Government of Canada Gouvernement du Canada

# *Canadian Environmental Protection Act, 1999*

# Federal Environmental Quality Guidelines

## *Iron*

**Environment and Climate Change Canada**

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## Introduction

Federal Environmental Quality Guidelines (FEQGs) describe acceptable quality of the ambient environment. They are based solely on the toxicological effects or hazard 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 the 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 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 Water Quality Guideline (FWQG) for the protection of aquatic life from adverse effects of iron (Fe) in freshwaters and is based on total iron (Table 1). A multiple linear regression (MLR) approach was used to incorporate toxicity modifying factors (TMFs) into the guideline. The FWQG for iron follows CCME methods and meets CCME minimum data requirements for a Type A statistical approach (CCME 2007). There is no pre-existing FWQG for iron, however, there is a 1987 CCME guideline (CCREM 1987). The CCME 1987 guideline was not adjusted for any water chemistry parameters and was developed prior to revised CCME (2007) protocol. The derivation of this FWQG for iron is based on the collection and evaluation of toxicity data identified up to January 2023. No FEQGs have been developed for the biological tissue compartments, sediment, soil, or marine water at this time.

Table 1. Federal Water Quality Guideline (FWQG) for total iron (µg/L).

| **Aquatic Life** | **Guideline Value (µg/L)[a]** |
|---|---|
| Freshwater | 110 |

[a] The FWQG in Table 1 is for waters with dissolved organic carbon (DOC) concentration of 0.5 mg/L and pH of 7.5. The FWQG for other DOC and pH values can be found using the iron FWQG look-up table and/or calculator (Appendix). The FWQG look-up table and calculator are valid between DOC 0.3 and 10.9 mg/L, and pH 6 and 8.5.

## Substance Identity

Iron (Fe) is a naturally occurring element (CAS Number 7439-89-6) and is the fourth most abundant element by mass in the earth's crust. Iron ores are rocks and minerals from which metallic iron (Fe) can be extracted when heated in the presence of a reducing agent such as coke (NRCan 2012). The ores are usually rich in iron oxides and carbonates. Iron is a transition metal with a density of 7.87 g/cm$^3$ and a molecular weight of 55.9 g/mol. Iron occurs in many minerals with the most important being magnetite, hematite, goethite, pyrrhotite, siderite, ilmenite, and pyrite. It is often a major constituent of soils (especially clays) and is found in waterways as a result of natural runoff, erosion of clay-based soils, and other geologic sources. Iron is essential for all forms of life and plays an important role in metabolic processes, but at higher concentrations it can be toxic (Vuori 1995; Crichton et al. 2002). Iron has complex chemistry in surface waters and can exist as ferrous (Fe(II)) and ferric (Fe(III)) forms. Fe(II) is the dominant form of iron under reducing conditions, whereas Fe(III) is the dominant form under oxidizing conditions. Because Fe(II) is rapidly oxidized to Fe(III) under most conditions, including those under which Fe(II) toxicity tests are conducted and that the oxidized form predominates in most water bodies (UKTAG 2012), this FWQG is developed for Fe(III). The FWQG applies to total iron, rather than the dissolved fraction, as iron precipitates can cause toxicity through physical effects (Sykora et al. 1972) and total iron correlates best with toxicity (CIMM 2010a,b; 2011; OSU 2013).

## Uses

Canada was the seventh-largest producer of iron ore in the world in 2021 (NRCan 2023). Iron ore production in Canada is primarily in Quebec, Newfoundland and Labrador, and Nunavut. Between 2012 and 2021, Canadian mine production of iron ore ranged from 32 to 58 million tonnes (Mt) annually (NRCan 2023). Canada exported 53.8 Mt and imported 8 Mt of iron ore in 2021, compared to 55.1 Mt and 7.1 Mt in 2020, respectively. Approximately 98% of extracted iron ore is used in the production of steel, which is a key component in the majority of manufacturing, transport, and building industries (Bury et al. 2012). The remaining 2% is used in various other applications, such as powdered iron for certain types of steel, auto parts and catalysts; radioactive iron for medicine; and iron blue in paints, inks, cosmetics, and plastics (NRCan 2023).

Anthropogenic sources of iron into surface water are often related to mining activities (BCMOE 2008). In addition, iron pyrites ($FeS_2$), which are common in coal seams, are exposed to weathering and bacterial action during mining, the oxidation of which results in the production of sulphuric acid and release of soluble ferrous (Fe(II)) iron (Smith et al. 1973; BCMOE 2008).

## Fate, Behaviour, and Partitioning in the Environment

Iron can occur in the environment as Fe(II) and Fe(III) oxidation states. The reduced form (i.e., Fe(II)) occurs under low redox conditions (e.g., groundwater, sediment porewater, and acidic streams) and exhibits a relatively high solubility. Under oxic aqueous conditions Fe(II) is rapidly oxidized to Fe(III), which forms oxides and hydroxides that have low solubility (Stumm and Morgan 1996; Bury et al. 2012). The relative presence of almost insoluble Fe(III) and the bioavailable and bioactive Fe(II) in surface waters are dependent on a wide range of factors including pH, dissolved oxygen, dissolved organic carbon (DOC), humic and other organic acids, exposure to sunlight, and chloride concentrations (BCMOE 2008). It has been found that Fe(II) has a relatively minor impact on biota compared to iron precipitates of Fe(III) in laboratory studies and that it is difficult to separate the effects of these two forms of iron in field studies (Rousch et al. 1997).

The oxidation rate of Fe(II) in water is faster in well-oxygenated waters at neutral pH (Bury et al. 2012). Under saturated oxygen and alkaline conditions (e.g., pH $\geq 8$), the oxidation of iron is rapid and does not change with increasing pH. Under these conditions, the half-life of Fe(II) is on the order of seconds (Bury et al. 2012). In mildly acidic (e.g., pH 6) and oxygen-saturated water, the oxidation rate of Fe(II) at 100 mg/L is approximately two hours at 25°C (Morgan and Lahav 2007). Thus, over the pH ranges associated with natural waters (i.e., pH 6 to 9), Fe(II) is expected to have a short half-life (seconds to a few hours) when present in oxic conditions.

When iron is released into natural bodies of water in the form of sulphate ($FeSO_4$) or pyrite ($FeS_2$), it oxidizes and forms $Fe(OH)_3$. This iron hydroxide may precipitate out and form a yellow brown slime on bottom sediments (Smith and Sykora 1976), which decreases light penetration and thus inhibits algal growth, causing an overall decrease in the production of the ecosystem (Maltby et al. 1987). Smith and Sykora (1976) reported mortality of trout and salmon eggs coated with Fe particulates. The hydroxide precipitate can also plug the gills of fish and benthic invertebrates, causing death by suffocation (Loeffelman 1985) and even interfere with the respiration in fish eggs (OME 1979).

Organic matter may control both the oxidation state and size of Fe species present in waters. Reduction in the ratio of Fe:organic carbon causes reduction in oxidation of Fe(II) and this has a potential for the iron load in natural waters to remain in a reduced form, even in well-oxygenated waters (Gaffney et al. 2008). Fe(II) and Fe(III)) differ in their binding affinities to humic and fulvic acids (UKTAG 2012). Fe(III) binds to fulvic and humic acids in fresh waters and these Fe(III)-dissolved organic matter (DOM) complexes are important for maintaining iron solubility (Tipping et al. 2002). The proportion of Fe found in this form is pH- and temperature-dependent, with the Fe(III)-DOM ratio decreasing as pH increases (Lofts et al. 2008). When complexed with organic compounds, Fe(III) can be photo-reduced by UV light to the soluble Fe(II) state, which can cause large diurnal fluctuations in the speciation and concentration of iron (BCMOE 2008).

## Ambient Concentrations

Iron concentrations in fresh water can be in the mg/L range, such as in rivers that pass through sulphide-rich soils, receive acid-mine drainage, or are otherwise exposed to various anthropogenic sources (Myllynen et al. 1997; Winterbourn et al. 2000; Linton et al. 2007). Environment and Climate Change Canada (ECCC) monitoring data, along with data from Alberta's Regional Aquatics Monitoring Program (RAMP), Ontario's Open Data from Provincial (Stream) Water Quality Monitoring Network, and British Columbia's Ministry of Water, Land and Resource Stewardship, for total iron concentrations in surface waters are summarized in Table 2. The total Fe concentrations ranged from <0.5 to 89200 μg/L with the mean and median concentrations of 21 to 1888 μg/L and 5 to 6889 μg/L, respectively.

Table 2. Concentrations of total iron in Canadian surface waters.

| Location | Sampling Years | Mean (μg/L) | Median (μg/L) | Minimum (μg/L) | Maximum (μg/L) |
|---|---|---|---|---|---|
| Lake Erie | 2004-2014 | 185 | 32 | 0.5 | 2400 |
| Lake Huron | 2004-2014 | 35 | 565 | <0.5 | 424 |
| Lake Ontario | 2005-2013 | 45 | 5 | <0.5 | 2090 |
| Lake Superior | 2005-2013 | 21 | 6 | <0.5 | 229 |
| Great Lakes Connecting Channels | 2003-2014 | 364 | 56 | <1.4 | 8470 |
| St. Lawrence | 2007-2014 | 632 | 452 | 0.03 | 12200 |
| Newfoundland | 2003-2013 | 354 | 212 | 3 | 15200 |
| New Brunswick | 2011-2013 | 113 | 85 | 20 | 350 |
| Nova Scotia | 2011-2013 | 311 | 250 | 20 | 1860 |
| Ontario (streams) | 2021 | 250 | 158 | 6 | 4470 |
| Manitoba | 2003-2014 | 1888 | 6889 | 3.8 | 24200 |
| Saskatchewan | 2003-2014 | 1005 | 506 | <0.5 | 41700 |
| Athabasca Region | 1997-2015 | 1653 | 973 | 4 | 46500 |
| Alberta | 2003-2015 | 1063 | 145 | 4.8 | 57100 |
| British Columbia | 2000-2023 | 542 | 123 | 0.7 | 30100 |
| Northwest Territories | 2003-2014 | 1870 | 224 | <0.5 | 89200 |

## Mode of Action

Dissolved concentrations of metals are typically considered to be most relevant to any evidence of ecological effects. However, this may not be the only cause of toxicity for iron. If the mode of action of iron is not only exerted via chemical toxicity, then other expressions of iron concentrations may be required. Total or particulate iron concentrations usually cause ecological effects via physical effects, such as smothering. Iron can adversely affect macroinvertebrates by reducing habitat quality and structure and by constraining food access (Linton et al. 2007). The precipitation of ferric hydroxide onto stream or lake bottoms can reduce light penetration and decrease plant productivity, thus decreasing food sources for the fish (Sykora et al. 1972).

Iron toxicity to algal species may be attributed to removal of essential nutrients, for example phosphate (Arbildua et al. 2017).

Iron oxide precipitates in well-oxygenated and circum-neutral pH waters that receive acid mine drainage and naturally high iron input can result in smothering of fish gills (Bury et al. 2012). In non-acid mine exposure scenarios, toxicity in Atlantic salmon (*Salmo salar*) was associated with increased iron accumulation on the gills, respiratory disruption, interference with gas exchange, fusion of gill lamellae, separation of the outer epithelial layer and/or necrosis of the lamellar epithelium (Peuranen et al. 1994; Dalzell and MacFarlane 1999; Teien et al. 2008). Iron was detected only at the gill epithelium, not inside, which indicated that the toxicity was mediated through action on the gill surface (Peuranen et al. 1994). High iron concentrations during fertilization have been shown to cause hardening of fish eggs, which may be of particular importance for salmonid spawning in headwaters that may receive high iron concentrations (Bury et al. 2012). Finally, iron can contribute to free radical production and oxidative damage (Bury et al. 2012).

The precipitation of ferric hydroxide can also affect fish according to their life stage. At low iron concentrations (~1.5 mg/L) the hatchability of fathead minnows (*Pimephales promelas*) was lower than at higher concentrations (Smith et al. 1973). Smaller particles have a greater potential to clog the pores of egg chorion and thus cause reduced dissolved oxygen diffusion and increased mortality. However, high concentrations of iron (up to 52.9 mg/L) can reduce visibility in the water and cause impaired food perception to fry and juvenile stages, causing prolonged stress and reduced growth (Smith et al. 1973).

## Aquatic Toxicity

The chronic freshwater toxicity studies for iron were identified and evaluated for data quality following CCME (2007) protocol. Because iron solubility is low and it readily sorbs to surfaces, iron toxicity studies were only considered if total iron concentrations were measured in the toxicity test. Unlike other divalent metals, the total iron fraction correlates best with toxicity (CIMM 2010a,b; CIMM 2011; OSU 2013). This suggests that there are non-dissolved iron species that are bioavailable to the test organisms or that toxicity is exerted by mechanisms beyond just chemical toxicity, for example physical effects. An underlying assumption for the selection of toxicity data was that the iron guidelines developed here would be also protective of physical effects, such as smothering.

Acceptable chronic toxicity data for iron were available for 27 species (ECCC 2024). The acceptable dataset is comprised of endpoints from both laboratory toxicity tests as well as mesocosm tests. The endpoints selected for guideline derivation are further discussed in the section “Federal Water Quality Guideline Derivation” and are presented in Table 4.

## Toxicity Modifying Factors

Within the acceptable toxicity dataset, several chronic studies have focused on how varying DOC, pH and hardness concentrations influence the bioavailability, and hence toxicity, of iron. These species include an alga (*Raphidocelis subcapitata,* formerly known as *Pseudokirchneriella subcapitata*), an invertebrate (*Ceriodaphnia dubia*), and a fish (*Pimephales promelas*) (Cardwell et al. 2023). The chronic toxicity data for iron (added as Fe(III)) for these species were used by Brix et al. (2023) to evaluate toxicity modifying factors (TMFs) and develop multiple linear regression (MLR) models for iron. These MLR models were incorporated in the development of the FWQGs for iron to adjust for site-specific water chemistry.

The details on the development of the MLR models for predicting iron toxicity can be found in Brix et al. (2023). Briefly, DOC, water hardness, and pH were examined as TMFs in three aquatic organisms (*R. subcapitata*, *C. dubia*, and *P. promelas*) representing three taxa. Stepwise MLR analyses were conducted to evaluate whether chronic iron toxicity to these three species could be modelled as a linear function of DOC, hardness, and pH (Brix et al. 2023). The results of the MLR analyses using effect concentrations at the 10% level (i.e., $EC_{10}$ endpoints) are presented in Table 3. In summary, DOC was a significant parameter in MLR models for *R. subcapitata*, *C. dubia*, and *P. promelas*, while pH was significant in *R. subcapitata* and *P. promelas* models, but not in the *C. dubia* model. Hardness was not found to be a statistically significant parameter in the models evaluated for any of the three species. Model evaluation (e.g., adjusted $R^2$, predicted $R^2$, observed versus predicted plots, residual analysis) and model validation (cross-validation to evaluate model performance) for the MLR models are described in Brix et al. (2023). A pooled model was not possible due to differences between species in the MLR models (Brix et al. 2023). Therefore, for the purposes of FWQG derivation, species-specific models were assumed to be representative of the three individual taxa and were applied accordingly for normalization of the iron toxicity dataset (i.e., *R. subcapitata* model applied to algal data, *C. dubia* model applied to invertebrate data and *P. promelas* model applied to fish and amphibian data).

Table 3. Summary results of multiple linear regression analysis (adapted from Brix et al. 2023).

| Species | n | Adj. $R^2$ | Pred. $R^2$ | DOC | pH | Hardness | Intercept |
|---|---|---|---|---|---|---|---|
| *R. subcapitata* | 25 | 0.87 | 0.84 | 0.744 | 0.332 | - | 5.435 |
| *C. dubia* | 27 | 0.74 | 0.71 | 0.600 | - | - | 7.577 |
| *P. promelas* | 18 | 0.84 | 0.81 | 1.102 | 0.787 | - | 2.176 |

Notes: Adj. = adjusted; DOC= dissolved organic carbon; Pred. = predicted.

### Federal Water Quality Guideline Derivation

The FWQG for iron is for chronic exposure and identifies the waterborne concentration of total iron intended to protect all forms of aquatic life for an indefinite exposure period. Chronic effect concentrations in the acceptable iron toxicity dataset were normalized to consistent DOC and pH values. Species-specific equations using the MLR-derived slopes for *R. subcapitata, C. dubia,* and *P. promelas* (Table 3) were used to normalize effect concentrations for algae, invertebrates, and fish and amphibians, respectively, and are included below:

***R. subcapitata* equation:**

Normalized EC = EXP(ln(ECmeas)-0.744*(ln(DOCmeas)-ln(DOCtarget))-0.332*(pHmeas -pHtarget))

***C. dubia* equation:**

Normalized EC = EXP(ln(ECmeas)-0.6*(ln(DOCmeas)-ln(DOCtarget)))

***P. promelas* equation:**

Normalized EC = EXP(ln(ECmeas)-1.102*(ln(DOCmeas)-ln(DOCtarget))-0.787*(pHmeas-pHtarget))

Where DOC = dissolved organic carbon; EC= effect concentration; meas = measured variable from original study; target = level to which variable is being normalized.

The selection of datapoints for guideline derivation followed CCME (2007) protocol and involved selecting the most sensitive and preferred endpoint (or geometric mean) for each species. Where there were multiple comparable endpoints available for the same species, effect, life stage and exposure duration, a geometric mean was calculated (ECCC 2024). A total of 27 species (five fish, 20 invertebrates, one amphibian, and one alga) were available and were used in derivation of the iron FWQG (Table 4). The dataset met CCME (2007) minimum data requirements for developing a guideline using a Species Sensitivity Distribution (SSD) (i.e., Type A guideline)[1]. A Type A guideline is a statistical approach that uses SSDs comprised of primarily "no effect" data to calculate $HC_5$ values (or hazard concentration of the fifth percentile), which in turn become the final guideline value (CCME 2007).

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[1] 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).

Table 4. Chronic freshwater toxicity data used in the Species Sensitivity Distribution (SSD) for deriving the Federal Water Quality Guideline (FWQG) for iron. The normalized effect concentrations are for water chemistry of pH 7.5 and dissolved organic carbon (DOC) 0.5 mg/L using species-specific multiple linear regression (MLR) models.

| **Species scientific name** | **Species common name** | **Group** | **Endpoint** | **Effect concentration (µg/L)** | **Normalized effect concentration (µg/L)** | **Reference** |
|---|---|---|---|---|---|---|
| *Tanytarsini* | Midge | Invertebrate | 10-d EC20 (Abundance) | 234 | 89.1 | Cadmus et al. 2018a |
| *Epeorus* sp. | Mayfly | Invertebrate | 10-d EC20 (Abundance) | 335 | 127.5 | Cadmus et al. 2018a |
| *Micrasema* sp. | Caddisfly | Invertebrate | 10-d EC20 (Abundance) | 356 | 135.5 | Cadmus et al. 2018a |
| *Prosopium williamsoni* | Mountain whitefish | Fish | 78-d EC10 (Biomass) | 868 | 199.3 | Cadmus et al. 2018a |
| *Lumbriculus variegatus* | Worm | Invertebrate | 35-d EC10 (Number of organisms) | 470 | 211.0 | Cadmus et al. 2018a |
| *Heterlimnius* sp. | Beetle | Invertebrate | 10-d EC20 (Abundance) | 747 | 284.4 | Cadmus et al. 2018b |
| *Orthocladiinae* | Midge | Invertebrate | 10-d EC20 (Abundance) | 776 | 295.4 | Cadmus et al. 2018a |
| *Cinygmula* sp. | Mayfly | Invertebrate | 10-d EC20 (Abundance) | 930 | 354.1 | Cadmus et al. 2018b |
| *Prostoia* sp. | Stonefly | Invertebrate | 10-d EC20 (Abundance) | 1176 | 447.7 | Cadmus et al. 2018a |
| *Oncorhynchus kisutch* | Coho salmon | Fish | 60-d EC10 (Survival) | 3035 | 595.8 | Smith and Sykora 1976 |
| *Taenionema* sp. | Stonefly | Invertebrate | 10-d EC20 (Abundance) | 1626 | 619.1 | Cadmus et al. 2018a |
| *Bufo boreas* | Boreal toad tadpole | Amphibian | 35-d EC10 (Biomass) | 2607 | 820.2 | Cadmus et al. 2018a |
| *Capnia* sp. | Stonefly | Invertebrate | 10-d EC10 (Abundance) | 2200 | 837.6 | Cadmus et al. 2018b |
| *Daphnia pulex* | Cladoceran | Invertebrate | 21-d EC10 (Reproduction) | 852 | 852.0 | Birge et al. 1985 |
| *Salmo trutta* | Brown trout | Fish | 79-d NOEC (Hatch, survival, weight) | ≥5146 | 1181.8 | Cadmus et al. 2018a |
| *Ceriodaphnia dubia* | Cladoceran | Invertebrate | 7-d EC10 (Mean reproduction) | Geometric mean (n=27) | 1288.5 | Cardwell et al. 2023 |
| *Baetis* sp. | Mayfly | Invertebrate | 10-d EC10 (Abundance) | 3905 | 1486.8 | Cadmus et al. 2018b |
| *Pimephales promelas* | Fathead minnow | Fish | 7-d EC10 (Mean biomass) | Geometric mean (n=18) | 1502.4 | Cardwell et al. 2023 |
| *Raphidocelis subcapitata* | Green algae | Plant/Algae | 72-h EC10 (Mean growth rate) | Geometric mean (n=25) | 1649.9 | Cardwell et al. 2023 |
| *Brachycentrus* sp. | Caddisfly | Invertebrate | 10-d EC10 (Abundance) | 5698 | 2169.4 | Cadmus et al. 2018b |
| *Salvelinus fontinalis* | Brook trout | Fish | >90-d NOEC (Hatch, survival, growth) | ≥12000 | 2355.7 | Smith and Sykora 1976 |
| *Daphnia magna* | Cladoceran | Invertebrate | 21-d EC16 (Reproduction) | 4380 | 2729.1 | Biesinger and Christensen 1972 |
| *Hexagenia limbata* | Mayfly | Invertebrate | 30-d NOEC (Survival, weight) | ≥7863 | 3529.5 | Cadmus et al. 2018a |
| *Ephemerella* sp. | Mayfly | Invertebrate | 10-d NOEC (Abundance) | ≥14073 | 5358.0 | Cadmus et al. 2018a |
| *Rhithrogena* sp. | Mayfly | Invertebrate | 10-d NOEC (Abundance) | ≥14073 | 5358.0 | Cadmus et al. 2018a |
| *Sweltsa* sp. | Stonefly | Invertebrate | 10-d NOEC (Abundance) | ≥14100 | 5368.3 | Cadmus et al. 2018b |
| *Dugesia dorotocephala* | Planarian | Invertebrate | 30-d NOEC (Population response) | ≥40134 | 18015.3 | Cadmus et al. 2018a |

Notes: ECx = Effect concentration affecting x% of test organisms; NOEC = no observed effect concentration

SSDs were created using R package (R version 4.3.1) ‘ssdtools’ (ssdtools version 1.0.2 as well as the corresponding “Shiny App” (shinyssdtools version 0.1.1) (Dalgarno 2018; Thorley and Schwarz 2018). The package can fit several cumulative distribution functions (CDFs) to the data using maximum likelihood estimation (MLE) as the regression method. The model averaging approach was examined for the iron dataset, however the resulting distribution of $HC_5$ values across the range of water chemistry combinations did not reflect the general understanding of iron speciation and toxicity. In particular, the trend in $HC_5$ values with increasing pH was widely inconsistent with individual species models. Consequently, the highest-weighted model across most water chemistry conditions (the log-normal distribution) was used to fit the SSDs.

The SSD and accompanying summary statistics for water of DOC 0.5 mg/L and pH 7.5 are presented in Figure 1 and Table 5, respectively.

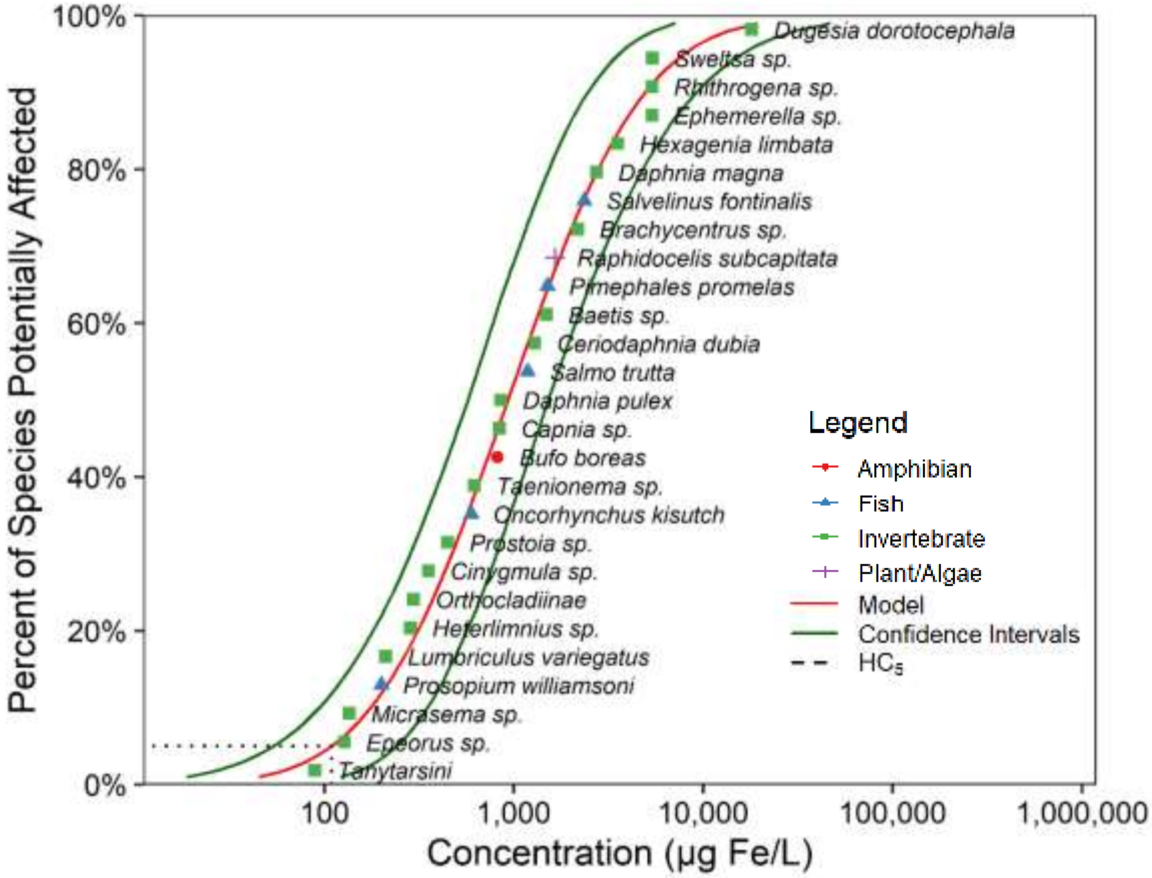

Figure 1: Species sensitivity distribution (SSD) for the chronic toxicity of iron at a dissolved organic carbon (DOC) of 0.5 mg/L and pH of 7.5. The 5th percentile hazard concentration ($HC_5$) is 110 µg Fe/L.

Table 5. Federal Water Quality Guideline (FWQG) summary statistics for water with a dissolved organic carbon (DOC) of 0.5 mg/L and pH of 7.5.

| **Distribution** | **AICc** | **Predicted $HC_5$ (µg/L)** | **95% LCL (µg/L)** | **95% UCL (µg/L)** |
|---|---|---|---|---|
| Log-normal | -64.6 | 110 | 54.8 | 247 |

Notes: AICc= Akaike information criterion corrected for small sample size; $HC_5$= hazard concentration for 5th percentile; LCL= lower confidence limit; UCL= upper confidence limit

The $HC_5$ value of the SSD represents the FWQG at that particular combination of DOC and pH. Over 300 SSDs were run across a range of water chemistry combinations within the model boundaries of the MLR equation, and $HC_5$ values at these various DOC and pH levels were incorporated into a final guideline look-up table (Table 6). Users can select a guideline for the water chemistry of their particular site using the look-up table or using the $HC_5$ calculator (Appendix).

Table 6. Look-up table of Federal Water Quality Guidelines (FWQGs) for total iron (µg Fe/L) for the protection of aquatic life at various dissolved organic carbon (DOC) and pH values.

| **DOC (mg/L)** | **pH 5.5** | **pH 5.7** | **pH 5.9** | **pH 6.0** | **pH 6.1** | **pH 6.3** | **pH 6.5** | **pH 6.7** | **pH 6.9** | **pH 7.1** | **pH 7.3** | **pH 7.5** | **pH 7.7** | **pH 7.9** | **pH 8.1** | **pH 8.3** | **pH 8.5** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0.1** | 13 | 15 | 16 | 17 | 18 | 20 | 22 | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 | 40 | 41 |
| **0.3** | 37 | 40 | 44 | 46 | 48 | 51 | 55 | 59 | 64 | 67 | 71 | 75 | 78 | 82 | 85 | 87 | 89 |
| **0.5** | 57 | 63 | 68 | 71 | 73 | 79 | 84 | 90 | 95 | 100 | 110 | 110 | 110 | 120 | 120 | 120 | 120 |
| **1** | 100 | 110 | 120 | 130 | 130 | 140 | 150 | 150 | 160 | 170 | 170 | 180 | 180 | 190 | 190 | 190 | 190 |
| **1.5** | 150 | 160 | 170 | 170 | 180 | 190 | 200 | 210 | 220 | 220 | 230 | 230 | 240 | 240 | 240 | 240 | 240 |
| **2** | 190 | 200 | 210 | 220 | 220 | 230 | 250 | 260 | 260 | 270 | 280 | 280 | 290 | 290 | 290 | 290 | 290 |
| **2.5** | 220 | 240 | 250 | 260 | 260 | 280 | 290 | 300 | 310 | 320 | 320 | 330 | 330 | 330 | 330 | 330 | 330 |
| **3** | 260 | 270 | 290 | 300 | 300 | 320 | 330 | 340 | 350 | 360 | 360 | 370 | 370 | 370 | 370 | 370 | 360 |
| **3.5** | 290 | 310 | 320 | 330 | 340 | 350 | 370 | 380 | 390 | 400 | 400 | 400 | 410 | 410 | 400 | 400 | 400 |
| **4** | 320 | 340 | 360 | 370 | 370 | 390 | 400 | 410 | 420 | 430 | 440 | 440 | 440 | 440 | 440 | 430 | 430 |
| **4.5** | 350 | 370 | 390 | 400 | 410 | 420 | 440 | 450 | 460 | 460 | 470 | 470 | 470 | 470 | 470 | 460 | 460 |
| **5** | 380 | 400 | 420 | 430 | 440 | 460 | 470 | 480 | 490 | 500 | 500 | 500 | 500 | 500 | 500 | 490 | 480 |
| **5.5** | 410 | 430 | 450 | 460 | 470 | 490 | 500 | 510 | 520 | 530 | 530 | 530 | 530 | 530 | 520 | 520 | 510 |
| **6** | 440 | 460 | 480 | 490 | 500 | 520 | 530 | 540 | 550 | 560 | 560 | 560 | 560 | 560 | 550 | 540 | 530 |
| **6.5** | 470 | 490 | 510 | 520 | 530 | 550 | 560 | 570 | 580 | 590 | 590 | 590 | 590 | 580 | 570 | 570 | 560 |
| **7** | 500 | 520 | 540 | 550 | 560 | 580 | 590 | 600 | 610 | 610 | 620 | 620 | 610 | 610 | 600 | 590 | 580 |
| **7.5** | 520 | 550 | 570 | 580 | 590 | 600 | 620 | 630 | 640 | 640 | 640 | 640 | 640 | 630 | 620 | 610 | 600 |
| **8** | 550 | 570 | 590 | 600 | 610 | 630 | 640 | 650 | 660 | 670 | 670 | 670 | 660 | 650 | 640 | 630 | 620 |
| **8.5** | 570 | 600 | 620 | 630 | 640 | 660 | 670 | 680 | 690 | 690 | 690 | 690 | 680 | 680 | 670 | 650 | 640 |
| **9** | 600 | 620 | 650 | 660 | 670 | 680 | 700 | 710 | 710 | 720 | 720 | 710 | 710 | 700 | 690 | 670 | 660 |
| **9.5** | 620 | 650 | 670 | 680 | 690 | 710 | 720 | 730 | 740 | 740 | 740 | 740 | 730 | 720 | 710 | 690 | 680 |
| **10** | 650 | 670 | 700 | 710 | 720 | 730 | 740 | 750 | 760 | 760 | 760 | 760 | 750 | 740 | 730 | 710 | 700 |
| **10.5** | 670 | 700 | 720 | 730 | 740 | 760 | 770 | 780 | 780 | 790 | 780 | 780 | 770 | 760 | 750 | 730 | 710 |
| **10.9** | 690 | 710 | 740 | 750 | 760 | 770 | 790 | 800 | 800 | 800 | 800 | 800 | 790 | 780 | 760 | 750 | 730 |

Notes: Guideline values are derived as hazardous concentrations for 5% of species ($HC_5$) from chronic Species Sensitivity Distributions (SSDs) fit with the log-normal model.
Values highlighted in orange (for pH 5.5 to <6, or dissolved organic carbon (DOC) 0.1 to <0.3) were calculated outside of the model bounds and should be used with caution. Guidelines highlighted in yellow represent the lowest guideline within the corresponding DOC level. Guidelines highlighted in dark green represent the highest guideline within the corresponding DOC level.

Selecting the appropriate iron FWQG for a particular site requires measurements of DOC and pH for the site. The FWQG table is valid between DOC of 0.3 and 10.9 mg/L and pH 6.0 and 8.5, which are the ranges of data used to derive the DOC and pH slopes, respectively. Where DOC and/or pH is unknown for a site, the lower bounds of the model should be used as a conservative estimate (i.e., DOC of 0.3 mg/L and pH of 6.0). For DOC or pH levels in between denominations of the look-up table, the more sensitive FWQG applies. Where DOC and pH values are above the upper limit of the guideline equation (i.e., DOC >10.9 mg/L or pH

>8.5) the upper bounds (10.9 mg/L and 8.5) apply. Ambient surface water chemistry may also fall below the range of data used to derive the DOC and pH slopes, where organism sensitivity to iron may be greater. Therefore, the look-up table includes extrapolations down to DOC 0.1 mg/L and pH 5.5 to yield more stringent values. However, it should be noted these extrapolations contain uncertainty as they are outside of model limits, and therefore should be used with caution. For DOC and pH values below these lower extrapolations, a site-specific approach should be considered. Sites that have water chemistry variables consistently outside the valid ranges may warrant consideration of deriving site-specific water quality objectives (CCME 2003).

## Protectiveness Assessment

To determine whether the iron guidelines achieve the intended level of protection as per CCME protocol (CCME 2007), a protectiveness assessment was completed using the results from all chronic acceptable aquatic toxicity studies in the dataset (ECCC 2024). Because the relative sensitivity of species to iron is dependent on the DOC and pH of the water, each guideline at the various water chemistry combinations was individually assessed for its protectiveness of the entire dataset adjusted to the same corresponding water conditions. As a first step, all acceptable endpoints were MLR-adjusted to each set of water conditions for which a guideline was derived. Secondly, each guideline value was compared to the corresponding MLR-adjusted dataset and it was examined to determine if any endpoints were below the guideline value at that water chemistry. The results of the protectiveness assessment were that four out of 165 (2.4%) acceptable toxicity data points were below guideline values at certain water conditions (with a maximum of three of these four endpoints being unprotected at the same time or at any one set of given water conditions). Endpoints that were below the guideline were further examined to determine if any of them triggered the Protection Clause (CCME 2007).

Two biomass $EC_{10}$ values for *P. promelas* were below the corresponding FWQG at some water chemistry conditions of low DOC and low to mid-level pH. At these water chemistries, there were an additional 29-30 biomass $EC_{10}$ values for *P. promelas* and one mortality maximum acceptable toxicant concentration (MATC) that were above the guideline. One biomass $EC_{10}$ for *Prosopium williamsoni* was below the guideline at a limited range of water conditions with low DOC and low to mid-level pH. This was the only acceptable endpoint for this species in the dataset. Lastly, one $EC_{20}$ for abundance of *Tanytarsini* was below the FWQG at most water chemistry conditions. This was the only acceptable endpoint for this species in the dataset.

None of the unprotected endpoints were for a species at risk (CCME 2007). The unprotected endpoints for *P. promelas* and *P. williamsoni* were not for lethal effects equal to or above a level of 15% (CCME 2007). The $EC_{20}$ for abundance for *Tanytarsini* could be considered a measurement of both mortality and reproduction. This endpoint was from a mesocosm study, was at an effect level close to 15%, and had some uncertainty in the concentration-response model associated with it. For these reasons, it was determined that the $EC_{20}$ for abundance of *Tanytarsini* did not trigger the Protection Clause. Overall, examination of the available data suggests that the Protection Clause (CCME 2007) is not applicable and the FWQG for total iron is protective. Note that only data derived from laboratory and mesocosm studies were used in this assessment. Assessing protectiveness using data from natural ecosystems, such as species diversity, is beyond the scope of this document.

## Additional Considerations

The FWQG applies to total iron, however some consideration should be given to the measurement of iron from natural water samples when comparing to the guideline value. When total iron is measured in field-collected water, all forms are captured, including fractions from suspended solids that have lower bioavailability, for example iron oxides and oxyhydroxides (Crespo et al. 2023). Some advances in analytical methodology have occurred regarding the determination of the bioavailable fraction of iron in water samples. For example, a pH 2 extraction method is described by Crespo et al. (2023) for defining iron fractions with higher bioavailability in water containing mineralized suspended solids. If guideline users experience exceedances while comparing water samples to the total iron guideline and there is reason to suspect a false-positive, other methods, such as the pH 2 extraction method, can be considered.

Additionally, because iron is a naturally occurring element in the environment, consideration can be given to natural background concentrations at sites with guideline exceedances. There may be cases where natural background concentrations exceed the guideline without apparent effects on aquatic organisms (e.g., if the substance is not present in a bioavailable form). Under these circumstances, it may be necessary to modify water quality guidelines to account for conditions that occur at the site. CCME (2003) provides guidance on two methods for establishing site-specific water quality objectives, which can be: 1) slightly above the natural background level, or 2) at the upper limit of natural background concentrations.

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## List of Acronyms and Abbreviations

AIC – Akaike information criterion
CAS – Chemical Abstracts Service
CCME – Canadian Council of Ministers of the Environment
CDF – cumulative distribution function
CEPA – Canadian Environmental Protection Act
CMP – Chemicals Management Plan
DOC – dissolved organic carbon
DOM – dissolved organic matter
EC – effect concentration
ECCC – Environment and Climate Change Canada
FEQG – Federal Environmental Quality Guideline
FWQG – Federal Water Quality Guideline
GC – Government of Canada
$HC_5$ – hazard concentration of the fifth percentile
LCL – lower confidence limit
MATC – maximum acceptable toxicant concentration
MLE – maximum likelihood estimation
MLR – multiple linear regression
NOEC – no observed effect concentration
NRCan – Natural Resources Canada
RAMP – Regional Aquatics Monitoring Program
SSD – species sensitivity distribution
TMF – toxicity modifying factor
UCL – upper confidence limit