# Aquatic Life Water Quality Standards Technical Support Document for Cadmium

Triennial Water Quality Standard Amendments to Minn. R. chs. 7050 and 7052.
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Minnesota Pollution Control Agency

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# Contents

*Abstract* ........ *1*
Introduction ........ 2
*Cadmium in the environment* ........ *2*
*General summary of cadmium toxicity* ........ *2*
How and Why Water Quality Standards are Developed ........ 2
*U.S. Environmental Protection Agency National Clean Water Act 304(a) aquatic life criteria* ........ *2*
Development of the Draft Cadmium Standards ........ 3
*Introduction* ........ *3*
*Comparison of Minnesota's Cadmium Criteria with EPA (2001) and Mebane (2010 rev.)* ........ *3*
Conversion factors for total to dissolved cadmium ........ 5
*Other data* ........ *6*
*Literature review* ........ *6*
*Implementation and water quality standards* ........ *7*
Conclusions ........ 7
References ........ 8
*Appendix A. Calculations for salmonids and nonsalmonids using data found in Mebane (2006) and EPA (2001)* ........ *9*
*Appendix B ECOTOX query for cadmium toxicity to aquatic animals, 2001-2008* ........ *10*

# Abstract

From the Minnesota *State Register*, Volume 33 (35), March 2, 2009:

*Cadmium has numerous municipal and industrial sources that may be discharged into surface waters. The EPA revised surface water aquatic life criteria values for cadmium in 2001 (Update of Aquatic Life AWQC – Cadmium 2001 (EPA822R01001)). Changes to the current Minnesota acute and chronic WQSs for cadmium would involve compiling, reviewing and developing a value for the short-term (acute) and long-term (chronic) protection of aquatic life communities (e.g. fish, invertebrates, aquatic plants, etc.). Efforts to revise the existing Minnesota standard will require reviewing existing toxicity data from the published literature and other sources.*

The Minnesota Pollution Control Agency (MPCA) has reviewed the U.S. Environmental Protection Agency (EPA) Ambient Water Quality Criteria (AWQC) for Cadmium. The AWQC provides technical review of current or new criteria for pollutants in surface waters that may affect beneficial uses of surface water. In the case of the cadmium AWQC the beneficial use is a healthy, viable aquatic life community. Based on aquatic toxicity-based methods in EPA's criteria document, MPCA is proposing to revise the current water quality standards (WQSs) for cadmium in Minn. R. chs. 7050 and 7052. The WQSs for cadmium continue to be dependent on total hardness. Parameters for the equations to calculate the WQSs have been updated to reflect additional toxicity data. The changes will result in lower cadmium concentrations for the WQSs.

# Introduction

## Cadmium in the environment

Cadmium is an elemental metal that enters the environment in greater amounts through human activities and lesser amounts through natural sources. Activities such as coal combustion, mine wastes, electroplating, iron and steel production, pigments, fertilizers, and pesticides (EPA 2001) all contribute to the environmental load of cadmium. Cadmium is also an essential micronutrient for plants, but at certain levels is toxic to aquatic life.

## General summary of cadmium toxicity

The primary mechanism of cadmium toxicity, like other metals, is binding to fish gills and disrupting cation transport channels on the membranes of the gills. It is difficult to measure the toxic form of cadmium because it binds to numerous constituents that depend on site-specific water chemistry. Dissolved cadmium is considered the toxic form. Its bioavailability is primarily dependent on the calcium and magnesium concentrations in the water because these cations compete with the cadmium for binding sites.

# How and Why Water Quality Standards are Developed

## U.S. Environmental Protection Agency National Clean Water Act 304(a) aquatic life criteria

National Ambient Water Quality Criteria (AWQC) is developed by the U.S. Environmental Protection Agency (EPA) to protect aquatic life, human use of aquatic life (i.e., fish consumption), recreation, and drinking water. States and tribes use the EPA criteria as the basis for the adoption of legally enforceable water quality standards (WQSs) into rules. States are required to adopt standards equal to, or “as protective as,” the criteria to protect the beneficial uses of state surface waters.[1] The Clean Water Act and EPA authorize states to make scientifically defensible changes to EPA criteria, including proposing a standard more stringent than the EPA criterion if the more stringent value is supported by local information. In 2001, EPA’s Office of Water and Office of Science and Technology published AWQC for cadmium (EPA 2001). The AWQC only address aquatic organism toxicity and not human health. This criterion is meant to ensure that the cadmium levels in freshwater are below levels considered harmful to the maintenance and propagation of cold-water and warm-water aquatic communities.

Minnesota’s current acute and chronic WQSs for cadmium need revision because, (1) the WQSs are the primary basis to assess cadmium impacts and define protection for aquatic life in Minnesota’s surface waters, (2) the revised algorithms are based on newer, more robust data, and (3) the CWA requires that states adopt the latest EPA criteria when applicable for protecting designated beneficial uses.

[1] Clean Water Act Section 303(c)(2)(B)

# Development of the Draft Cadmium Standards

## Introduction

Minnesota currently has numeric WQSs for cadmium in Minn. R. chs. 7050 and 7052. The Minnesota Pollution Control Agency (MPCA) in the future will be proposing to update the WQSs in both rules as they relate to aquatic life protection. The draft WQSs are based on the EPA revised surface water AWQC for cadmium in 2001 (EPA 2001). The draft cadmium WQSs are based on updated toxicity studies and subsequent revised calculations.

The current cadmium WQSs for Minnesota are based on EPA's 1984 criteria. EPA's 2001, updated criteria is a revised calculation based on additional toxicity studies performed in the interim. A more recent and extensive review was completed by Mebane (2010 rev.) that provided additional values for acute and chronic cadmium criteria by including toxicity studies between 2001 and 2006. Mebane also validated the criteria by evaluating them for Idaho data sets that were not used for EPA national criteria development. Additional guidance and further technical discussion on developing water quality standards is found in MPCA (2010).

## Comparison of Minnesota's Cadmium Criteria with EPA (2001) and Mebane (2010 rev.)

EPA (2001) summarized the new criteria as follows:

*Freshwater aquatic life should be protected at a total hardness of 50 mg/L as $CaCO_3$ if the four-day average concentration (in µg/L) of dissolved cadmium does not exceed the numerical value given by 0.938 [$e^{(0.7409[\ln(hardness)]-4.719)}$] more than once every three years on the average, and if the 24-hour average dissolved concentration (in µg/L) does not exceed the numerical value given by 0.973[$e^{(1.0166[\ln(hardness)]-3.924)}$] more than once every three years on the average. For example, at a hardness of 50, 100, and 200 mg/L as $CaCO_3$ the four-day average dissolved concentrations of cadmium are 0.15, 0.25 and 0.40 µg/L, respectively, and the 24-hour average dissolved concentrations are 1.0, 2.0, and 3.9 µg/L.*

EPA (2001) reported on acceptable acute toxicity results for 65 species (39 species of invertebrates, 24 species of fish, 1 salamander species, and 1 frog species), representing 55 genera. Acceptable chronic toxicity results were available for 21 species (7 invertebrates and 14 fishes). Chronic toxicity endpoints included growth and reproduction.

Water hardness (calcium and magnesium ion concentrations) continues to be the best surrogate for estimating cadmium toxicity levels. Hardness has been used to calculate cadmium criteria because calcium and magnesium compete for the metal binding sites on the fish gill. Hardness is also a surrogate for pH, alkalinity, and ionic strength. The statistical relationship between hardness and cadmium is based on a regression of log-transformed concentrations for all-species combined. The dissolved fraction of the metal (what passes through a 0.45 micron filter) is considered the potentially toxic form. A conversion factor (CF) is multiplied by the total metal concentrations to get the dissolved metal concentration. For cadmium, the CF is also hardness dependent.

The 2001 EPA update of the cadmium criteria was calculated based on 226 acute test values and 34 chronic values, which are 93 and 9, respectively, more than the number of test values used for the original 1984 EPA report (Table 1). Mebane (2010 rev.), as a United States Geological Survey (USGS) employee working with the state of Idaho, updated the cadmium criteria values in 2006 using EPA guidelines (USEPA 1985). The report summarizes test results for 277 acute, 93 chronic, and 102 "other" endpoints. Acute criteria (species mean acute values (SMAVs)) were derived from 68 species representing 58 genera. Chronic criteria SMCVs were derived from 28 species representing 21 genera. Mebane calculated Final Acute Values (FAV) and Final Chronic Values (FCV) from the fifth percentile of

species-sensitivity distribution models, based on genus mean values. Appendix A is a comparison of FAV and Criterion Maximum Concentration (CMC) calculations from EPA 2001 and Mebane (2010 rev.). Minnesota rule uses the term Maximum Standard (MS) instead of the national criteria term CMC. For the FAV and CMC, the slope was determined using the acute toxicity data (i.e., GMAVs) and their associated hardness values. An intercept was then calculated from the pooled slope. The final equation for the acute criteria for dissolved cadmium for the protection of cold-water species (Class 2A) is:

$$CMC = \exp[(0.8403)(\ln \text{hardness}) - 3.575]$$

and for Class 2B waters[2] is:

$$CMC = \exp[(0.8403)(\ln \text{hardness}) - 2.116]$$

These equations are based on dissolved cadmium because most acute toxicity data is reported for this fraction. The equation for the draft Class 2B standard was developed by excluding salmonid acute values from the lowest four species sensitivity ranks. EPA's guidance (EPA 1985) recommends a minimum taxonomic diversity of eight families as discussed in MPCA (2010). This was met for the acute and the chronic aquatic life criteria development for cadmium. See MPCA (2010) for further discussion of this approach.

**Table 1. Count of tests and genera used in development of the criteria**

| Source | Test Values | General |
|---|---|---|
| *Acute (CMC) Criteria* | | |
| EPA 1984 | 133 | 44 |
| EPA 2001 | 226 | 55 |
| Mebane 2010 revised | 277 | 57 |
| *Chronic (CCC) Criteria* | | |
| EPA 1984 | 25 | 44 |
| EPA 2001 | | |
| | 34 | 16 |

Mebane (2010 rev.) calculated an FAV of 2.451 µg/L but lowered it to the lowest species mean acute value, (1.5 µg/L), because the calculated FAV was not protective of the three trout species important to Idaho. The FAV was divided by two to get (CMC) (i.e., acute criterion).

To supplement the literature search by EPA (2001), Mebane searched publications between January 2000 and April 2005, in addition to reviewing earlier toxicity studies. EPA (2001) concluded that plants were less sensitive to cadmium than aquatic animals; EPA also evaluated dietary effects of cadmium to wildlife and found no adverted toxicity endpoints. Therefore, Mebane (2006) did not include plant toxicity or dietary effects to wildlife. For this document, the ECOTOX database (EPA 2007) was queried for additional toxicity endpoints for cadmium, published between 2001 and 2008. Acute cadmium criteria from EPA and Mebane (2006) are compared in Table 9 of the Mebane report.

For the draft WQS for cadmium, the MPCA evaluated and developed protective values for both cold water fisheries (Class 2A) and for cool-warm water fisheries that do not include salmonids (Class 2B), as shown in Appendix A. Salmonids are cold water species and are often one of the most sensitive species to metal toxicity. Consequently, acute criteria values for cadmium are more protective of cold water species than for cool-warm water species. The chronic criteria values, as developed by EPA, are the

[2] The criterion equation consists of a slope and an intercept. The slope (0.8403) is the pooled slope of the relations between ln hardness and ln toxicity value for multiple species. The intercept is calculated by rearranging the hardness-toxicity value equation to solve for the intercept using the pooled slope and a specific hardness. To calculate the intercept, a total hardness of 50 mg/L as $CaCO_3$ was used.

same for all waters. Table 2 compares the current and draft cadmium criteria at a range of total hardness values. The CMC at total hardness of 50 mg/L for Mebane (2010 rev.) is 0.75 µg/L while EPA (2001) calculated a value of 1.4 µg/L. The values calculated from Mebane will be used as the basis for the acute (FAV and MS) draft Class 2A and Class 2B WQS for cadmium. The draft chronic standard (CS) for this draft WQS will use the national chronic (CCC) value as revised by EPA (2001). Overall, these draft criteria are more restrictive than the present cadmium criteria found in Minn. R. chs. 7050 and 7052.

Recently, the EPA began efforts to consider existing methods of culturing and performing toxicity tests using the amphipod *Hyalella azteca*. This effort may put into question the results of some past toxicity tests using the organism. The EPA cadmium criteria reported *H. azteca* as the organism most sensitive in chronic exposures. The source of that report was unpublished, but the test results have been corroborated as viable (C. Ingersoll, personal communication).

## Conversion factors for total to dissolved cadmium

The CF from total recoverable cadmium to dissolved cadmium is dependent on total hardness. The dissolved fraction decreases with increasing hardness. Draft acute WQSs were developed for the dissolved fraction because most acute toxicity data used measures of dissolved cadmium. Draft chronic WQSs were developed using total cadmium because most chronic toxicity values were measured based on the total metal concentration. The freshwater conversion factors differ between acute and chronic criteria as follows:

$$CF_{acute} = 1.136672 - [(\ln \text{hardness}) (0.041838)]$$

$$CF_{chronic} = 1.101672 - [(\ln \text{hardness}) (0.041838)]$$

where (ln hardness) is the natural logarithm of total hardness, in mg/L as $CaCO_3$ (USEPA 1985). EPA's CF is used for the chronic equation, but not the acute because the acute toxicity was based on dissolved cadmium to begin with.

**Table 2. Comparison of alternative criteria**

| Criteria | Source | Equation Parameters[1] slope | intercept | CF[2] | Total Cadmium (µg/L) at Four Levels of Hardness (mg/L, $CaCO_3$) 50 | 100 | 200 | 400 |
|---|---|---|---|---|---|---|---|---|
| **Acute (CMC)** | | | | | | | | |
| Cold water (includes salmonids) | MN 7050 | 1.128 | 3.828 | $CF_{acute}$ | 1.79 | 3.92 | 8.57 | 18.73 |
| | MN 7052 | 1.128 | 3.6867 | $CF_{acute}$ | 2.07 | 4.52 | 9.87 | 21.58 |
| | EPA 2001 | 1.1066 | 3.924 | $CF_{acute}$ | 1.50 | 3.23 | 6.95 | 14.97 |
| | Mebane (2010 rev.) | 0.8403 | 3.572 | | 0.79 | 1.47 | 2.74 | 5.09 |
| Cool or warm water (excludes salmonids) | MN 7050 | 1.128 | 1.685 | $CF_{acute}$ | 15.30 | 33.44 | 73.08 | 159.71 |
| | EPA 2001 | 1.066 | 1.702 | $CF_{acute}$ | 11.80 | 24.71 | 51.73 | 108.30 |
| | Mebane (2010 rev.) | 0.8403 | 2.116 | | 3.40 | 6.31 | 11.73 | 21.83 |
| **Chronic (CC)** | | | | | | | | |
| All waters (includes salmonids and nonsalmonids) | MN 7050 | 0.7852 | 3.490 | $CF_{chronic}$ | 0.66 | 1.13 | 1.95 | 3.37 |
| | MN 7052 | 0.7852 | 2.715 | $CF_{chronic}$ | 1.43 | 2.46 | 4.24 | 7.31 |
| | EPA 2001 | 0.7409 | 4.719 | $CF_{chronic}$ | 0.16 | 0.27 | 0.45 | 0.76 |

[1]General equation: exp [(slope)( ln hardness) – intercept]
where "exp" is the natural antilogarithm (base e) of the expression in parenthesis and "ln hardness" is the natural logarithm of total hardness in milligrams per liter as calcium carbonate (mg/L, $CaCO_3$)

[2]Mebane equations are for dissolved cadmium; the other equations are for total cadmium and require multiplying by the following conversion factors to calculate dissolved cadmium:

$CF_{acute}$ = 1.136672 - [(ln hardness) (0.041838)]

$CF_{chronic}$ = 1.101672 - [(ln hardness) (0.041838)]

## Other data

EPA (2001) discussed “other data” that reported toxicity studies not acceptable for inclusion in the acute or chronic toxicity values. These included studies of indeterminate or unreported endpoints, unacceptable test methods and other studies that did not report useable data. These include studies where the test organisms were fed during the acute tests. There are also numerous plant toxicity studies.

## Literature review

EPA’s ECOTOX database was queried for cadmium toxicity values for 2001-2008. One thousand one hundred forth eight records were obtained for aquatic toxicity endpoints of cadmium. Records were not accepted if, (1) they were not for relevant North American species, and (2) endpoints were not appropriate. The paring of records resulted in 20 references. Of these, six had been evaluated by Mebane and three had endpoint concentrations that were far higher than other reports for the same species. Consequently, eleven references were remaining with potentially new toxicity values (Appendix B). These studies were reviewed and none of the endpoints were sensitive enough to have replaced the most sensitive genera used.

## Implementation and water quality standards

Ambient total cadmium concentrations in Minnesota were evaluated for the last 10 years based on a query of the STORET database. From 245 cases, the median is 0.041 µg/L, which is identical to the geometric mean (indicating a lognormal distribution). The interquartile range ($25^{th}$-$75^{th}$ percentiles) is 0.027 to 0.066 µg/L. Therefore, typical background concentrations of cadmium are well below the lowest chronic standard at a total hardness of 25 mg/L, $CaCO_3$.

The previous discussion has focused on developing cadmium WQSs based on the dissolved fraction measured in aquatic toxicity tests and for implementation in surface waters. The dissolved fraction better represents the concentration of cadmium available for uptake by aquatic organisms. Minn. R. chs. 7050 and 7052 have a history of listing metals as "total" and that is also how effluent limits are calculated. Acute and chronic WQSs are summarized in Table 4, using the conversion factor from dissolved to total cadmium for the acute criteria. Other than the change in the equations for Minnesota WQSs by use class, there is no change to the implementation of the cadmium WQSs. Therefore, these are the equations on a "total" fraction basis are being proposed for the rules, Minn. R. chs. 7050 and 7052.

**Table 3. Equations for total cadmium (µg/L) WQSs using water hardness (mg/L).**

| Criteria | Equations for Total Cadmium |
|---|---|
| **Acute** (USGS-2006) | |
| Salmonids (Class 2A and Class 2A Lake Superior waters) | FAV = exp (0.8403 [ln (hardness)] – 2.868) / (1.136672 – [ln (hardness)] (0.041838) |
| | MS = exp (0.8403 [ln (hardness)] – 3.572) / (1.136672 – [ln (hardness)] (0.041838) |
| Nonsalmonids (Class 2B) | FAV = exp (0.8403 [ln (hardness)] – 1.409) / (1.136672 – [ln (hardness)] (0.041838) |
| | MS = exp (0.8403 [ln (hardness)] – 2.116) / (1.136672 – [ln (hardness)] (0.041838) |
| **Chronic** (EPA 2001) | |
| Salmonids & Nonsalmonids (All Class 2) | CS = exp (0.0.7409 [ln (hardness)] – 4.719) |

# Conclusions

The thorough analysis by Mebane (2010 rev.), following the EPA's methodology, is the preferred basis for revised cadmium acute water quality criteria. The toxicity database was updated by Mebane, resulting in a more substantiated set of standardized genus mean acute values for the calculation of the acute criteria. A query of the ECOTOX database, summarized in this document, indicates there are no additional toxicity results that would change the outcome of the Mebane analysis. *Hyalella azteca* is the most sensitive species to cadmium under chronic conditions for the cadmium chronic criteria developed by EPA, which is being considered for revision as the draft CS in this document. At a total hardness of 100 mg/L as $CaCO_3$, the draft chronic criteria value, 0.27 µg/L is less than one quarter the value of the existing Minnesota chronic criterion (1.13 µg/L) for total cadmium in Minn. R. ch. 7050. Acute (Maximum Standard) values for Class 2B (cool or warm) surface waters used toxicity data from nonsalmonid organisms. At a total hardness of 100 mg/L as $CaCO_3$, the draft acute criterion (6.31 µg/L) is 19 percent of the existing criteria (33.44 µg/L). The draft acute value for the Class 2A (cold) surface waters (1.47 µg/L) is 38 percent of the existing criteria.

# References

Mebane, C.A. 2006 (2010 rev.). Cadmium risks to freshwater life: Derivation and validation of low-effect criteria values using laboratory and field studies (version 1.2). U.S. Geological Survey Scientific Investigation Report 2006-5245. 130 pp. http://pubs.water.usgs.gov/sir20065245 [Revision History File for sir20065245: http://pubs.usgs.gov/sir/2006/5245/RevisionHistory082010.htm].

MPCA, 2010. Water Quality Standards Guidance and References to Support Development of Statewide Water Quality Standards. In: Minnesota Pollution Control Agency, Draft.

USEPA (1985) Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. PB85- 227049. *National Technical Information Service, Springfield, VA.* (ed C. E. Stephan, D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman, W.A. Brungs).found at: http:/epa.gov/waterscience/criteria/aqlife.html.

U.S. Environmental Protection Agency. 2001. Update of Ambient Water Quality Criteria for Cadmium. EPA-822-R-01-001, April 2001.

U.S. Environmental Protection Agency. 2007. ECOTOX User Guide: ECOTOXicology Database System. Version 4.0. Available: http:/www.epa.gov/ecotox/.

**Appendix A. Calculations for salmonids and nonsalmonids using data found in Mebane (2006) and EPA (2001)**

**Mebane (USGS) 2006**

**With salmonids**

| **Genus** | **Rank** | **GMAV (µg/L)** | **Cum Prob** | **ln GMAV** | **(ln GMAV)^2** | **SQRT P** |
|---|---|---|---|---|---|---|
| Cottus | 4 | 2.610 | 0.07 | 0.959 | 0.9204 | 0.263 |
| Salmo | 3 | 2.610 | 0.05 | 0.959 | 0.9204 | 0.227 |
| Salvelinus | 2 | 2.126 | 0.03 | 0.754 | 0.5689 | 0.186 |
| Oncorhynchus | 1 | 2.019 | 0.02 | 0.703 | 0.4937 | 0.131 |
| n= | 57 | | | | | |
| S= | 2.388 | 5.704 | 0.172 | 2.849 | 2.903 | 0.163 |
| L= | 0.362 | 1.927 | | | | |
| A= | 0.896 | | | | | |
| **FAV (µg/L) =** | **2.450** | Adjusted to **1.50** to protect trout | | | | |
| **CMC (µg/L) =** | **1.225** | Adjusted CMC = | **0.75** | | | |

**Without salmonids**

| **Genus** | **Rank** | **GMAV (µg/L)** | **Cum Prob** | **ln GMAV** | **(ln GMAV)^2** | **SQRT P** |
|---|---|---|---|---|---|---|
| Pimephales | 4 | 16.50 | 0.07 | 2.803 | 7.8588 | 0.272 |
| Hyalella | 3 | 5.39 | 0.06 | 1.685 | 2.8377 | 0.236 |
| Etheostoma | 2 | 3.32 | 0.04 | 1.200 | 1.4399 | 0.192 |
| Cottus | 1 | 2.61 | 0.02 | 0.959 | 0.9204 | 0.136 |
| n= | 53 | | | | | |
| S= | 13.98 | 195.30 | 0.19 | 11.05 | 13.06 | 0.17 |
| L= | -1.26 | 11.69 | | | | |
| A= | 1.86 | | | | | |
| **FAV (µg/L) =** | **6.45** | | | | | |
| **CMC (µg/L) =** | **3.23** | | | | | |

ln CMI = ln(hardness-specifed conc) - (slope x ln(specified hardness))

| slope | ln CMI | |
|---|---|---|
| 0.8403 | -3.575 | using CMC = 0.75 |
| | -2.116 | using CMC = 3.23 |

**EPA 2001**

**With salmonids**

| **Genus** | **Rank** | **GMAV (µg/L)** | **Cum Prob** | **ln GMAV** | **(ln GMAV)^2** | **SQRT P** |
|---|---|---|---|---|---|---|
| Salmonids | 4 | 3.836 | 0.07 | 1.344 | 1.8075 | 0.267 |
| Stripped Bass | 3 | 2.928 | 0.05 | 1.074 | 1.1542 | 0.231 |
| Brk/Bull Trout | 2 | 1.963 | 0.04 | 0.674 | 0.4549 | 0.189 |
| Brown Trout | 1 | 1.613 | 0.02 | 0.478 | 0.2286 | 0.134 |
| n= | 55 | | | | | |
| S= | 6.782 | 45.997 | 0.179 | 3.189 | 3.645 | 0.169 |
| L= | -0.500 | 5.570 | | | | |
| A= | 1.017 | | | | | |
| **FAV (µg/L) =** | **2.764** | Adjusted to 2.108 to protect rainbow trout | | | | |
| **CMC (µg/L) =** | **1.382** | Adjusted CMC = | **1.054** | | | |

**Without salmonids**

| **Genus** | **Rank** | **GMAV** | **Cum Prob** | **ln GMAV** | **(ln GMAV)^2** | **SQRT P** |
|---|---|---|---|---|---|---|
| Simocephalus | 4 | 30.21 | 0.08 | 3.408 | 11.6156 | 0.277 |
| Pimephales | 3 | 29.21 | 0.06 | 3.375 | 11.3873 | 0.240 |
| Daphnia | 2 | 24.93 | 0.04 | 3.216 | 10.3431 | 0.196 |
| Stripped Bass | 1 | 2.928 | 0.02 | 1.074 | 1.1542 | 0.139 |
| n= | 51 | | | | | |
| S= | 18.97 | 359.88 | 0.19 | 30.65 | 34.50 | 0.18 |
| L= | -1.27 | 16.17 | | | | |
| A= | 2.97 | | | | | |
| **FAV (µg/L) =** | **19.45** | | | | | |
| **CMC (µg/L) =** | **9.73** | | | | | |

ln CMI = ln(hardness-specifed conc) - (slope x ln(specified hardness))

| slope | ln CMI | |
|---|---|---|
| 1.0166 | -3.924 | using CMC = 1.054 |
| | -1.702 | using CMC = 9.73 |

REMOVED

| | |
|---|---|
| 1.613 | Salmo |
| 1.963 | Salvelinus |
| 3.836 | Oncorhynchus |
| 22.54 | Ptychocheilus |

## Appendix B. ECOTOX query for cadmium toxicity to aquatic animals, 2001-2008

| | | **LC50** | | **Species Scientific Name** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Author | Pub Yr | Source | Title | Ceriodaphnia dubia | Daphnia ambigua | Daphnia magna | Daphnia pulex | Hyalella azteca | Cottus bairdi | Oncorhynchus mykiss | Salvelinus confluentus |
| **Endpoint: LC50 (acute)** | | | | | | | | | | | |
| Barata, C., I. Varo, J.C. Navarro, S. Arun, and C. Porte | 2005 | Comp.Biochem.Physiol.C 140(2):175-186 | Antioxidant Enzyme Activities and Lipid Peroxidation in the Freshwater Cladoceran Daphnia magna Exposed to Redox Cycling Compounds | | | 6.26 | | | | | |
| Besser, J.M., C.A. Mebane, D.R. Mount, C.D. Ivey, J.L. Kunz, I.E. Greer, T.W. May, and C.G. Ingersoll | 2007 | Environ.Toxicol.Chem. 26(8):1657-1665 | Sensitivity of Mottled Sculpins (Cottus bairdi) and Rainbow Trout (Oncorhynchus mykiss) to Acute and Chronic Toxicity of Cadmium, Copper, and Zinc | | | | | | 1.73 | 3.70 | |
| Borgmann, U., Y. Couillard, P. Doyle, and D.G. Dixon | 2005 | Environ.Toxicol.Chem. 24(3):641-652 | Toxicity of Sixty-Three Metals and Metalloids to Hyalella azteca at Two Levels of Water Hardness | | | | | 0.15 | | | |
| Hansen, J.A., P.G. Welsh, J. Lipton, D. Cacela, and A.D. Dailey | 2002 | Environ.Toxicol.Chem. 21(1):67-75 | Relative Sensitivity of Bull Trout (Salvelinus confluentus) and Rainbow Trout (Oncorhynchus mykiss) to Acute Exposures of Cadmium and Zinc | | | | | | | 0.35 | 0.83 |
| Mebane, C.A., D.P. Hennessy, and F.S. Dillon | 2007 | Water Air Soil Pollut. :26 p. (DOI - 10.1007/s11270-007-9524-8) | Developing Acute-to-Chronic Toxicity Ratios for Lead, Cadmium, and Zinc Using Rainbow Trout, a Mayfly, and a Midge | | | | | | | 0.84 | |
| Mohammed, A. | 2007 | Toxicol.Environ.Chem. 89(2):347-352 | Comparative Sensitivities of the Tropical Cladoceran, Ceriodaphnia rigaudii and the Temperate Species Daphnia magna to Seven Toxicants | | | 520 | | | | | |
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| | | LC50 | | Species Scientific Name | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Author | Pub Yr | Source | Title | Ceriodaphnia dubia | Daphnia ambigua | Daphnia magna | Daphnia pulex | Hyalella azteca | Cottus bairdi | Oncorhynchus mykiss | Salvelinus confluentus |
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| **Endpoint: EC50 (acute)** | | | | | | | | | | | |
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| **Endpoint: MATC (chronic)** | | | | | | | | | | | |
| Besser, J.M., C.A. Mebane, D.R. Mount, C.D. Ivey, J.L. Kunz, I.E. Greer, T.W. May, and C.G. Ingersoll | 2007 | Environ.Toxicol.Chem. 26(8):1657-1665 | Sensitivity of Mottled Sculpins (Cottus bairdi) and Rainbow Trout (Oncorhynchus mykiss) to Acute and Chronic Toxicity of Cadmium, Copper, and Zinc | | | | | | 0.88 | 1.90 | |
| Mebane, C.A., D.P. Hennessy, and F.S. Dillon | 2007 | Water Air Soil Pollut. :26 p. (DOI - 10.1007/s11270-007-9524-8) | Developing Acute-to-Chronic Toxicity Ratios for Lead, Cadmium, and Zinc Using Rainbow Trout, a Mayfly, and a Midge | | | | | | | 0.16 | |