and found no structural alterations when rats were given 1 ppm of fluoride in their drinking water.[115] Cytochemical investigations on the nervous system, liver, and kidney of squirrel monkeys after prolonged periods (up to 14 months) of fluoride intake via drinking water revealed that the nervous system was not affected at concentrations up to 5 ppm.[116]

Fluoride is also reported to be clastogenic (ability to disrupt chromosomes) and mutagenic (ability to alter genetic material) in mammalian cells. This finding is based on observations of changes in the frequency of sister chromatid exchange, chromosome aberrations, inhibition of DNA synthesis, or repair mechanisms and induction of gene mutations.[66,117] However, the available evidence on the potential mutagenicity of fluoride is conflicting, with many studies concluding that fluoride is not mutagenic for any mammal at low concentrations.[117,118] The concentration of fluoride necessary to induce genetic damage is well above the levels recommended for the fluoridation of community water supplies.[119,120]

Very few studies assessed sublethal effects such as behaviour, learning, and memory in mammals at exposure levels relevant to CWF. The National Toxicology Program (2016) investigated the impacts of fluoride on the neurobehaviour of rats and mice by undertaking a systematic review of the existing animal studies to develop level-of-evidence conclusions.[121] The animal studies used drinking water containing fluoride doses of 0.9 ppm to 271 ppm to test learning and memory, 0.9 ppm to 226 ppm to test motor and sensory function, and 0.9 ppm to 90 ppm to test for depression and anxiety.[121] There were no effects in learning and memory, motor activity, depression, or anxiety at 0.9 ppm; however, deficits in learning and memory were reported at fluoride concentrations of 2.26 ppm following 30 days of treatment for mice and six months of treatment for rats.[121]

Aquatic Receptors

Fluoride has a wide range of adverse effects on aquatic organisms, including effects on reproduction and development, growth inhibition, abnormal behaviour, endocrine disruption, and neurotoxicity.[122] Fluoride accumulates in hard or mineralized tissues such as bones, teeth, and invertebrate exoskeletons.[72] Factors such as water hardness, temperature, pH, chloride concentration, and species, age, and body size all influence the susceptibility of aquatic organisms to fluoride.[122] The risk for a range of aquatic receptors is discussed here.

Aquatic Plants

Generally, aquatic plants have high toxicity thresholds for fluoride. The no-observed-effect concentration for growth inhibition of several phytoplankton species ranged from 25 ppm to greater than 110 ppm.[122] Short-term toxicity tests with the freshwater algae *Selenastrum capricornutum* showed 50% growth inhibition at a fluoride concentration of 123 ppm (96 hours of acute exposure).[123] Chronic toxicity tests (exposure for longer than seven days) with various freshwater algae species show some degree of growth inhibition at fluoride concentrations ranging from 25 ppm to 380 ppm.[122,123] The lowest reported effect concentration for a freshwater aquatic plant is 2 ppm, which inhibited the growth of *Chlorella pyrenoidosa* by 37%.[124-126] However, Nichol et al. (1987) reported that fluoride concentrations up to 150 ppm had no effect on the growth of *C. pyrenoidosa.*[127] Li et al. (2013) also conducted a fluoride toxicity test on *C. pyrenoidosa* and 50% growth inhibition was observed at 168 ppm after eight days of exposure.[128] Among marine algae, the lowest reported effect concentration was 82 ppm for *Skeletonema costatu*m, with five other marine species showing growth inhibition at fluoride concentrations ranging from 100 ppm to 200 ppm.[123]

Aquatic Invertebrates

Fluoride toxicity to aquatic invertebrates increases with increasing fluoride concentration, exposure time, and water temperature, and decreases with increasing intraspecific body size and water hardness.[122,123] Net-spinning caddisfly larvae appear to be among the most sensitive invertebrates tested.[123] The concentrations causing 50% mortality in freshwater invertebrates from acute exposures (48 hours) range from 52.6 ppm to 128 ppm, and from chronic exposures (144 hours) of 11.5 ppm to 24.2 ppm. These effects were observed in soft water at temperatures between 15 ˚C and 18 ˚C.[123,129] In hard water, short-term toxicity tests (24 hours to 48 hours of acute exposure) for the planktonic crustacean *Daphnia magna* show 50% mortality at concentrations between 98 ppm and 352 ppm.[123] Dave (1984) reported the no-observed-effect concentration on growth, reproduction, and survival of *Daphnia magna* to be 3.7 ppm in hard water.[130] Short-term (96 hours of acute exposure) toxicity studies also showed sublethal effects on the larval migration of five caddisfly species at concentrations between 22.95 ppm and 43.09 ppm of fluoride.[131] The estimated safe concentrations for these caddisfly species, based on sublethal chronic toxicity bioassays, ranged from 0.39 ppm to 1.79 ppm in soft water.[131] The fingernail clam is also sensitive to fluoride, showing 50% mortality at a concentration of 2.8 ppm over an exposure period of eight weeks.[132] For two estuarine crayfish species, female fecundity appeared to be the most sensitive parameter and a maximum acceptable toxicant concentration of 4.5 ppm was set based on this parameter.[133] The New Zealand mud snail also showed sensitivity to fluoride based on reproductive parameters, with a derived no-observed-effect concentration of 4.6 ppm.[134] The most sensitive marine organisms tested were brine shrimp larvae, which showed growth impairment at 5 ppm after 12 days of exposure.[135]

Fish

Fish are more susceptible to fluoride at higher temperatures and in soft waters (i.e., less than 50 mg of calcium carbonate per litre) because the bioavailability of fluoride ions is reduced with increasing water hardness.[72] Fluoride toxicity decreases with increasing intraspecific fish size.[123] Trout appear to be among the most sensitive fish species tested. The fluoride level necessary to cause 50% mortality in test fish decreases as the exposure time increases. For rainbow trout, the concentration that is lethal to 50% of the fish ranges from 138.5 ppm (at 72 hour of acute exposure) to 2.7 ppm (at 480 hours of chronic exposure).[123] These effects were observed in soft water at temperatures between 12 ˚C and 15 ˚C. In hard water, the 50% lethal concentration for rainbow trout was 140 ppm to 193 ppm (at 96 hours of acute exposure). For brown trout, the concentration necessary to cause 50% mortality in the test fish ranges from 223 ppm (at 72 hours of acute exposure) to 97.5 ppm (at 192 hours of chronic exposure). These effects were observed in soft water at a temperature of 16 ˚C.[123] Pimentel and Bulkley (1983) recommended maximum chronic exposure levels of 2.5 ppm for rainbow trout in soft water and 9.6 ppm in hard water.[136] Camargo (2003) estimated safe concentrations (i.e., no-observed-effect concentrations) of 5.14 ppm for rainbow trout and 7.49 ppm for brown trout in soft water.[123]

Other fish species are less sensitive to fluoride. For the common carp, the fluoride concentration necessary to cause 50% mortality (at 480 hours of chronic exposure) was 81 ppm in soft water (McPherson et al., 2014).[122] For fathead minnow, 50% mortality (at 96 hours of acute exposure) occurred at 315 ppm of fluoride in soft water.[122] For Siberian sturgeon, 20% mortality occurred at less than 51.8 ppm of fluoride (at 90 days of chronic exposure) and the concentration causing growth inhibition in 10% of the test fish was 7.7 ppm in soft water.[137] For the three-spined stickleback, the concentration necessary to cause 50% mortality (at 96 hours of acute exposure) was 340 ppm to 460 ppm in hard water.[123]

Few studies indicate that low levels of fluoride (1.5 ppm or less) have adverse effects on fish. Delayed hatching of rainbow trout has been reported at 1.5 ppm of fluoride (Foulkes and Anderson, 1994; Osterman, 1990).[73,138] Damkaer and Dey (1984) suggest that fluoride released from an aluminum plant at concentrations of 0.3 ppm to 0.5 ppm had a negative effect on the passage time of adult Pacific salmon at John Day Dam in British Columbia.[139] The resultant effects on the population dynamics in the environment were not modelled in the study and are therefore unknown. Those authors conducted behavioural tests to confirm the cause-and-effect relationship by means of a two-choice flume where upstream migrants could choose to proceed into the left or right arms. Of the chinook and coho salmon moving upstream into one arm or the other, 75% and 66% chose the non-fluoride side, respectively. Chum salmon did not indicate as strong an avoidance response as the chinook or coho salmon. Their results suggest that 0.2 ppm may be near or below the threshold for fluoride sensitivity in chinook and coho salmon. Damkaer and Dey (1984) also reported elevations in levels of blood-thyroxine in smolting juveniles kept in fluoride concentrations of 0.3 ppm and 0.5 ppm.[139] Blood-thyroxine has been implicated in the migratory behaviour of juvenile salmonids.[140]

Amphibians

With respect to amphibians, Cameron (1940) reported that 2 ppm of fluoride in distilled water and 4 ppm in well water caused a delay in the development of frog tadpoles.[141] In pond water, 25 ppm of fluoride produced no retardation, but 30 ppm had an adverse effect. The differences between the effect concentration in the pond water versus the distilled or well water is likely due to differences in the overall water chemistry (i.e., the presence of other elements in the water). Consistent with this older publication, Kuusisto and Telkka (1961) reported that frog tadpoles exposed to 1 ppm of fluoride in tap water had delayed metamorphosis.[142] However, more recent work by Goh and Nef (2003) using an established method for the evaluation of the developmental toxicities of chemicals (e.g., frog embryo teratogenesis assay-*Xenopus*) found that the minimum concentration to inhibit embryo growth was 140 ppm.[143]

Risk

The potential environmental (toxicological) risks associated with CWF were characterized by evaluating information from assessment of the interaction among exposure, receptor, and hazard. In an ecological risk assessment, survival, reproduction, and growth are the basic measurement endpoints on which risk to individual receptors, populations, and communities is based.[144,145] However, exposure of receptors at field- or CWF-relevant levels of fluoride is often at sublethal concentrations; therefore, in addition to the aforementioned general measurement endpoints of biological effect, sublethal endpoints, such as behavioural responses, were also considered as part of this qualitative ecological risk assessment.

Although fluoride from community water supplies can be released into soil, groundwater, and sediment, numerous natural and anthropogenic sources also contribute fluoride to these environmental media. Given the lack of published exposure data for soil, groundwater, and sediment from CWF, it is difficult to attribute a fluoride concentration that ecological receptors may be exposed to in these media and thus, an assessment of risk cannot be made. However, it is worth considering that fluoride is naturally present in Canadian soils at concentrations between 300 ppm and 700 ppm and that most soils retain fluoride strongly. This means that fluoride in soil is not readily bioavailable for plants, soil invertebrates, and microbes to uptake. Moreover, these ecological receptors generally have a high fluoride tolerance (reported effect concentrations ranging from 55 ppm to 2,500 ppm). At a maximum acceptable limit of 1.5 ppm of fluoride in community water, CWF would not contribute an appreciable amount of fluoride to soil, and given the limited mobility in soil, even less would reach ecological receptors. The Canadian Council of Ministers of the Environment (CCME) recommends that the maximum concentration of total fluoride in irrigation water should not exceed 1 ppm for continuous use on all soils. Ontario, Manitoba, and Saskatchewan also recommend these limits,[63] while British Columbia recommends a maximum of 2 ppm.[72] Municipal water is not typically used as irrigation water. According to Statistics Canada, less than 1% of the irrigation water that comes from off-farm sources is obtained from tap water and treated waste water.[146]

There is enough information in the literature to allow for a qualitative ecological risk assessment of the aquatic environment. The maximum acceptable limits for CWF is 1.5 ppm;[15] therefore, the assumed worst-case environmental exposure concentration will be equal to this maximum. This concentration is below the acute and chronic toxicity levels for aquatic organisms, which range from 2 ppm to greater than 200 ppm; however, it is higher than the level at which some sublethal effects (e.g., migration and metamorphosis) have been reported for aquatic species. It is also above the Canadian guideline of 0.12 ppm for the protection of freshwater aquatic life.[147] This guideline was derived from the lowest acceptable adverse effect level for the most sensitive caddisfly species *Hydropsyche bronta*. This organism showed 50% mortality at 11.5 ppm of fluoride (144 hours) and CCME subsequently applied a safety factor of 0.01 ppm to derive the guideline (CCME, 2001).[148] It should be acknowledged that background concentrations of fluoride in surface waters often exceed this Canadian guideline.[62] Moreover, this Canadian guideline is conservatively protective because it does not consider factors that can reduce fluoride toxicity (i.e., lower water temperature, higher water hardness, higher chloride, and calcium and magnesium concentrations). As such, exceedance of this guideline does not necessarily mean adverse effects will occur.

What is more, aquatic organisms will not be exposed to raw municipal water; when fluoridated municipal water is released into the receiving aquatic environment, a minimum 10-fold dilution is likely to occur.[149] Therefore, even at the highest acceptable fluoride concentration (1.5 ppm), it is likely that fluoride in surface waters from CWF would be lower. Osterman (1990) showed that CWF has little impact on the surrounding aquatic environment and estimated that overall, fluoride concentrations in the St. Lawrence river would be raised by 0.001 ppm to 0.002 ppm as a result of CWF.[73] Other studies have also shown that rivers receiving municipal effluents returned to their background fluoride levels within 5 km to 19 km of the outfall.[77,78] With consideration for transport and dilution, fluoride concentrations in surface waters are expected to return to background values, which are below the lethal and sublethal toxicity thresholds for even the most sensitive aquatic organisms. Therefore, unacceptable risk to aquatic organisms exposed to fluoride from CWF is not expected.

Birds and mammals could be exposed to fluoride from CWF by drinking surface water, while domestic mammals and livestock could be exposed by drinking municipal water. There is some evidence that laboratory rats exposed to fluoride concentrations of 1 ppm in their drinking water experience adverse effects on a cellular level (e.g., enzyme inhibition); however, no effects on survival, growth, or reproduction were reported at these levels of exposure.[106,107,112] It is difficult to determine the extent to which data for laboratory rats drinking distilled or tap water spiked with fluoride can be reasonably extrapolated to project the response of wild mammals exposed to fluoride in the aquatic environment. Ideally, dosage routes and regimens in laboratory studies should be designed to mimic actual wildlife exposure scenarios. Nevertheless, even at the maximum acceptable fluoride concentration for CWF (1.5 ppm), the concentration in receiving surface waters, after dilution, should not exceed the recommended levels for birds and mammals that may drink from these waters. As for domestic mammals and livestock that drink municipal water directly, the CCME recommends that the concentration of fluoride in the drinking water should not exceed 2 ppm and that this limit should be reduced to 1 ppm in cases where the feed of animals contains fluoride.[63] British Columbia recommends a maximum total fluoride level of 1.5 ppm in drinking water for wildlife, cattle, breeding stock, and other long-lived mammals; and 4 ppm for all other livestock on a normal diet (British Columbia Ministry of Environment, 1995).[72] Therefore, these domestic animals are not expected to exceed their fluoride tolerance levels from drinking municipal water unless their diet also contains a substantial amount of fluoride.

Conclusions

Overall, based on the information extracted from the relevant literature, the following general themes about CWF and environmental risk emerged:

1. Fluoride is ubiquitous in the environment, but the contribution from CWF is minimal (< 1%).[62]
2. Fluoride from CWF can enter soil, groundwater, surface water, and sediment.
3. Fluoride from community water supplies can enter the soil, groundwater, surface waters, and sediment, and many different organisms can be exposed through these media.
4. Fluoride concentrations associated with a wide range of adverse effects on ecological receptors are typically not associated with CWF.
5. Based on the review of primary and grey literature sources, and with consideration of the fate and behaviour of fluoride in the environment (i.e., dilution and attenuation capacity), unacceptable risks to aquatic and terrestrial organisms exposed to fluoride from CWF is not expected.

The assessment of potential risks to ecological receptors from CWF is not without limitations; indeed, limitations are a fundamental component of all risk assessments. The primary limitations associated with this Environmental Assessment are provided in the following list. Although these limitations are unlikely to reverse the conclusions herein, they may influence the strength of the arguments.

- Dilution, anion exchange, precipitation, formation of mixed solids, and complexation reduce the levels of free fluoride in the aquatic environment. Furthermore, water temperature, hardness, and the presence of chloride, calcium, and magnesium also affect fluoride availability. The extent to which these factors reduce the exposure concentration of aquatic receptors must be assessed on a site-specific basis.

- Some authors do not report the form of fluoride used in the toxicity tests. Other authors report sodium fluoride as the form administered but dose levels are not always converted to fluoride equivalents; as such, dose levels reported as fluoride equivalents may sometimes overestimate the actual dose and, consequently, the effect level may be lower than what is reported.
- Some authors do not provide key information on the test performance criteria (e.g., sensitivity of test, positive and negative control responses, degree of biological variability). It is acknowledged that in vitro test methods may not replicate the metabolic processes relevant to chemical toxicity that occur in vivo.
- Some of the studies relied upon in this assessment are over 50 years old. This does not diminish the quality of those works but rather highlights the paucity of studies in recent years, despite widespread CWF practices, and the need for further research.
- Water ingestion rates for birds and mammals must be considered, as it is the actual amount of fluoride consumed that is relevant, and not its concentration in the water alone.
- Some information on fluoride bioaccumulation in the skeleton and soft tissue of aquatic and terrestrial organisms exists, yet there are uncertainties associated with potential food chain biomagnification and whether fluoride concentrates in organisms at higher trophic levels.[148]
- Fluoride effects may be reported in the presence of confounding variables that were not accounted for (e.g., the presence of other compounds, the nutritional status of the organism).
- The specific cation associated with a fluoride salt may affect fluoride toxicity. Fluoride is one of the main ions responsible for solubilizing beryllium, aluminum, scandium, niobium, tantalum, iron, and tin in natural waters;[72] therefore, there are uncertainties associated with the interactive or synergistic effects of fluoride.
- Fluoride is persistent in the environment and inputs from CWF and other sources (natural and anthropogenic) are cumulative over the years. However, since CWF is not a substantial source of fluoride, it may take a very long time to build up appreciable amounts of fluoride in the environment. Nevertheless, the repercussions of the continual addition of fluoride to community water on ecological receptors in the long term are unknown. The distribution and deposition of fluoride from CWF in different environmental media (i.e., soil, sediment, groundwater, and surface water) must be continuously monitored.

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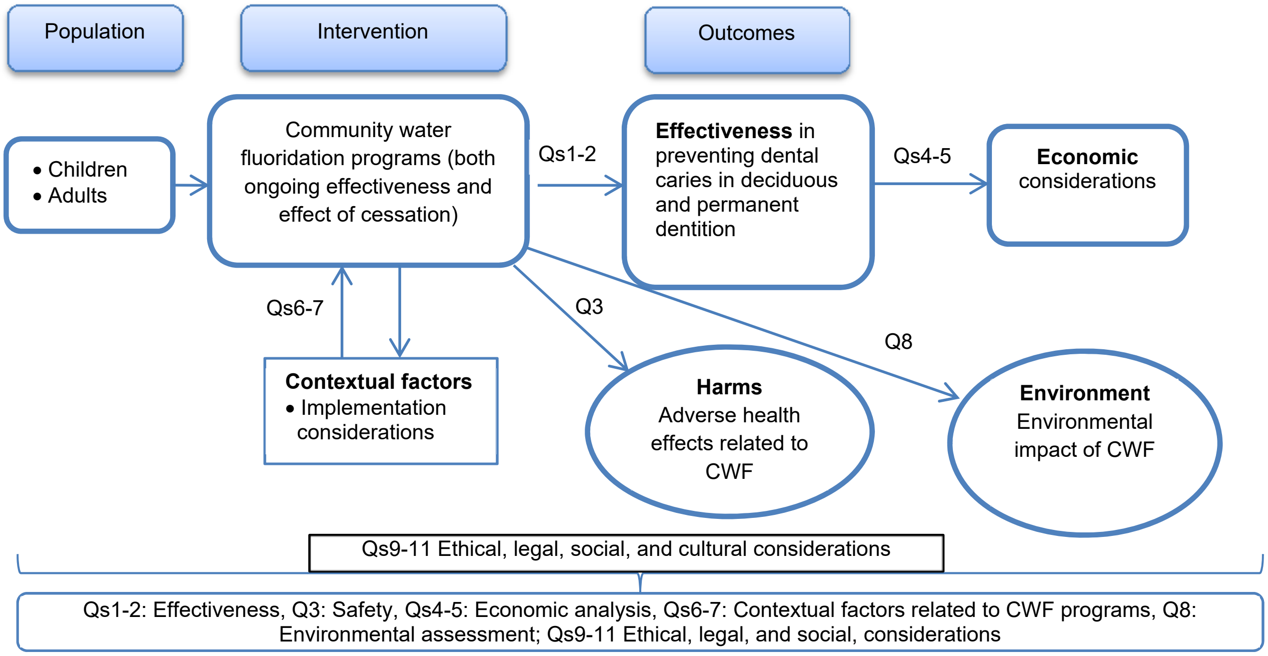
Appendix 1: Analytical Framework

Policy Question: Should community water fluoridation be encouraged and maintained in Canada?



Research Questions	Methods
Q1. What is the effectiveness of community water fluoridation compared with non-fluoridated drinking water in the prevention of dental caries in children and adults?	Update of two published systematic reviews
Q2. What are the effects of community water fluoridation cessation compared with continued community water fluoridation, the period before cessation of water fluoridation, or non-fluoridated communities on dental caries in children and adults?	
Q3. What are the negative effects of community water fluoridation (at a given fluoride level) compared with non-fluoridated drinking water (fluoride level < 0.4 parts per million) or fluoridation at different levels on human health outcomes?	
Q4. What is the budget impact of introducing water fluoridation in a Canadian municipality without an existing community water fluoridation program from a societal perspective?	Budget impact analyses
Q5. What is the budget impact of ceasing water fluoridation in a Canadian municipality that presently has a community water fluoridation program from a societal perspective?	
Q6. What are the main challenges, considerations, and enablers to implementing or maintaining community water fluoridation programs in Canada?	Consultations with targeted experts and stakeholders Narrative summary of the published and grey literature Survey on implementation issues related to community water fluoridation
Q7. What are the main challenges, considerations and enablers to the cessation of community water fluoridation programs in Canada?	

Research Questions	Methods
Q8. What are the potential environmental (toxicological) risks associated with community water fluoridation?	Narrative summary of the published and grey literature Qualitative risk assessment
Q9. What are the major ethical issues raised by the implementation of community water fluoridation?	Review of the bioethics literature and analysis of ethical issues raised by reports answering Qs1-8
Q10. What are the broader legal, social, and cultural considerations to consider for implementation and cessation?	
Q11. What are the major ethical issues raised by the cessation of community water fluoridation?	

Appendix 2: Study Selection Process