Environment and Climate Change Canada Environnement et Changement climatique Canada

Canadian Environmental Protection Act, 1999

Federal Environmental Quality Guidelines

Strontium

Environment and Climate Change Canada

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Introduction

Federal Environmental Quality Guidelines (FEQGs) provide thresholds of acceptable quality of the ambient environment. They are based on the toxicological effects or hazards of specific substances or groups of substances. FEQGs serve three functions: first, they can be an aid to prevent pollution by providing targets for acceptable environmental quality; second, they can assist in evaluating the significance of concentrations of chemical substances currently found in the environment (monitoring of water, sediment, soil and biological tissue); and third, they can serve as performance measures of the success of risk management activities. The use of FEQGs is voluntary unless prescribed in permits or other regulatory tools. Thus FEQGs, which apply to the ambient environment, are not effluent limits or "never-to-be-exceeded" values but may be used to derive effluent limits. The development of FEQGs is the responsibility of the Federal Minister of Environment and Climate Change Canada under the Canadian Environmental Protection Act (CEPA) (Government of Canada (GC) 1999). The intent is to develop FEQGs as an adjunct to risk assessment/risk management of priority chemicals identified in the Chemicals Management Plan (CMP) or other federal initiatives.

Where data permit, FEQGs are derived following CCME protocols. FEQGs are developed where there is a federal need for a guideline (e.g., to support federal risk management or other monitoring activities) but where the CCME guidelines for the substance have not yet been developed or are not reasonably expected to be updated in the near future. More information on FEQGs is available at https://www.canada.ca/en/health-canada/services/chemical-substances/fact-sheets/federal-environmental-quality-guidelines.html.

This factsheet describes the Federal Water Quality Guideline (FWQG) for the protection of aquatic life from adverse effects of strontium (Table 1). It is based on toxicity data identified up to June 2015. No FEQGs for strontium have been developed for the biological tissue, sediment or soil compartments at this time.

Table 1. Federal Freshwater Quality Guideline for Strontium (dissolved).

Aquatic Life	Guideline Value (mg/L)[a, b]
Freshwater	2.5

[a] Given that dissolved strontium concentrations are approximately equivalent to total strontium concentrations, this guideline can be compared to total strontium concentrations when dissolved strontium concentrations are unavailable.

[b] While hardness was shown to be a toxicity modifying factor for strontium (Nautilus Environmental 2013), there are insufficient data on the relationship between hardness and strontium toxicity to develop a factor for adjusting strontium toxicity according to hardness at this time.

Substance Identity

Strontium (Sr) is an alkaline earth metal (CAS Number 7440-24-6) with properties similar to calcium. Strontium is very reactive with oxygen and water and exists primarily in the 2+ oxidation state. It is found naturally only in compounds with other elements in the environment (WHO 2010; Ropp 2013). It is most commonly found in the carbonate mineral strontianite ($SrCO_3$) and in the sulfate mineral celestite ($SrSO_4$) (Ropp 2013). These minerals are found predominantly in sedimentary rocks (Kogel et al. 2006). Strontium is a mixture of four naturally occurring stable isotopes: ^{84}Sr, ^{86}Sr, ^{87}Sr and ^{88}Sr, the latter being the most prevalent (Chowdhury and Blust 2012). The FEQG focuses on stable strontium.

Uses

Strontianite and celestite minerals are the only naturally-occurring strontium compounds that contain enough strontium to make recovery practical (Ober 2014). Celestite occurs more frequently in sedimentary deposits of sufficient size to make mining attractive, and it is mainly used in the production of other strontium compounds (MacMillan 2000; Ober 2014). Deposits of strontium were identified in British Columbia, Newfoundland, Ontario and Nova Scotia. In the Loch Lomond Sedimentary Basin of Nova Scotia, the Lake Enon and MacRae deposits were mined from 1970 to 1976, until production of low grade strontium was no longer economically sustainable (Fowler 1991; Kogel et al. 2006).

Until 2003, Canadian company Timminco Limited was the world's leading producer of strontium metal from imported strontium carbonate. There has been no production of strontium in Canada since Timminco ceased strontium production at its Ontario plant in 2003 (NRCAN, personal communication, 2016). In 2003, Canada exported 39 900 kg of strontium metal to the United States (Kogel et al. 2006). Though production has ceased, Canada continues to import strontium. Between 2012 and 2015, Canadian imports of strontium carbonate ranged from 611,000 to 836,000 kg (NRCAN, personal communication, 2016). Production of $SrCO_3$ in the United States ended in 2006 and no strontium minerals have been mined in the U.S. since 1959. The highest producers of strontium are Spain, China and Mexico. Global production in 2014 was 318 000 tonnes (USGS 2015). In 2007, the annual amount of strontium compounds placed on the Canadian market was about 5 400 tonnes (WHO 2010).

Strontium compounds are used in pyrotechnics and signal flares, and ceramic ferrite magnets. Strontium nitrate gives the bright red colour to fireworks and signal flares, and can be combined with copper compounds to make purple (Ober 2014). Other uses of strontium compounds include strontium metal in master alloys, strontium chromate for pigments and fillers, strontium carbonate in the electrolytic production of zinc, strontium oxide in ceramic and glass production, and strontium chloride in toothpaste for sensitive teeth (MacMillan et al. 2000; Ober 2014; USGS 2015).

Natural and anthropogenic sources of strontium in Canada include land disturbance, strontium deposits where strontium was previously explored or mined and discharges from non-nuclear industries, such as metal refineries, wood, pulp and ceramic industries (Chowdury and Blust 2012).

Fate, Behaviour and Partitioning in the Environment

Strontium is mainly present in the dissolved phase of aquatic systems and its concentrations are generally higher in marine (8.1 – 10.0 mg/L) than freshwater (0.002 – 0.2 mg/L) environments (Chowdhury and Blust 2012). The ocean is the largest reservoir of dissolved strontium, from which strontium can be released into the air via sea spray (WHO 2010). Strontium binds weakly to particles and is highly mobile between sediment and water, within sediment, from catchments to water systems, and to estuaries via rivers. Distribution coefficient estimates for strontium (expressed as the concentration ratio between the particulate phase and the dissolved phase under equilibrium conditions) are 180 L/kg for freshwater, 200 L/kg for marine, and 8 L/kg for coastal ecosystems (IAEA 2004; 2009). Strontium is emitted into the atmosphere principally in the oxide form, which reacts rapidly in the presence of moisture or carbon dioxide to form strontium hydroxide or strontium carbonate. Strontium hydroxide then ionises to form Sr^{2+} and $SrOH^+$ cations (WHO 2010).

The water solubility of the two most common strontium compounds, $SrSO_4$ and $SrCO_3$, is 0.14 g/L at 30°C and 0.11 g/L at 18°C, respectively (ATSDR 2004; WHO 2010). Strontium enters water through normal weathering processes, mineral leaching from soils, granites and sedimentary rocks, or with sewage from institutions that use strontium compounds (ATSDR 2004; Malina 2004).

Due to the interactions between strontium and calcium in aquatic organisms, water hardness, which is largely determined by calcium concentration, plays a role in strontium toxicity. Toxicity to organisms is reduced with increasing water hardness levels (Nautilus Environmental 2013). This is thought to be due to competition between calcium and strontium for uptake (see Mode of Action section below). Bioconcentration of strontium is inversely correlated with calcium concentrations in ambient water. Bioaccumulation occurs more in organisms occupying soft water than seawater because of high calcium concentrations in seawater. Strontium in the environment is not generally considered a concern to aquatic organisms (Chowdhury and Blust 2012). However, strontium has been identified as one of twenty-seven metal indicators in the Lower Athabasca Region Surface Water Quality Management Framework (Government of Alberta 2012) to assess ecosystem health of the lower Athabasca River and is being monitored via various provincial and federal initiatives [e.g. Regional Aquatics Monitoring Program (RAMP), and Joint Canada-Alberta Implementation Plan for Oil

Sands Monitoring). While a chronic effects benchmark for freshwater aquatic life was developed for strontium (McPherson et al. 2014), the dataset did not meet the requirements prescribed by CCME (2007).[1] As such, a freshwater FEQG for strontium has been developed herein to help inform water quality assessments conducted for the oilsands area.

Ambient Concentrations

Strontium is found in nearly all fresh water (ATSDR 2004). In typical fresh water it is mostly present as free metal ions (~95%) and some complexes of sulphate and carbonate (Chowdhury and Blust 2012). In both rivers and lakes of the Athabasca oilsands region at concentrations < 1000 µg/L, nearly all strontium appeared to be in the dissolved form (RAMP 2015). Assuming the same phenomenon is true for laboratory waters, the guideline value is expected to apply to dissolved strontium. Given that dissolved strontium concentrations are approximately equivalent to total strontium concentrations, this guideline can be compared to total strontium concentrations when dissolved strontium concentrations are unavailable.

Strontium levels in water and fish were measured in Canada. Median total and dissolved strontium concentrations in Canadian fresh water ranged from 0.0041 to 0.50 mg/L and 0.042 to 0.32 mg/L, respectively (Table 2). The median (and range) of strontium concentrations in fish fillets and whole body homogenates measured in lakes across Canada from 2004 and 2014 were 0.23 mg/kg (0.031-36.1 mg/kg) and 2.01 mg/kg (0.14-95 mg/kg), respectively (ECCC unpublished). More recent water quality data for Ontario streams and nearshore areas of the Great Lakes can be accessed through Ontario's Open Data Catalogue.

Table 2. Total and Dissolved Strontium Concentrations in Canadian Fresh Water (ECCC unpublished, unless otherwise specified).

Jurisdiction	Years Monitored	Total or Dissolved	Median (mg/L)	Min (mg/L)	Max (mg/L)
Liard River, NWT[a]	1960-1975	Total	0.20	-	0.25
Nelson-Saskatchewan-Mississippi River Basin[a]	1960-1975	Total	0.020-0.50	-	0.040-0.78
Lake Erie[b]	1981	Total	0.14	0.11	0.16
	1981	Dissolved	0.14	0.10	0.18
Lake Michigan[b]	1981	Total	0.12	0.10	0.12
	1981	Dissolved	0.11	0.087	0.12
Lake Superior[c]	1983	Dissolved	0.042	0.033	0.064
Lake Huron[d]	1981	Dissolved	0.097	-	-
Lake Ontario[d]	1985	Dissolved	0.18	-	-
NS	2011-2013	Total	0.017	0.0028	0.94
NB	2011-2013	Total	0.023	0.014	0.39
NL	2003-2013	Total	0.014	<0.00005	0.25
QC	2007-2014	Total	0.090	0.00004	9.24
		Dissolved	0.096	0.012	0.22
ON (Rainy R.)	2014	Total	0.022	0.017	0.031
MB	2003-2014	Total	0.31	0.021	0.71
		Dissolved	0.30	0.022	0.71

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[1] Specifically, the toxicity dataset included lethal endpoints, unacceptable geomeans of either two different endpoints or exposure durations and was missing the requisite number of fish species for deriving a Type A guideline. A detailed analysis of the dataset used in McPherson et al. (2014), including which data were included/excluded in the FWQG derivation, can be made available upon request.

Jurisdiction	Years Monitored	Total or Dissolved	Median (mg/L)	Min (mg/L)	Max (mg/L)
SK	2003-2015	Total	0.34	0.029	1.740
		Dissolved	0.32	0.026	1.45
AB	2003-2015	Total	0.25	0.039	0.91
		Dissolved	0.24	0.022	0.87
Athabasca Region[e]	1997-2015	Total	0.14	0.0001	3.30
		Dissolved	0.13	0.0001	3.08
BC-coastal lakes	2005-2014	Total	0.0041	0.00033	0.069
BC- NE rivers	2013-2014	Total	0.082	0.021	0.32
NWT	2003-2014	Total	0.16	<0.00005	2.58
		Dissolved	0.16	<0.00005	2.57

[a] Fisheries and Environment Canada 1977; [b] Rossman 1984; [c] Rossman 1986; [d] Rossman and Barres 1988; [e] RAMP 2015

Mode of Action

Strontium is similar to, but not an exact substitute for, calcium in biological processes because of the difference in the sizes of their atomic radius (ATSDR 2014). However, strontium has been found to accumulate in the bony tissues of fish, especially in soft waters, and is readily incorporated into fish otoliths ("earstones" made of calcium carbonate and which aid in fish balance and hearing) (Chowdhury and Blust 2012; Mugiya and Tanaka 1995). Due to its preferential accumulation in bones, at high concentrations it has the potential to interfere with bone development (ATSDR 2014).

In fish, gills are the major site of strontium uptake, and evidence suggests strontium enters the body using calcium transport systems and is cleared from the blood very rapidly. In fish and algae, strontium is thought to mimic calcium sorption and compete with calcium binding at ion-exchange sites of the cell wall (Chowdhury and Blust 2012, Sikes 1978). Uptake of strontium ions into fish strongly depends on the concentration of calcium ions in the water. With increasing Ca^{2+} concentrations, uptake of Sr^{2+} decreased in the whole body, viscera, bone, muscle, gills and blood of carp. Conversely, waterborne Sr^{2+} significantly inhibits Ca^{2+} uptake, though to a lesser degree. However, the uptake system has a higher affinity for Ca^{2+} and can become saturated with Ca^{2+} faster than Sr^{2+} (Chowdhury et al. 2000; Chowdhury and Blust 2012). In algae, strontium was found to act as a competitive inhibitor of total calcium uptake but enhanced calcium internal transport (Sikes 1978). However, during transport or binding processes, biological systems favour calcium over strontium by a factor of 2-3 (Chowdhury and Blust 2012).

Aquatic Toxicity

All relevant aquatic toxicity data for strontium were critically reviewed for acceptability for use in environmental quality guideline derivation. The data are current to June 2015. Of the 11 long-term studies found, three provided acceptable toxicity data. The three studies provided effect endpoints for seven different aquatic species (three fish, three invertebrates, one algae), ranging from 2.9 to 255 mg/L. Each species for which appropriate toxicity data were available was ranked according to preferred endpoint, then sensitivity. Acceptable chronic aquatic toxicity data considered for developing a freshwater FWQG are presented in Table 3. The most sensitive species in the dataset was the invertebrate *Ceriodaphnia dubia* and the least sensitive species was the fathead minnow *(Pimephales promelas)*.

In the derivation of a guideline value, the influence of toxicity modifying factors (e.g. pH, temperature, hardness, organic matter, oxygen) should be incorporated into the guideline where scientifically defensible (CCME 2007). While hardness was shown to be a toxicity modifying factor for strontium (Nautilus Environmental 2013), there are insufficient data on the relationship between hardness and strontium toxicity to develop a factor for adjusting strontium toxicity according to hardness at this time.

Table 3. Long-term Aquatic Toxicity Data Used for Developing the FWQG for Strontium.

Species	Group	Endpoint	Concentration (mg/L)	Reference
Zebrafish *(Danio rerio)*	▲	6-d LC$_{14}$ (survival)	2.9	Pasqualetti et al. (2013)
Water Flea *(Ceriodaphnia dubia)*	🟩	6-d IC$_{10}$ (reproduction)	8.1*	Pacholski (2014); Calculated by McPherson et al. (2014) from Cook (2008)
Water Flea *(Daphnia magna)*	🟩	21-d IC$_{10}$ (reproduction)	23	Pacholski (2014)
Amphipod *(Hyalella azteca)*	🟩	14-d IC$_{10}$ (growth)	30	Nautilus Environmental (2012)
Algae *(Pseudokirchneriella subcapitata)*	🔴	3-d IC$_{10}$ (growth)	36	Pacholski (2014)
Rainbow trout (*Oncorhynchus mykiss)*	▲	21-d LC$_{10}$ (survival)	67	Pacholski (2014)
Fathead minnow *(Pimephales promelas)*	▲	7-d LC$_{10}$ (survival)	255	Pacholski (2014)

Legend: ▲ = Fish; 🟩 = Invertebrate; 🔴 = Plant
*Geomean

Federal Water Quality Guideline Derivation

Federal Water Quality Guidelines (FWQGs) are preferably developed using the CCME (2007) protocol and are intended to protect all forms of aquatic life for indefinite exposure periods. In the case of strontium, there were sufficient chronic toxicity data to meet the minimum data requirements for a CCME Type A guideline[2]. A model averaged species sensitivity distribution (SSD) was fit to the long-term toxicity data (Figure 1 and Table 3) using the web application, ssdtools (version 0.0.3) (Dalgarno 2018). This web application fits toxicity data to multiple cumulative distribution functions (e.g. log-normal, log-logistic, log-gumbel, gamma, weibull) and constructs an average SSD and HC$_5$ estimate based on the relative goodness of fit of each respective model. More information on this approach can be obtained from CCME (2019). In the case of strontium, the toxicity data fits each model relatively equally. The log-normal is weighted the greatest, followed by log-logistic, weibull, log-gumbel and gamma, and the 5th percentile of the model averaged SSD plot is 2.5 mg/L.

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[2] CCME (2007) provides two approaches for developing water quality guidelines, depending on the availability and quality of the available data. The preferred approach is to use the statistical distribution of all acceptable data to develop Type A guidelines. The second approach is based on extrapolation from the lowest acceptable toxicity endpoint to develop Type B guidelines. For further detail on the minimum data requirements for CCME guidelines see CCME (2007).

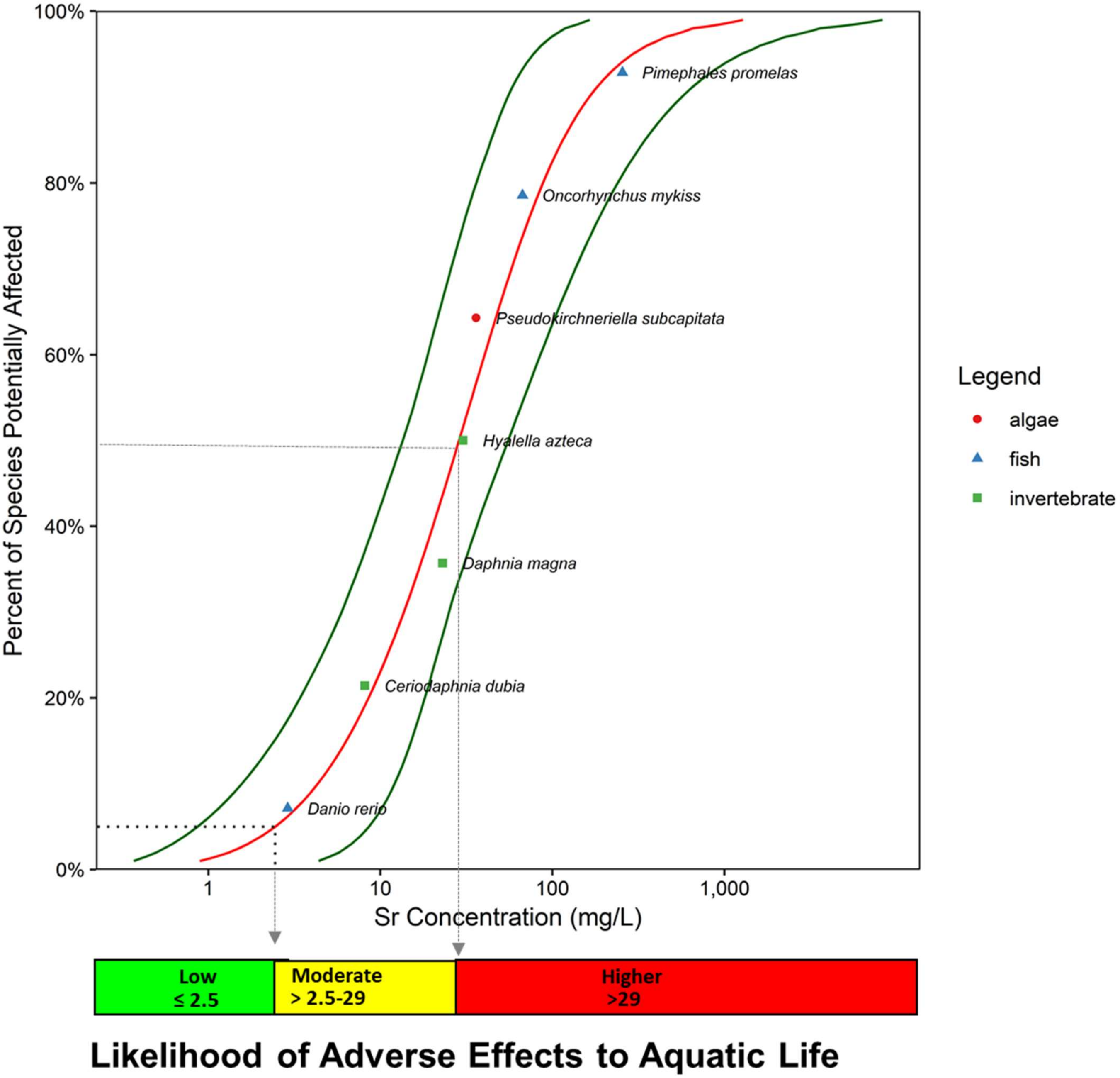

Figure 1. Species sensitivity distribution (SSD) for the chronic toxicity of strontium and relative likelihood of adverse effects of strontium to freshwater species.

The 5th percentile calculated from the SSD (2.5 mg/L), is the FWQG for protection of freshwater organisms (Figure 1). The guideline represents the concentration at or below which there would be no, or only a very low, likelihood of adverse effects on aquatic life. In addition to this guideline, two other concentration ranges are provided for use in risk management. At concentrations between > 5th percentile and the 50th percentile of the SSD (i.e. > 2.5 to 29 mg/L) there is a moderate likelihood of adverse effects to aquatic life. Concentrations greater than the 50th percentile (> 29 mg/L) have a higher likelihood of being associated with adverse effects. Risk managers may find these additional concentration ranges useful in defining short-term and or interim risk management objectives for a phased risk management plan. The moderate and higher concentration ranges may also be used in setting less protective interim targets for waters that are already highly degraded or where there are socio-economic considerations that preclude the ability to meet the FWQG.

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List of Acronyms and Abbreviations

CCME - Canadian Council of Ministers of Environment
CMP - Chemicals Management Plan
FEQG - Federal Environmental Quality Guideline
FWQG - Federal Water Quality Guideline
HC_5 – concentration at the 5th percentile of an SSD plot, below which adverse effects are unlikely
IC - inhibition concentration
LC – lethal concentration
USGS – United States Geological Survey