Government of Canada Gouvernement du Canada

Canada

Canadian Environmental Protection Act, 1999

Federal Environmental Quality Guidelines

Selenium

Environment and Climate Change Canada

August 2022

Introduction

Federal Environmental Quality Guidelines (FEQGs) describe acceptable quality of the ambient environment. They are based solely 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 effectiveness 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 Minister of Environment under the *Canadian Environmental Protection Act, 1999* (CEPA) (Canada 1999). The intent is to develop FEQGs as an adjunct to risk assessment or risk management of priority chemicals identified in the Chemicals Management Plan (CMP) or other federal initiatives.

Where data permit, FEQGs are derived following Canadian Council of Ministers of Environment (CCME) protocols. FEQGs are developed where there is a federal need for a guideline (e.g., to support federal risk management or 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. For more information, please visit the Federal Environmental Quality Guidelines (FEQGs) page.

This factsheet describes the federal fish tissue quality guidelines for the protection of fish and tissue quality guideline for bird egg (Table 1). FEQGs are not developed for the water, sediment or soil compartments; however, recent water-based guidelines developed in North America are presented.

Table 1. Federal environmental quality guidelines for selenium.

Fish Tissue (µg/g dry weight)		Bird Egg (µg/g dry weight)
Egg-ovary	Whole-body	
14.7	6.7	11

Substance Identity

Selenium (Se) is a naturally occurring element (CAS RN 7782-49-2), found in minerals such as pyrite, chalcopyrite, pyrrothite and sphalerite and in crude oil and coal deposits (ECCC, HC 2017). Anthropogenic sources of selenium include selenium production and processing facilities, use of selenium-containing products, and disposal and management of selenium-containing waste. Selenium occurs in various oxidation states and common species are selenate (SeO_4^{-2}), selenite (SeO_3^{-2}), elemental selenium (Se^0) and organic and inorganic selenides (Se^{-2}). Selenium is nutritionally essential for organisms; however, introduction of selenium into the environment from both natural and anthropogenic sources can lead to elevated concentrations in surface water, groundwater, soils and vegetation (BCMOE 2014; USEPA 2016). Among all trace nutrients, the difference between essentiality and toxicity is narrowest for selenium and thus the risk of adverse impact from environmental contamination is extremely high (Luoma and Rainbow 2008).

Open-pit coal mining in British Columbia and Alberta has resulted in the mobilization of selenium from waste rock leachate with high concentrations of selenium to surface and groundwater, potentially threatening fish and bird populations (BCMOE 2014). Uranium mining in Saskatchewan has been associated with increased selenium concentrations in receiving waters and deformities observed in fish (Muscatello et al. 2006; Muscatello and Janz 2009). Selenium releases have been also reported from waste rock of other mining and processing facilities (Nriagu and Wong 1983; Manitoba Conservation 2007; Stillings 2017).

On the basis of the screening assessment of selenium and its compounds (ECCC, HC 2017), the Government of Canada concluded that selenium and its compounds meet the criteria under paragraph 64(*a*) of CEPA, as they are entering or may enter the environment in a quantity or concentration or under conditions that have or may have an immediate or long-term harmful effect on the environment or its biological diversity. However, it was concluded that selenium and its compounds do not meet the criteria under paragraph 64(*b*) of CEPA, as they are not entering the environment in a quantity or concentration or under conditions that constitute or may constitute a danger to the environment on which life depends. Selenium and its compounds were also determined to meet the persistence and bioaccumulation criteria as set out in the *Persistence and Bioaccumulation Regulations* of CEPA (Canada 2000).

Sources and Uses

Canada is among the top five producers of selenium, along with the US, Japan, Belgium and Chile (BCMOE 2014). In Canada, selenium is recovered as a by-product from copper or zinc refining processes (ECCC, HC 2017). Between 2015 and 2019, Canadian production of selenium ranged between 72 and 175 tonnes (NRCan 2021). Selenium and its compounds can be used as a component of pigments (in plastics, paints, ceramics and glass), in rubber (accelerator in rubber vulcanization), agriculture (soil supplement, animal feed and pesticides), lubricants and metallurgical applications, electronic equipment, rechargeable batteries, drugs including natural health products (as a medicinal ingredient in multi-vitamin/mineral supplements and anti-dandruff shampoos), supplemented foods, specific foods for special dietary uses, cosmetics and consumer products. Details of these uses and sectors where a potential risk to the environment was identified are presented in ECCC, HC (2017).

Fate, Behaviour and Partitioning in the Environment

Selenium can enter the aquatic ecosystem in any form, but the soluble forms of selenium that reside in the aquatic ecosystems generally consist of selenate (SeO_4^{2-}) and selenite (SeO_3^{2-}) (Maher et al. 2010). Selenite is typically present in larger proportions in the effluents of coal power plants and petroleum refineries, whereas selenate is most likely found in mine effluents and agricultural run-offs (Maher et al. 2010; Young et al. 2010). Many selenium compounds can react with water and enter the environment in a dissolved phase. Within the environmentally relevant pH range of 6 to 8, only selenate, elemental selenium, selenite and bi-selenite are present in water (ECCC, HC 2017). Over this pH range, the predominant dissolved forms are selenate and selenite in oxygenated fresh waters (Brookins 1988; Belzile et al. 2000; Ralston et al. 2009). At pH values below 7, in mildly-reducing conditions, selenite species are reduced to elemental selenium (ATSDR 2003).

Selenium bioavailability varies with the selenium speciation, concentration of selenium in the ecosystem, biological productivity, and parameters that affect bioavailability (DeForest et al. 2017). For example, an increase of sulfate concentration in water reduces bioavailability at the base of the food web (Lo et al. 2015) and thereby to organisms at higher trophic levels (DeForest et al. 2017). An increase in sulfate concentration reduces selenate toxicity to aquatic invertebrates and fish, but has no effect on selenite toxicity (Carlton 1998; USEPA 2016). Dietary selenium exposure has been widely examined and has been considered a critical exposure pathway for assessing selenium toxicity at environmentally relevant concentrations.

Enrichment factors (EFs, ratio of particulate-bound selenium to selenium in the water phase) are highly variable, but are generally higher by about two-fold in lentic (standing water) versus lotic systems (flowing water) (ECCC, HC 2017). From a very large dataset, DeForest (2017) reported median EFs of 1387 and 633 L/kg dw for lentic and lotic systems, respectively. Higher EFs in lentic systems are mainly due to higher biological activity and the somewhat higher proportion of selenite in these environments. In a mass balance study of a wetland system, Martin et al. (2018) reported that selenium enrichment could be attributed to: (i) removal of dissolved selenium from solution as reduced selenium phases in sub-oxic portions of the lower water column and sediment porewater; (ii) deposition of selenium-bearing inorganic and organic particles; and (iii) plant uptake.

Sediment plays an important role in selenium cycling in the aquatic environment. Partitioning of selenium between sediment and water is system specific and is controlled by several physical, biological and chemical processes (Simmons and Wallschläger 2005; Chapman et al. 2010). Selenium adsorbs to the surface of iron- or manganese-rich sediment (ECCC, HC 2017) and the precipitation of selenium upon contact with ferric compounds is pH dependent (Maher et al. 2010). Finally, certain bacteria in the sediment use selenate or selenite as terminal receptor of electrons in respiration (Oremland et al. 1989) and thus they are a very important part of selenium cycling in the environment (Nancharaiah and Lens 2015). Over time, organic selenium generally transforms to an inorganic species through photo-oxidation and mineralisation (Chen et al. 2005).

Behaviour of selenium in soil is also dependent on a large number of factors: redox conditions, pH, iron hydroxide content, clay content, organic materials and the presence of competing anions (CCME 2009). For example, selenides are found in more acidic soils containing high concentrations of organic matter. Elemental selenium can be formed in moist anoxic soils, while selenate is the predominant species in alkaline, oxygenated soils (ECCC, HC 2017). Selenite is soluble but less mobile than selenate due to greater adsorption to soil minerals and organic material (ECCC, HC 2017). Due to selenate being more mobile, remobilisation of selenium may be caused by the dissolution of selenate in irrigation waters (Chapman et al. 2010).

The atmosphere is also an important environmental compartment for selenium although the biogeochemical cycling of selenium occurs mainly in water, sediment and soil (ECCC, HC 2017). Up to 30% of the selenium present in feed coal for combustion is emitted in a vapor phase (Chapman et al. 2010). The inorganic forms are mainly selenium dioxide (due to the burning of fossil fuels) and elemental selenium adsorbed to particulates (ECCC, HC 2017). Selenium dioxide, having a vapour pressure of 12.5 mm Hg at 70°C, is more volatile than elemental selenium. Elemental selenium itself has a low vapour pressure of 1 mm Hg, and thus is not usually found in the air as vapour (ASTDR 2003). Two other gaseous organic species can be produced by biotransformation; dimethyl selenide ($(CH_3)_2Se$) and dimethyl diselenide ($(CH_3)_2Se_2$) (Terry et al. 2000; Guo et al. 2001). Selenium compounds do not have a long residence time in the air (ECCC, HC 2017).

Bioaccumulation and trophic transfer through aquatic food webs are the major biogeochemical pathways of selenium in aquatic ecosystems (USEPA 2018). Key factors affecting selenium bioaccumulation are physical and chemical properties of the environment (e.g., pH, redox potential, temperature and hydrology), the chemical form of selenium, the ambient selenium concentration, the exposure route and duration, and the species exposed and their trophic level. Selenium can be actively taken up by the primary producers (e.g., algae, plants and microbes) and converted to organo-selenium compounds, thereby providing the base from which selenium enters the aquatic food web (ECCC, HC 2017). The absorption of selenium by organisms in aquatic systems through direct contact with water is low compared to absorption through diet (Presser and Luoma 2010). Details on bioaccumulation and bioconcentration of selenium in aquatic organisms (algae, plants, invertebrates and fish) are presented in published assessments (BCMOE 2014, USEPA 2016, 2018; ECCC, HC 2017).

Ambient Concentrations

Detailed monitoring data for selenium in Canadian surface waters, sediment, fish tissue and birds are presented in BCMOE (2014) and only a brief summary is presented here. Because these data came from multiple sources, method detection limits (MDL) varied considerably. Selenium water concentrations in Newfoundland and Labrador were generally less than 1.0 µg/L. Elevated concentrations were reported at some urban sites or sites with saltwater intrusion. Monitoring for Atlantic Provinces recorded selenium concentrations at or below the MDL of 0.01 µg/L. The reported mean and maximum concentrations for PEI were 0.08 and 0.16 µg/L, respectively. Monitoring data for 29 rivers in Nova Scotia and New Brunswick included concentrations below the MDLs of 1 and 1.2 µg/L respectively, with the exception of two samples. Data collected from a federal water quality monitoring station in Quebec showed selenium concentrations at or below the MDL of 0.05 µg/L. An average selenium concentration of 0.1 µg/L was reported within the freshwater fluvial reach of the St. Lawrence River, Quebec.

Selenium concentrations in the Great Lakes were generally below the MDL of 0.1 µg/L to 1.0 µg, with the exception of Lake Erie, where concentrations ranged between below detection and 36 µg/L, the higher values in Lake Erie were likely due to anthropogenic discharges. The data from 14 long-term monitoring stations of the Ontario Ministry of Environment showed that most sites have selenium concentrations below the MDL of 1.0 µg/L during the early years of monitoring and below the reduced MDL of 0.05 µg/L in later years. Exceptions to these low concentrations were sites associated with point source inputs from mining effluents or atmospheric emissions.

Selenium concentrations in surface waters of Manitoba were generally near or below the MDL of 0.4 µg/L since 2001 and the previous MDL of 2.0 µg/L prior to 2001. However, elevated concentrations were reported from areas influenced by mining and smelting activities. Typically, low selenium concentrations in water (less than 1 µg/L) were reported from Saskatchewan during the early years of monitoring, however, in some areas selenium concentrations may be elevated due to geologic formations or anthropogenic activities (e.g., uranium mining operations in northern Saskatchewan). In major rivers in Alberta, the average selenium concentrations ranged between 0.3 and 0.7 µg/L (MDL = 0.1 µg/L). These average concentrations are representative of background, but anthropogenic activities in some areas have increased selenium concentrations in surface waters (e.g., open-pit coal mining and oil and gas industry). Selenium concentrations in British Columbia waters are typically less than 1 µg/L, but can be elevated above 1 µg/L in areas where there are natural selenium sources from seleniferous rock or inputs from anthropogenic activities (e.g., open-pit coal mining).

Sediment background selenium concentrations range from 0.2 to 2 µg/g dw and concentrations are typically at the lower end in sediments of undisturbed waters (USDOI 1998; Luoma and Rainbow 2008). ECCC, HC (2017) reported Canadian median selenium concentration of 0.51 µg/g dw and in Great Lakes, concentrations ranged from 0.35 to 0.75 µg/g dw (Eisler 1985). Selenium concentrations in Nova Scotia (Kejimkujik Lake), New Brunswick (Grand Lake), Ontario (Winnange, Harp, Mary lakes) and Quebec (Matagami, Edouard, Ouescapis lakes) were 1.12; 0.19; 0.25- 0.59; and 0.52- 1.10 µg/g dw, respectively. Samples from Yukon (Lake Kusawa), Northwest Territories (Flat River), Saskatchewan (Vulture, David, Delta, Unknown lakes), Alberta (Upper McLeod, North Saskatchewan rivers) and British Columbia (Fraser River Basin, Murray River, Elk River Watershed) recorded sediment selenium concentrations of 0.72; 0.5-3.1; 0.54- 62.2; 0.3- 9.6; <0.5- 1.5 µg/g dw, respectively.

Across Canada, the background fish-tissue selenium concentrations are generally comparable. Mean concentrations for brook trout in New Brunswick ranged from 0.6 to 2.6 µg/g dw. Mean concentrations in lake trout and walleye at Quebec sites ranged from 1.21 to 2.96 µg/g dw. At four Great Lakes sites, Ontario, lake trout tissue concentrations ranged from 1.94 to 3.63 µg/g dw. Selenium concentrations in fish tissue are measured for many sites in western Canada. For example, in the Yukon River basin, tissue concentrations in northern pike, longnose sucker and burbot ranged from 0.92 to 3.4 µg/g dw. In Saskatchewan, northern pike and white sucker mean tissue selenium concentration ranged from 1.17 to 1.21 µg/g dw, whereas at Manitoba sites, mean concentrations ranged from 3.67 to 4.38 µg/g dw. In western Alberta, at a reference and a mine-affected stream, mean selenium concentrations in rainbow trout egg were 8.96 and 25.4 µg/g dw, respectively, whereas concentrations in brook trout were 3.33 and 19.97 µg/g dw, respectively. In northeastern BC at Blind Creek, mean tissue selenium concentration in rainbow trout increased from 3.4 µg/g dw prior to mining to 7.1 µg/g dw after 4 years of mining. In samples collected from the Elk River (BC), mean selenium concentrations at lotic minimally impacted sites, the whole body, muscle and ovary tissue concentrations for westslope cutthroat trout were 5.2, 4.6 and 7.6 µg/g dw, respectively, whereas in areas exposed to coal mining effluents, muscle tissue concentrations were as high as 19.5 µg/g dw at lotic sites and 92.4 µg/g dw at lentic sites.

The majority of Canadian selenium data for bird egg concentrations is from western Canada. In the Chilliwack area of BC, two populations of American dippers recorded mean egg Se concentrations of 2.67 and 2.96 µg/g dw, respectively. Near coal mining activities in the Rocky Mountain foothills of Alberta, mean selenium concentration in American dipper eggs at the reference sites (4.9 µg/g dw) were significantly lower than mining sites (6.3 µg/g dw). In Elk River (BC), although no significant difference was observed in selenium concentration in eggs of American dippers between reference (7.4 µg/g dw) and impacted sites (8.0 µg/g dw), concentrations in eggs of red-winged blackbirds showed a significant difference between reference (2.96

µg/g dw) and impacted sites (21.7 µg/g dw). Mean egg selenium concentrations were measured in several aquatic bird species in the Elk Valley (Canada goose, mallard, American coot, hooded merganser, blue-winged teal, green-winged teal, ring-necked duck, Barrow's goldeneye and bufflehead). Mean egg selenium concentration ranged from 1.38 µg/g dw in Canada goose at a reference site, to 29.6 µg/g dw (American coot) at impacted site.

Mode of Action

Selenium is required in trace amounts for the normal functioning of cells; however, excess amounts can have toxic effects (USEPA 2016). Among the biologically essential elements, selenium is also one of the most toxic (Chapman et al. 2010). It has been generally believed that selenium toxicity is due to elevated selenium having the capacity to substitute for sulfur in cysteine and methionine, and the non-discriminant inclusion of selenomethionine during protein synthesis, potentially causing changes in tertiary protein structure and function by altering the disulfide linkages (Janz 2012). It is possible that teratogenesis in embryos is caused by this mechanism. Further evidence of selenium toxicity relating to the replacement of sulfur by selenium is suggested when observing the effects of selenosis in adult mammals and birds. One of the main symptoms of selenosis is damage to body structures containing keratin, which is high in sulfur (Spallholz and Hoffman 2002). However, this explanation has been questioned due to the more active regulation processes for selenocysteine, and due to methionine not having a major role in tertiary protein structure, therefore selenomethionine substitution should not have a major impact on the functioning of proteins (Janz 2012).

It has been more recently theorised that selenium is toxic because in excess it leads to the production of the superoxide anion and further reactive oxygen species, causing oxidative stress (Palace et al. 2004; Janz 2012). Selenium can oxidise thiols such as one of the functional groups found in glutathione, thus creating a metabolic intermediate, such as methylselenol or dimethyselenide. The selenide can then be oxidised by oxygen (O_2) to create superoxide anion (O_2^-) (Spallholz and Hoffman 2002; Palace et al. 2004; Janz 2012). At high concentrations of selenium, these species are found in quantities too great for antioxidant defenses to prevent oxidative damage (Janz 2012).

Federal Environmental Quality Guidelines Derivation

Federal Tissue Quality Guidelines for Fish

Selenium distribution through the aquatic food web (e.g., plants, invertebrates and fish) has been shown to result in bioaccumulation of selenium in aquatic-dependent wildlife and causing reproductive impairments and malformations (Ohlendorf et al. 1986; Hoffman et al. 1988; Hothem and Ohlendorf 1989). There is a general agreement that freshwater fishes are the most sensitive to selenium and that fish tissue selenium concentrations are most reliable indicators of potential toxicity (BCMOE 2014; USEPA 2016; DeForest et al. 2017; ECCC, HC 2017). Chronic exposure to selenium causes toxicity to fish at concentrations only slightly above essentiality (Lemly 1997). Reproductive impairments in fish are well documented and the most sensitive life stages are egg and larvae. Exposure to selenium in fish during the larval stage primarily occurs through maternal transfer to the eggs and yolk sac absorption. Reduced hatching, teratogenicity (deformities) and edema are the most common effects observed in early life stages of fish (Lemly 2002; Janz et al. 2010; DeForest et al 2017). Significant correlation of selenium concentration measured in fish ovaries and eggs with these endpoints make them reliable predictors of selenium toxicity to fish (ECCC, HC 2017). ECCC, HC (2017) derived a predicted no-effect concentration (PNEC) for selenium based on selenium residues in egg-ovary.

In addition to a fish egg-ovary PNEC, a whole-body tissue PNEC for fish was also derived since monitoring data for egg-ovary are sparse and their collection is limited by the time of year. The data for selenium concentration in adult fish muscle or whole-body are more frequently available (ECCC, HC 2017). The concentration of selenium in fish tissues is an indicator of selenium bioavailability and represents accumulation from all possible exposure pathways. Both fish egg-ovary (14.7 µg/g dw) and whole body

tissue (6.7 µg/g dw) PNECs are adopted as federal environmental quality guidelines for selenium. The methodology used for their derivation, including toxicity data considered, are summarized here from ECCC, HC (2017).

Fish egg-ovary tissue residue guideline:

Available toxicity data for fish egg and ovary were compiled and evaluated in ECCC (2017). When multiple acceptable endpoints of the same type were available for an individual species, a geometric mean was calculated following the principles of the CCME (2007) protocol. Similar to the PNEC derivation (ECCC, HC 2017), selenium residues in eggs and ovaries are considered to be at a ratio of one-to-one for guideline development. Egg-ovary selenium concentrations associated with toxic effects ranged from 16.2 to 54 µg/g dw (Table 2). Bluegill sunfish (*Lepomis macrochirus*), white sturgeon (*Acipenser transmontanus*) and brown trout (*Salmo trutta*) were the most sensitive species, whereas dolly varden (*Salvelinus malma*) was the most tolerant species.

Acceptable toxicity data for each species were ranked according to sensitivity in a species sensitivity distribution (SSD) using the SSD Master software (CCME 2013). Several cumulative distribution functions were fit to the dataset and the logistic model provided the best fit among the models considered (Figure 1). Similar to PNEC, the 5th percentile (HC_5) of the SSD (14.7 µg/g dw) is the fish egg-ovary guideline. The federal fish egg-ovary guideline is similar to guidelines published by other jurisdictions (11 µg/g dw by British Columbia (2014) and 15.1 µg/g dw by the USEPA (2016) and others (10 µg/g dw (Lemly 1996) and 20 µg/g dw (DeForest et al. 2012).

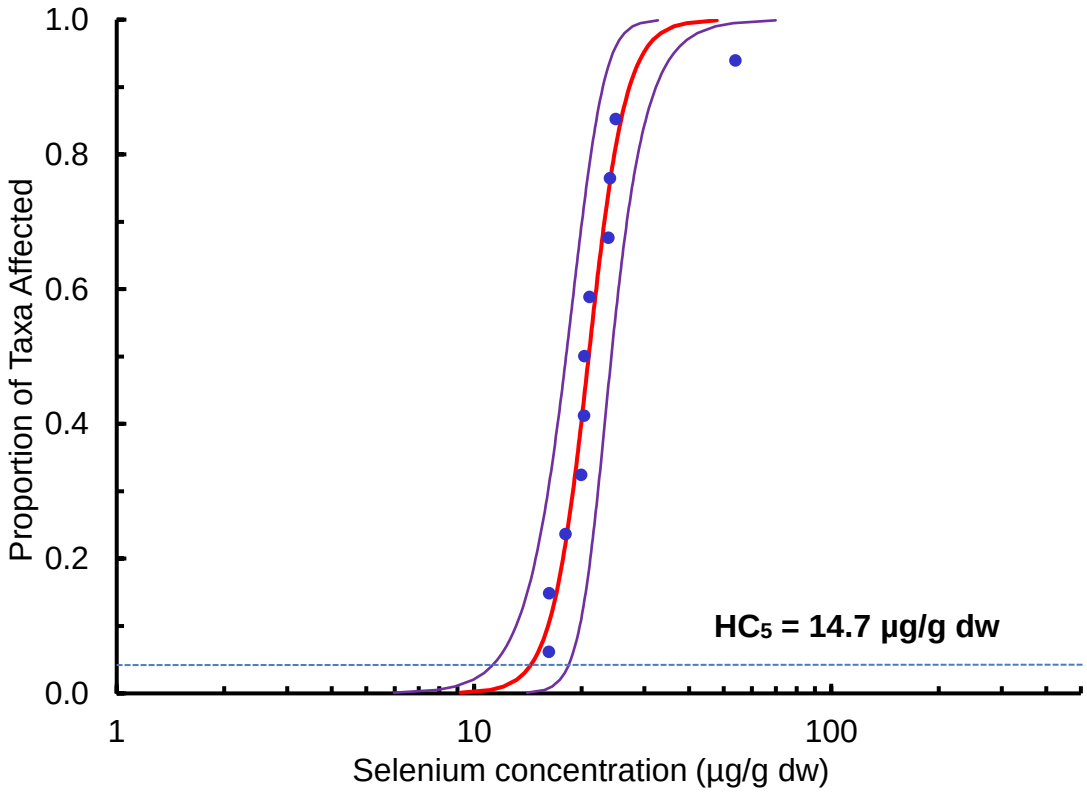

Figure 1: Species sensitivity distribution (SSD) based on selenium residues in fish eggs/ovaries that lead to reproductive toxicity. The 5th percentile of the distribution (HC_5) is the fish egg-ovary tissue guideline. Source: ECCC, HC (2017)

Fish whole-body tissue residue guideline:

Because of the scarcity of monitoring data for fish eggs and ovaries, it is practical to derive a whole-body tissue guideline for fish. The concentration of selenium in adult fish muscle or whole-body homogenate is more frequently available, and is a good measure of exposure to selenium in fish. The more sensitive and significant reproductive-based endpoints from the egg-ovary data (Table 2) were extrapolated to whole-body tissue values using species-specific egg-ovary to whole-body conversion factors developed by the USEPA (2016).

The toxicity-modifying factors that may affect the bioavailability of selenium were not separately taken into account, because the data used are tissue residues and therefore inherently account for the influence of these factors on the toxicokinetics of selenium (ECCC, HC 2017).

The whole-body selenium concentrations (Table 2) were plotted using the SSD Master software (CCME 2013) and the logistic model provided the best fit of the models tested (Figure 2). The HC_5 of the SSD was 6.7 µg/g dw and similar to PNEC this value was selected as the whole-body tissue guideline for the freshwater fish. The value is not generally below essential requirements, noting the value is above median concentrations from minimally exposed areas, ranging from 1.6 to 2.2 µg/g dw (ECCC, HC 2017). Similar to the egg-ovary guideline, this whole-body tissue guideline is comparable to whole-body tissue guidelines developed by the other jurisdictions: 4 µg/g dw by BCMOE (2014) and 8.5 µg/g dw by the USEPA (2016) and that the egg-ovary FEQG supersedes the whole-body tissue FEQG.

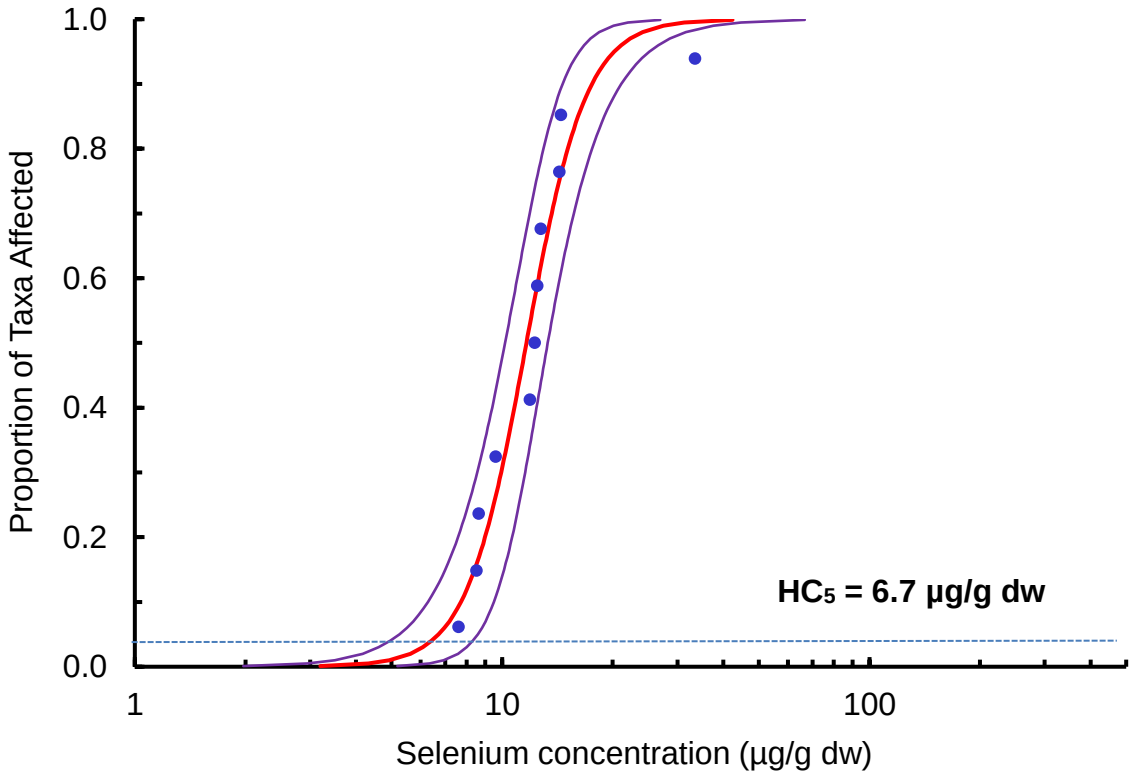

Figure 2: Species sensitivity distribution (SSD) for selenium residues in fish whole-body translated from egg-ovary reproductive endpoints using species-specific conversion factors. The 5th percentile of the distribution (HC_5) is the fish whole-body tissue guideline. Source: ECCC, HC (2017)

Table 2. Chronic toxicity data used for deriving fish egg-ovary and whole-body tissue guidelines for selenium.

Species	Endpoint	Concentration (mg/kg dw)	Egg or Ovary	E-O/WB[a]	WB[b] (mg/kg dw)	Reference
Bluegill (*Lepomis macrochirus*)	EC_{10} larval edema	16.22	O	2.13	7.62	Hermanutz et al. 1992, 1996; Doroshov et al. 1992
White Sturgeon (*Acipenser transmontanus*)	EC_{10} larval deformities	16.27	E	1.69	9.63	Linville 2006
Brown trout *(Salmo trutta*)	EC_{10} larval survival	18.09	E	1.45	12.48	Covington et al.2018; US EPA 2016
Brook trout (*Salvelinus fontinalis*)	NOEC larval deformities	20	E	1.38	14.49	Holm 2002; Holm et al. 2003, 2005
Largemouth bass (*Micropterus salmoides*)	EC_{10} larval survival & mort	20.35	O	1.42	14.33	Carolina Power & Light 1997
Northern pike (*Esox lucius*)	EC_{10} larval deformities	20.4	E	2.39	8.54	Muscatello et al. 2006
Rainbow trout (*Oncorhynchus mykiss*)	EC_{10} skeletal deformities	21.1	E	2.44	8.65	Holm 2002; Holm et al. 2003, 2005
Fathead minnow (*Pimephales promelas*)	LOEC larval deformities	23.85	O	2	11.93	Schultz and Hermanutz 1990
Westslope cutthroat trout (*Oncorhynchus clarki lewisi*)	EC_{10} alevin mortality	24.06	E	1.96	12.28	Rudolph et al. 2008; Nautilus Environmental 2011
Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*)	MATC alevin mortality	25	E	1.96	12.76	Formation Environmental 2012
Dolly varden (*Salvelinus malma*)	EC_{10} larval deformities	54	E	1.61	33.54	McDonald et al. 2010

[a] egg-ovary to whole-body conversion factors developed by the USEPA (2016); [b] converted whole-body tissue concentration

Tissue Quality Guideline for Bird Egg

The bird egg guidelines for selenium are recommended as the most direct estimate of selenium toxicity in aquatic-dependent wildlife and can be used as a surrogate for all wildlife species (BCMOE 2014, USEPA 2018). In the absence of a CCME protocol for developing bird egg guidelines, *ad hoc* approaches have been used for developing the federal tissue residue guidelines for bird eggs. The USEPA (2018) developed draft bird egg selenium criterion (guideline) of 11.2 µg/g dw for the fresh waters of California. This draft USEPA guideline is adopted as the federal tissue quality guideline for bird eggs. Because the guideline is based on bird eggs from aquatic species, exceedances for non-aquatic birds may require further investigation. Details on toxicity study and endpoint selection and methodology for developing bird egg criteria are presented in USEPA (2018), and only summary details are presented here (Table 3).

Egg-laying vertebrates such as fish and birds are most sensitive to selenium effects (Janz et al. 2010). For example, among the wildlife species studied at Kesterson Wildlife Refuge (California), the most frequent and extreme toxicity was observed in aquatic birds, whereas small mammals showed almost no effects (Ohlendorf et al. 1989). This difference is likely due to a much wider range between biologically essential and toxic exposure concentrations of selenium in mammals than in birds (Janz et al. 2010). Egg selenium concentrations of <0.66 µg/g dw in birds may indicate inadequate selenium in the diet, resulting in poor adult health and reproduction (USEPA 2018). The diet and subsequent maternal transfer of selenium in birds is the main exposure route for selenium. The most effective measurement of potential toxic effects of selenium in birds is through selenium measurement in eggs (Adams et al. 1998; Ohlendorf and Heinz 2011). Moreover, due to rapid selenium accumulation and loss, including maternal transfer, observed in birds, selenium levels measured in eggs most likely represent contamination of the local environment. In areas not receiving selenium contamination, reported selenium concentrations in bird eggs were 3 to 4 µg/g dw, with maximum individual values usually <5 µg/g dw, whereas eggs from contaminated areas (Kesterson Reservoir) contained over 40 µg/g. Measuring selenium in eggs is also advantageous because eggs are easier to collect than adult birds, and the loss of an egg from the nest likely has lesser effect on a population. Moreover, an egg sample is a representative of an integration of exposure of adult females ranging from few days to weeks before egg laying.

Birds are very sensitive to selenium toxicity and the sensitive chronic effects are related to reproductive impairments, such as decreased fertility, reduced egg hatchability and increased frequency of deformity in embryos (Ohlendorf et al. 1986; Ohlendorf and Heinz 2011). Selenium exposure may cause many deformities in bird embryos, including hydrocephaly, missing eyes, twisted bills and deformed limbs (USEPA 2018). Toxicity studies on birds show that thresholds for reduced egg hatchability are usually below those for teratogenic effects (Ohlendorf 2003).

Chronic toxicity data were available for eleven bird species and among them mallard (*Anas platyrhynchos*) was the most sensitive, whereas red-winged blackbird (*Agelaius phoeniceus*) was the least sensitive species. Hatchability was consistently the most sensitive endpoint for mallard. Among the six mallard studies (Heinz et al. 1987, 1989; Heinz and Hoffman 1996, 1998; Stanley et al. 1994, 1996), hatchability data from three studies (Heinz et al. 1987, 1989; Stanley et al. 1996) were used to derive the USEPA bird egg guideline (Table 3). Duckling growth, weight and production were all equally sensitive to hatching success in Stanley et al. (1996), and the number of normal hatchlings and nestling weight were similar in sensitivity to hatchability in Heinz et al. (1989). Because of very little variation in selenium concentrations within a single clutch (i.e., no influence by laying sequence), sampling to measure egg selenium concentrations would not be dependent on egg laying sequence to reduce differences caused by intra-clutch variability (USEPA 2018).

The USEPA (2018) used toxicity data from three mallard studies (Table 3) for calculating a bird egg EC_{10} of 11.2 µg/g dw. This calculated EC_{10} is the selenium bird egg guideline with the lower and upper 95% confidence limits of 7.4 and 15 µg/g dw, respectively. The selenium EC_{10} was derived using a four-parameter generalized linear model instead of the toxicity relationship analysis program (USEPA 2015) because this program was not designed to work with data pooled from multiple studies (USEPA 2018).

Table 3. Effect of dietary selenium on hatchability of mallard eggs and associated selenium concentrations in mallard eggs. Source: USEPA 2018

Diet Se mg/kg[a]	N (hens)	Egg Hatchability %	% Hatchability as % Control	Percent Moisture	Egg Se (mg/kg dw)	Reference
Control	11	64.4	100	71	0.17	Heinz et al. 1987
10	5	34.6	54	71	15.9	Heinz et al. 1987
Control	32	57.3	100	70	0.60	Heinz et al. 1989
1	15	65.0	114	70	2.77	Heinz et al. 1989
2	15	59.6	104	70	5.33	Heinz et al. 1989
4	15	54.3	95	70	11.3	Heinz et al. 1989
8	15	42.3	74	70	36.7	Heinz et al. 1989
16	9	7.4	13	70	60.0	Heinz et al. 1989
Control	33	62	100	71	0.93	Stanley et al. 1996
3.5	29	61	98	71	12.1	Stanley et al. 1996
7	34	41	66	71	24.5	Stanley et al. 1996

[a] Selenium concentration in diet is presented as nominal; control diets typically contained 0.4 mg Se/kg dw

Recent Water-based Guidelines from other Jurisdictions

The tissue-based environmental quality guidelines described above have the greatest certainty, as this metric is most directly related to the site of toxic action. However, water quality guidelines are generally the most common metric used to monitor environmental conditions and regulatory performance. In part, this may be because the water compartment is easier to sample than biological components. In addition, excessive fish sampling may potentially affect fish populations; however, the use of non-destructive sampling techniques (e.g., muscle plugs) can help in addressing this concern. Consequently, although no water PNECs were developed as part of the screening assessment (ECCC, HC 2017), recent water quality guidelines recommended by the USEPA (2016) and the BCMOE (2014) are presented here for possible use in Canada.

In addition to fish whole-body and egg-ovary tissue-based guidelines, the BCMOE (2014) also developed water-based selenium guidelines. They compared the CCME (1987) water quality guideline for the protection of aquatic life (1 µg/L) with the published toxicity thresholds and water quality guidelines of other jurisdictions. They concluded that the CCME guideline of 1 µg/L is likely protective for the most sensitive environments and recommended the guideline as an alert concentration. The alert guideline exceedances at sensitive sites can help in early detection of potential selenium concerns, in setting increased monitoring efforts and as part of a tiered, adaptive management approach to initiate early proactive management actions (BCMOE 2014). They also proposed a water column guideline for the protection of aquatic life of 2 µg/L and assessed its applicability by comparing the guideline value to ambient selenium surface water concentrations in British Columbia, Alberta and across Canada. Collectively, with the review of existing toxicological data, these results provide support to BC's water quality guideline of 2 µg/L, or a lower value for very sensitive environments or species. Based on jurisdictional needs and policy goals, the BC water quality guidelines can be used for Canadian sites.

The USEPA (2016) derived water column criteria for lentic (1.5 µg/L) and lotic (3.1 µg/L) waters by translating the fish egg-ovary concentration to an equivalent water-column concentration using a mechanistic bioaccumulation model of Presser and Luoma (2010). This model quantifies bioaccumulation in fish tissue by assuming that net bioaccumulation is a balance between assimilation efficiency from diet, ingestion rate, rate of direct uptake in dissolved forms, loss rate and growth rate. Because the potential of selenium bioaccumulation can depend on several site-specific biogeochemical factors, translation of the egg-ovary criterion to the water column criterion can be improved by deriving a site-specific criterion using site-specific selenium data and information on food-web dynamics. For their modelling exercise, the USEPA (2016) calculated selenium concentrations in the water column for a large number of study sites (26 lentic and 39

lotic) for fish species. DeForest et al. (2017) used a quantile regression approach for deriving selenium screening guidelines and described selenium concentration relationships between compartments that can potentially reduce uncertainty associated with the selection of partitioning factors. The USEPA (2018) has further added a bird egg criterion and a performance-based approach for translating the tissue criteria into a corresponding water-column criterion on site-specific basis. The USEPA approaches can be considered for deriving the site-specific water guideline if users are able to collect and validate the required site-specific data. Similar to USEPA, the water guideline is only to be used when the whole–body fish tissue guideline is not available and that the egg-ovary guideline supersedes both whole-body tissue and water guidelines. Similarly, the bird egg guideline supersedes the translated water column guideline when data from both compartments are available.

Site-specific water quality guidelines have long been recognized as a mechanism of increasing the precision and applicability of general water quality guidelines (CCME 2003). Accordingly, a number of approaches are available to calculate water concentrations using site-specific transfer factors. Details on background concentrations, recalculation, water effect ratio and resident species procedures are presented in detail in CCME (2003).

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List of Acronyms and Abbreviations

ATSDR – Agency for Toxic Substances and Disease Registry
BCMOE – British Columbia Ministry of Environment
CAS RN – Chemical Abstracts Service Registry Number
CCME – Canadian Council of Ministers of Environment
CEPA – Canadian Environmental Protection Act
CMP – Chemicals Management Plan
dw – dry weight
EC_x – effect concentration to x % of test species
EF – enrichment factor
FEQG – Federal Environmental Quality Guideline
FSeQG – Federal Sediment Quality Guideline
FWQG – Federal Water Quality Guideline
HC – Health Canada
MATC – maximum acceptable toxicant concentration (geometric mean of the NOEC and LOEC)
MDL – method detection limit
PNEC – predicted no-effect concentration
SAR – screening assessment report
SSD – species sensitivity distribution
USDOI – United States Department of Interior
USEPA – United States Environmental Protection Agency