United States
Environmental Protection
Agency

Office of Water
4304T

EPA-822-R-07-001
February 2007

# AQUATIC LIFE AMBIENT FRESHWATER QUALITY CRITERIA - COPPER

## 2007 Revision

# AQUATIC LIFE AMBIENT FRESHWATER QUALITY CRITERIA - COPPER

## 2007 Revision

(CAS Registry Number 7440-50-8)

February 2007

U.S. Environmental Protection Agency
Office of Water
Office of Science and Technology
Washington, DC

# NOTICES

# FOREWORD

Section 304(a)(l) of the Clean Water Act of 1977 (P.L. 95-217) requires the Administrator of the Environmental Protection Agency to publish water quality criteria that accurately reflect the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare that might be expected from the presence of pollutants in any body of water, including ground water. This document is a revision of criteria based upon consideration of comments received from independent peer reviewers and the public. Criteria contained in this document supplement any previously published EPA aquatic life criteria for the same pollutant(s).

The term "water quality criteria" is used in two sections of the Clean Water Act, section 304(a)(l) and section 303(c)(2). The term has a different program impact in each section. In section 304, the term represents a non-regulatory, scientific assessment of health or ecological effects. Criteria presented in this document are such scientific assessments. If water quality criteria associated with specific waterbody uses are adopted by a state or tribe as water quality standards under section 303, they become enforceable maximum acceptable pollutant concentrations in ambient waters within that state or tribe. Water quality criteria adopted in state or tribal water quality standards could have the same numerical values as criteria developed under section 304. However, in many situations states or tribes might want to adjust water quality criteria developed under section 304 to reflect local environmental conditions. Alternatively, states or tribes may use different data and assumptions than EPA in deriving numeric criteria that are scientifically defensible and protective of designated uses. It is not until their adoption as part of state or tribal water quality standards that criteria become regulatory. Guidelines to assist the states and tribes in modifying the criteria presented in this document are contained in the Water Quality Standards Handbook (U.S. EPA 1994). The handbook and additional guidance on the development of water quality standards and other water-related programs of this agency have been developed by the Office of Water.

This document is guidance only. It does not establish or affect legal rights or obligations. It does not establish a binding norm and cannot be finally determinative of the issues addressed. Agency decisions in any particular situation will be made by applying the Clean Water Act and EPA regulations on the basis of specific facts presented and scientific information then available.

Ephraim S. King, Director
Office of Science and Technology

# ACKNOWLEDGMENTS

Document Update: 2007

Luis A. Cruz
(document coordinator and contributor)
U.S. EPA
Health and Ecological Effects Criteria Division
Washington, DC

Cindy Roberts
(contributor)
U.S. EPA
Office of Research and Development
Washington, DC

Mary Reiley
(contributor)
U.S. EPA
Health and Ecological Effects Criteria Division
Washington, DC

Robert Santore
(contributor)
HydroQual, Inc.
Syracuse, New York

Paul Paquin
(contributor)
HydroQual, Inc.
Syracuse, New York

Gary Chapman
(contributor)
Great Lakes Environmental Center
Columbus, Ohio

Jennifer Mitchell
(contributor)
U.S. EPA (formerly)
Health and Ecological Effects Criteria Division
Washington, DC

Charles Delos
(contributor)
U.S. EPA
Health and Ecological Effects Criteria Division
Washington, DC

Joseph Meyer
(contributor)
University of Wyoming
Laramie, Wyoming

Rooni Mathew
(contributor)
HydroQual, Inc.
Syracuse, New York

Tyler K. Linton
(contributor)
Great Lakes Environmental Center
Columbus, Ohio

Statistical Support and Contributor:
Russell Erickson
Office of Research and Development
Environmental Research Laboratory
Duluth, Minnesota

# CONTENTS

## FIGURES

## TABLES

## APPENDICES

# ACRONYMS

| | |
|---|---|
| ACR | Acute-Chronic Ratio |
| BL | Biotic Ligand |
| BLM | Biotic Ligand Model |
| CCC | Criterion Continuous Concentration |
| CF | Conversion Factors |
| CMC | Criterion Maximum Concentration |
| CWA | Clean Water Act |
| DIC | Dissolved Inorganic Carbon |
| DOC | Dissolved Organic Carbon |
| DOM | Dissolved Organic Matter |
| EC | Effect Concentration |
| EPA | Environmental Protection Agency |
| FACR | Final Acute-Chronic Ratio |
| FAV | Final Acute Value |
| FCV | Final Chronic Value |
| FIAM | Free Ion Activity Model |
| GMAV | Genus Mean Acute Value |
| GSIM | Gill Surface Interaction Model |
| LC50 | Lethal Concentration at 50 Percent Effect Level |
| LOAEC | Lowest Observed Adverse Effect Concentration |
| NASQAN | National Stream Quality Accounting Network |
| NOAEC | No Observed Adverse Effect Concentration |
| pH | Negative logarithm of the concentration (mol/L) of the $H_3O^+[H^+]$ ion; scale range from 0 to 14 |
| SMAV | Species Mean Acute Values |
| STORET | EPA STOrage and RETrieval Data System |
| WER | Water-Effect Ratio |
| WET | Whole Effluent Toxicity |
| WQC | Water Quality Criteria |

## 1.0 INTRODUCTION

Copper is an abundant trace element found in the earth's crust and is a naturally occurring element that is generally present in surface waters (Nriagu, 1979). Copper is a micronutrient for both plants and animals at low concentrations and is recognized as essential to virtually all plants and animals (Kapustka et al., 2004). However, it may become toxic to some forms of aquatic life at elevated concentrations. Thus, copper concentrations in natural environments, and its biological availability, are important. Naturally occurring concentrations of copper have been reported from 0.03 to 0.23 µg/L in surface seawaters and from 0.20 to 30 µg/L in freshwater systems (Bowen, 1985). Copper concentrations in locations receiving anthropogenic inputs can vary anywhere from levels that approach natural background to 100 µg/L or more (e.g., Lopez and Lee, 1977; Nriagu, 1979; Hem, 1989) and have in some cases been reported in the 200,000 µg/L range in mining areas (Davis and Ashenberg, 1989; Robins et al., 1997). Mining, leather and leather products, fabricated metal products, and electric equipment are a few of the industries with copper-bearing discharges that contribute to anthropogenic inputs of copper to surface waters (Patterson et al., 1998).

Over the past 20 years, the U.S. Environmental Protection Agency (EPA) has published a number of guidance documents containing aquatic life criteria recommendations for copper (e.g., U.S. EPA 1980, 1985, 1986, 1996). The present document contains EPA's latest criteria recommendations for protection of aquatic life in ambient freshwater from acute and chronic toxic effects from copper. These criteria are based on the latest available scientific information, supplementing EPA's previously published recommendations for copper. This criteria revision incorporated new data on the toxicity of copper and used the biotic ligand model (BLM), a metal bioavailability model, to update the freshwater criteria. With these scientific and technical revisions, the criteria will provide improved guidance on the concentrations of copper that will be protective of aquatic life. The BLM is not used in the saltwater criteria derivation because further development is required before it will be suitable for use to evaluate saltwater data.

This document provides updated guidance to states and authorized tribes to establish water quality standards under the Clean Water Act (CWA) to protect aquatic life from elevated copper exposure. Under the CWA, states and authorized tribes are to establish water quality criteria to protect designated uses. Although this document constitutes EPA's scientific recommendations regarding ambient concentrations of copper, it does not substitute for the CWA or EPA's regulations, nor is it a regulation itself. Thus, it cannot impose legally binding requirements on EPA, states, tribes, or the regulated community, and might not apply to a particular situation based on the circumstances. State and tribal decision makers retain the discretion in adopting approaches, on a case-by-case basis, that differ from this guidance when appropriate. EPA may change this guidance in the future.

Although the BLM has been used in place of the formerly applied hardness-based approach, the updated freshwater criteria derivations in this document are still based on the principles set forth in the *Guidelines for Deriving Numerical Water Quality Criteria for the Protection of Aquatic Life and Their Uses* (Stephan et al. 1985, hereafter referred to as the Guidelines). Section 2 of this document provides an overview of copper bioavailability and the BLM. Additional information on the generalized BLM framework, theoretical background, model calibration, and application for the BLM can be found in the published literature. Section 3 of this document discusses general procedures and requirements for applying the BLM to criteria. Section 4 provides the derivation of criteria Final Acute Value (FAV) and Final Chronic Value (FCV) for freshwater organisms. Section 5 discusses plant data and Section 6 discusses other data not included in the criteria derivation. Sections 7 and 8 provide the final criteria statements and information on implementation. Various supplementary information is provided in several appendices.

## 2.0 APPROACHES FOR EVALUATING COPPER BIOAVAILABILITY

### 2.1 *General Aspects of Copper Bioavailability*

The toxicity of a chemical to an aquatic organism requires the transfer of the chemical from the external environment to biochemical receptors on or in the organism at which the toxic effects are elicited. Often, this transfer is not simply proportional to the total chemical concentration in the environment, but varies according to attributes of the organism, chemical, and exposure environment so that the chemical is more or less "bioavailable". Definitions of bioavailability vary markedly (e.g., National Research Council, 2003) and are often specific to certain situations, but a useful generic definition is the relative facility with which a chemical is transferred from the environment to a specified location in an organism of interest.

Of particular importance to bioavailability is that many chemicals exist in a variety of forms (chemical species). Such chemical speciation affects bioavailability because relative uptake rates can differ among chemical species and the relative concentrations of chemical species can differ among exposure conditions. At equilibrium in oxygenated waters, "free" copper exists as cupric ion - Cu(II) weakly associated with water molecules ($Cu{\cdot}nH_2O^{+2}$), but this species is usually a small percentage of the total copper. Most dissolved copper is part of stronger complexes with various ligands (complexing chemicals that interact with metals), including dissolved organic compounds, hydroxides, carbonates, and other inorganic ligands. Substantial amounts of copper can also be adsorbed to or incorporated into suspended particles. More information on copper speciation in freshwater can be found in Kramer et al. (1997), Bryan et al. (2002), and Smith et al. (2002).

Copper toxicity has been reported to vary markedly due to various physicochemical characteristics of the exposure water (e.g., either laboratory or field), including temperature, dissolved organic compounds, suspended particles, pH, and various inorganic cations and anions, including those composing hardness and alkalinity (see reviews by Sprague, 1968; Hunt, 1987; Campbell, 1995; Allen and Hansen, 1996; Paquin et al., 2002). Many of these physicochemical factors affect copper speciation, and their effects on copper toxicity therefore could be due to effects on copper bioavailability. That bioavailability is an important factor is evident from uptake of copper by aquatic organisms being reduced by various organic compounds and inorganic ligands known to complex copper (Muramoto, 1980; Buckley et al., 1984; Playle et al., 1993 a,b; MacRae et al., 1999).

A "ligand" is a complexing chemical (ion, molecule, or molecular group) that interacts with a metal like copper to form a larger complex. A "biotic ligand" is a complexing chemical that is a component of an organism (e.g. chemical site on a fish gill). For certain ligands, some studies have demonstrated that the concentration of free copper associated with a specified level of accumulation or toxicity changes little as the ligand concentration is varied, despite major changes in the proportion of copper bound to the ligand (see review by Campbell, 1995). This suggests that, even at low concentrations, free copper is more important to bioavailability than the ligand-bound copper. This is expected if accumulation and toxicity are dependent on the binding of copper to a biochemical receptor "X" on the surface of the organism, forming a chemical species X-Cu (receptor-bound metal) that is a first limiting step in accumulation and toxicity. By standard chemical equilibrium expressions, the amount of such species and the consequent biological effects would be a function of the activity of just free copper (Morel, 1983 a), a relationship commonly referred to as the free ion activity model (FIAM). Ligand-bound copper (Cu-L) would contribute to copper bioavailability if (a) a species X-Cu-L is formed that is important to copper accumulation/toxicity, (b) the microenvironment near the organism surface is such that Cu-L dissociates and increases the free copper activity interacting with "X", or (c) copper uptake is via mechanisms that do not entail binding to such a receptor and can accommodate different copper species. Some studies have indicated dissolved complexes of copper do contribute to bioavailability (reviews by Sprague, 1968; Hunt, 1987; Campbell, 1995; Allen and Hansen, 1996; Paquin et al., 2002).

The effects of physicochemical factors on copper toxicity are diverse and the specific chemistry of the exposure water will determine whether or not there are appreciable effects on copper speciation and a resulting strong relationship of toxicity to free copper. Usually copper toxicity is reduced by increased water hardness (reviews by Sprague, 1968; Hunt, 1987; Campbell, 1995; Allen and Hansen, 1996; Paquin et al., 2002), which is composed of cations (primarily calcium and magnesium) that do not directly interact with copper in solution so as to reduce bioavailability. In some cases, the apparent effect of hardness on toxicity might be partly due to complexation of copper by higher concentrations of hydroxide and/or carbonate (increased pH and alkalinity) commonly associated with higher hardness. However, significant effects on toxicity often are still present when hardness is increased in association with anions which do not interact strongly with copper (Inglis and Davis, 1972; Chakoumakos et al., 1979; Miller and Mackay, 1980; Erickson et al., 1987). Hardness cations could have some limited effect on copper speciation by competing with copper for the same dissolved ligands, but increased hardness would then increase free copper and thus increase, not decrease, toxicity. Sodium has also been reported to affect copper toxicity (Erickson et al., 1996 b) and pH effects can be partly due to effects of hydrogen ion other than on copper speciation (Peterson et al., 1984).

The effects of hardness cations could be explained by the competing with copper for the biochemical receptor "X", thus reducing copper uptake (Zitko, 1976; Zitko et al., 1976; Pagenkopf, 1983). Reduced metal bioavailability due to increased hardness cations has been experimentally demonstrated (Playle et al., 1992; Meyer et al., 1999, 2002), although this does not specifically establish cation competition as the mechanism. Pagenkopf (1983) provided a mathematical description of a Gill Surface Interaction Model (GSIM) that addressed the effects on metal toxicity of both metal speciation and cations via the interactions of gill surface biochemical receptors with the free toxic metal, other metal species, hardness cations, and hydrogen ion.

The empirical evidence demonstrates that copper toxicity is affected by exposure conditions and that much of these effects is plausibly attributed to effects of ligands and cations on copper bioavailability. However, it should not be presumed that all of the observed effects of the physicochemical factors on copper toxicity reflect effects on bioavailability, or that bioavailability effects are just due to ligand complexation and cation competition. For example, acute copper toxicity in aquatic organisms has been related to disruption of osmoregulation, specifically sodium/potassium exchange (Lauren and MacDonald, 1986; Wood, 1992; Wood et al., 1997; Paquin et al., 2002), which can be affected by calcium other than by competition with copper for the same biochemical receptor. Similarly, reported effects of sodium and potassium on copper toxicity (Erickson et al., 1996 b) might simply reflect favorable or unfavorable ion exchange gradients, rather than any effect on copper bioavailability. Nevertheless, the effects of ligand complexation and cation competition on copper bioavailability provide a reasonable conceptual framework for improved descriptions of how copper toxicity differs across exposure conditions.

## 2.2 *Existing Approaches*

EPA aquatic life criteria for metals address the reported effects of hardness on metal toxicity using empirical regressions of toxic concentrations versus hardness for available toxicity data across a wide range of hardness (Stephan et al., 1985). Such regressions provided the relative amount by which the criteria change with hardness, but have certain limitations. The regressions were not just of hardness, but of any other factor that was correlated with hardness in the toxicity data set used for the regressions, particularly pH and alkalinity. Although these regressions therefore address more bioavailability issues than hardness alone, they best apply to waters in which the correlations among hardness, pH, and alkalinity are similar to the data used in the regressions. The separate effects of these factors are not addressed for exposure conditions in which these correlations are different. In addition, some physicochemical factors affecting metal toxicity, such as organic carbon, are not addressed at all.

Existing EPA metals criteria also address bioavailability by using dissolved metal as a better approximation for metal bioavailability than total metal (U.S. EPA, 1993). Although this approach accounts for the low bioavailability of metal on suspended particles, it does not address the major effects of various dissolved species on bioavailability. This approach could conceivably be further developed to include just part of the dissolved copper, but this not only requires resolving what species to include, how to weight them, and how to assess their concentrations, but also would not address the effects of cations and other factors that affect toxicity in addition to metal speciation. Such a "bioavailable fraction" approach is not justified, because no fraction of metals species provides a constant measure of toxicity.

To address more completely the modifying effects of water quality than the hardness regressions achieve, EPA issued guidance in the early 1980s on the water-effect ratio (WER) method (Carlson et al., 1984; U.S. EPA, 1983, 1992, 1994). The WER is "a biological method to compare bioavailability and toxicity in receiving waters versus laboratory test waters" (U.S. EPA, 1992). A WER is calculated by dividing the acute LC50 of the metal, determined in water collected from the receiving water of interest, by the LC50 of the metal determined in a standard laboratory water, after adjusting both test waters to the same hardness. The standard laboratory water LC50 is used as the denominator to reflect that this LC50 is measured in test water that has water quality characteristics representative of the test waters used to develop the Water Quality Criteria (WQC) toxicity database, at least as a good approximation. The national hardness-based acute criterion concentration is then multiplied by this ratio (i.e., the WER) to establish a site-specific criterion that reflects the effect of site water characteristics on toxicity. However, a WER accounts only for interactions of water quality parameters and their effects on metal toxicity to the species tested and in the water sample collected at a specific location and at a specific time. There is also significant cost to generate a single WER.

Because of the limitations of these past approaches for addressing bioavailability in metals criteria, there is a need for an approach that (1) explicitly and quantitatively accounts for the effect of individual water quality parameters that modify metal toxicity and (2) can be applied more cost-effectively and easily, and hence more frequently across spatial and temporal scales. An assessment framework that incorporates the bioavailability mechanisms discussed in Section 2.1 was therefore used to address more comprehensively the effects of physicochemical exposure conditions on copper toxicity with lower costs than required by the WER approach.

## 2.3 *The Biotic Ligand Model and Its Application to Criteria Development*

The interactions of toxic metal species and other exposure water constituents with biological surface receptors described by Zitko (1976), Morel (1983), and Pagenkopf (1983) provided the basic conceptual and mathematical structure for the bioavailability model to be used here (Figure 1). Subsequent experimental work has supported various model tenets by demonstrating the effects of complexing ligands and competing cations on accumulation of toxic metals at fish gills and the relationship of toxic effects to accumulation, and has also provided estimates of various model parameters (Playle et al., 1992, 1993a,b; Janes and Playle, 1995; MacRae et al., 1999, Meyer et al., 1999, 2002; McGeer et al., 2002). Various efforts in metal speciation modeling also have provided the ability to do better speciation calculations, especially regarding complexation of metals by organic matter (e.g., Tipping, 1994). This experimental work has supported further metal toxicity model development (Meyer, 1999; Brown and Markich, 2000; McGeer et al., 2002; Di Toro et al., 2001; Santore et al., 2001; Paquin et al., 2002). This bioavailability modeling approach is now commonly termed "Biotic Ligand Models" to broaden the scope beyond gill surfaces and to acknowledge that the biochemical receptor "X" discussed in Section 2.1 is a metal-binding ligand that is treated similarly to ligands in the exposure water, except that it is on the organism and is the keystone for metal accumulation and toxicity.

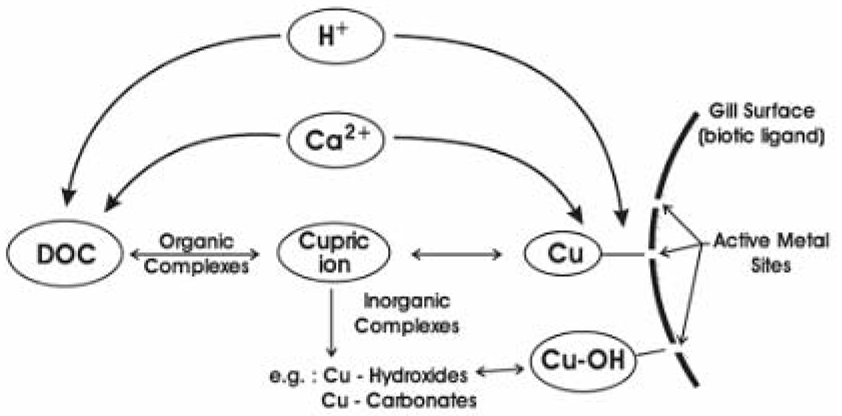


**Figure1. Conceptual Diagram of Copper Speciation and Copper-Gill Model (after Pagenkopf, 1983)**

Briefly, available evidence indicates that both free copper and copper monohydroxide bind to a biotic ligand "Lb" on the organism's surface (Lb-Cu and Lb-CuOH) and that death occurs when a certain amount of the total biotic ligand sites are occupied by copper. This ligand must be at the organism surface because the model describes its interactions with the external exposure water. However, this does not mean that this ligand is the site of toxic action; rather it is only necessary to assume that copper accumulation at the site(s) of toxic action is proportional to binding at the biotic ligand (i.e., the biotic ligand controls bioavailability). Other cations also will bind to the biotic ligand, affecting copper bioavailability because higher concentrations of copper are needed for copper to reach toxic levels. The binding to the biotic ligand is considered to be at equilibrium, with apparent (activity-corrected) equilibrium constants $K_{LbCu}$, $K_{LbCuOH}$, and $K_{LbCj}$, respectively, for free copper, copper hydroxide, and the "jth" competing cation. Chemical speciation in the exposure water is also considered to be at equilibrium, and chemical speciation calculations are conducted to compute the free copper, copper hydroxide, and competing cation activities to which the biotic ligand is exposed. Because binding to the actual biotic ligand cannot be measured, it is expected that accumulation relationships for some measurable variable (e.g., the total metal in gill tissue) provide a reasonable surrogate for the actual biotic ligand. Because criteria deal with concentrations eliciting a certain level of effects on groups of organisms (e.g., LC50s), model calculations are for an organism with characteristics appropriate for such group-wide statistics.

How the BLM is applied to criteria can be best discussed by starting with the following general expression for the BLM:

$$EC = EC_0 \cdot f_C \cdot f_L \qquad \text{Equation 1}$$

where EC is the total dissolved copper concentration eliciting an effect, $EC_0$ is a baseline EC in the absence of any complexing ligands and competing cations, $f_C$ should be a factor (<1) for how much competing cations increase EC, and $f_L$ should be a factor (<1) for how much complexing ligands increase EC. For the BLM used here:

$$EC_0 = \frac{f_{LbT}}{(1 - f_{LbT}) \cdot K_{LbCu}} \qquad \text{Equation 2}$$

$$f_C = 1 + \sum_{j}^{m} \left( K_{C_jLb} \cdot [C_j] \right) \qquad \text{Equation 3}$$

$$f_L = \frac{1}{\alpha_{Cu^{+2}} + \frac{K_{LbCuOH}}{K_{LbCu}} \cdot \alpha_{CuOH}} \qquad \text{Equation 4}$$

where $f_{LbT}$ is the fraction of the biotic ligand sites that must be occupied by copper to elicit the toxicity of interest (e.g., a lethal accumulation divided by the accumulation capacity), *m* is the number of competing cations included in the model, [Cj] is the concentration of the jth competing cation, $\alpha_{Cu+2}$ is the ratio of free copper concentration to total dissolved copper concentration, $\alpha_{CuOH}$ is the ratio for the copper hydroxide complex, and the ratio $K_{LbCuOH}/K_{LbCu}$ specifies the bioavailability of CuOH relative to free copper. Thus, in the absence of complexing ligands and competing cations, the toxic concentration is only a function of the binding strength of free copper and the copper occupied fraction of biotic ligand sites needed to elicit toxicity. The increase in the effect concentration due to competing cations is simply a sum of the products of their concentrations and binding constants. The increase in the effect concentration due to complexing ligands is the inverse of the sum of the products of the relative bioavailabilities and concentration fractions of the species that bind to the biotic ligand (free copper and copper hydroxide).

If toxicity to all the biological species in the criteria (at least the most sensitive ones) were determined based on measured accumulation properties and the relationship of toxicity to accumulation, the above model equations would be directly applied in criteria calculations. However, this is not the case. Although gill accumulation properties and lethal accumulations have been measured for certain species and conditions, and this has been useful in validating BLM assumptions and formulations, the data that must be applied to the criteria consists of water effect concentration (ECs) for biological species for which this accumulation information is generally not available. The BLM therefore is needed, not to make absolute calculations regarding toxic concentrations, but to extrapolate toxic concentrations from one exposure condition to another:

$$EC_A = EC_B \cdot \frac{f_{C,A} \cdot f_{L,A}}{f_{C,B} \cdot f_{L,B}} \qquad \text{Equation 5}$$

where the A and B subscripts refer to different exposure conditions. The general procedure that was followed for criteria development here was to use the above equation to normalize all available toxicity data to a reference exposure condition, calculate criteria values at the reference condition, and again use the above equation to compute criteria at other conditions.

This means that the BLM assumptions and parameters that just pertain to $EC_0$ are not important to its application to criteria, which actually simplifies model validation and parameterization needs. In particular, there is no need to estimate $f_{LbT}$, or the lethal accumulations and accumulation capacities that define this fraction. Furthermore, the absolute values of $K_{LbCu}$ and $K_{LbCuOH}$ do not need to be known, only their relative value (and if copper binding to the biotic ligand was dependent only on free copper, the value of $K_{LbCu}$ would not be needed at all). Absolute values are only needed for the binding constants for the competing cations, as well as the various constants needed in speciation calculations to estimate $\alpha_{Cu+2}$ and $\alpha_{CuOH}$. For BLM application to criteria, the important concern is whether $f_C$ and $f_L$ are suitably formulated and parameterized, and not with issues that relate to lethal accumulations and accumulation capacities.

## 2.4 *BLM Uncertainties and Performance*

The BLM employed here uses equilibrium reactions of copper and other cations with a single, simple type of surface ligand as the focus for all the effects of physicochemical exposure conditions on toxicity, and thus is a simple, approximate representation for the complex set of chemical reactions and transfers involved with environmental copper concentrations eliciting toxicity. As already noted, cation effects might involve mechanisms other than competition for a surface ligand. The microenvironment at the gill might change copper speciation. Multiple mechanisms that do not react the same to external conditions might be involved in copper bioavailability and toxicity. Accumulation parameters based on bulk gill measurements will likely not be the same as those for the biotic ligand. Nonequilibrium processes might be important, especially regarding the relationship of copper-binding on a surface ligand to toxic action.

However, any model is a simplification of reality and the existence of uncertainties does not preclude a model from being useful and justified. Despite its simplicity, the BLM used here provides a reasonable mechanistic framework for the well-established effects of copper speciation, explicitly addressing the relative bioavailability of different copper species. It also includes a plausible mechanism that allows the effects of cations to be addressed and uses a comprehensive model for calculating the required concentrations of various chemical species. Even if the mechanistic descriptions are incomplete, this model allows the major empirical effects of complexing ligands and competing cations to be described in a more comprehensive and reasonable fashion than other approaches.

Because this model is used in criteria to predict relative effects of physicochemical exposure factors, its utility for criteria can be judged based on how well it predicts the relative effects of these factors in copper toxicity studies. Examples of BLM performance for various exposure factors and studies are provided in the technical support document for this criteria. Figure 2 shows one example from a study on the effects of various exposure conditions on the acute lethality of copper to fathead minnows. This set of exposures consisted of synthetic exposure solutions of various total ion concentrations with fixed ratios of the major cations and anions, at a fixed pH (8.0) and low dissolved organic matter (< 0.5 mg/L). Observed dissolved LC50s (solid circles with uncertainty bars) varied by 24-fold for only a 9-fold change in total ions. These large effects reflect the combined influences of increased alkalinity (copper carbonate complex formation), hardness, and sodium. Considering the wide range of the observed LC50s and that the model was not fitted to these data, BLM-predicted LC50s (open symbols) were rather accurate, ranging from 55 to 87% (average 75%) of the observed value. More importantly for criteria, the predicted relative change across the range of total ion concentration was 20-fold, very close to that observed.

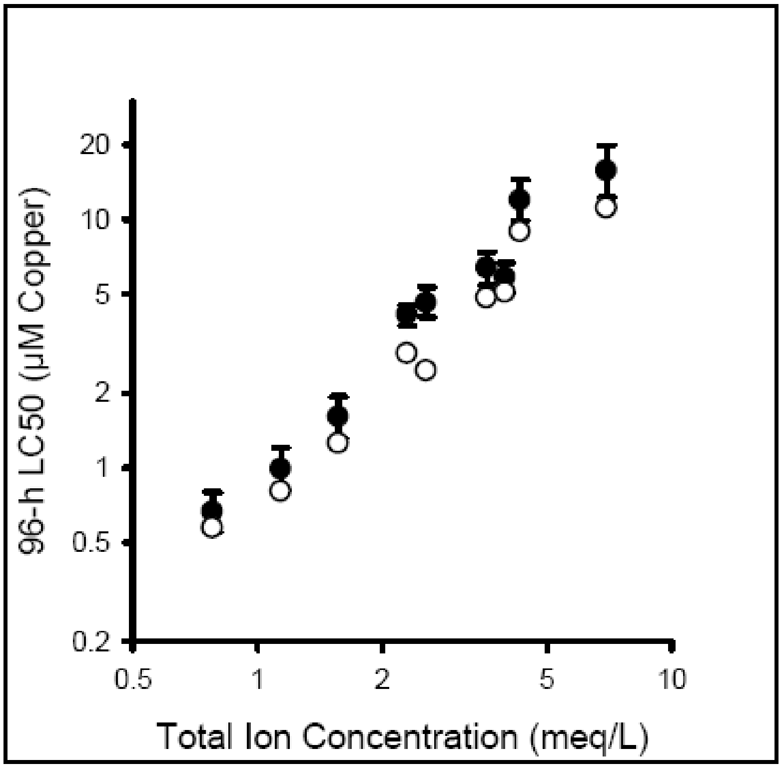


Figure 2. Effects of increasing total ion concentration on the acute lethality of copper to fathead minnows at constant pH=8 and low DOC < 0.5 mg/L. Solid symbols represent observed values, open symbols represent predicted values.

Model performance can also be judged across a variety of factors as in Figure 3, which shows predicted versus observed LC50s for a large number of exposures in the cited study, which varied hardness, alkalinity, sodium, and pH together and separately over a wide range. Observed LC50s varied by about 60-fold, but predicted values deviated from observed values by only 0.12 log units (a factor of 1.3) on average, and at worst only slightly more than a factor of 2. Again, more information on model performance is provided in the Technical Support Document and the figures here just provide some examples demonstrating the utility of this model for use in criteria.

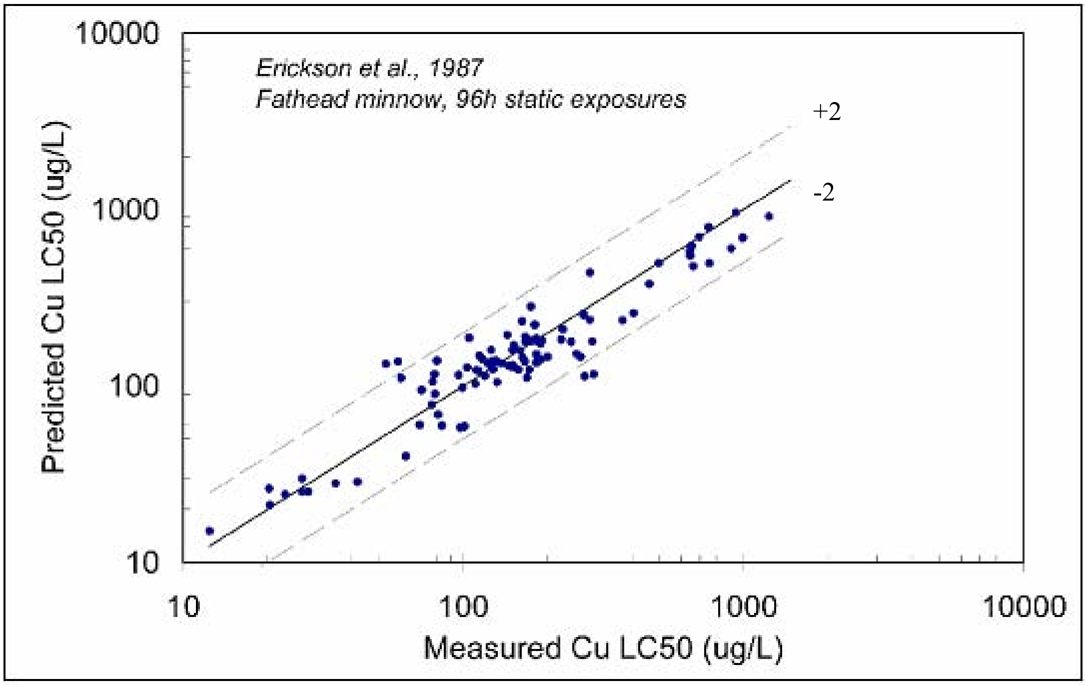


Figure 3. Comparison of Predicted and Measured Acute Copper Toxicity to *P. promelas*.

The use of the BLM to predict the bioavailability and toxicity of copper to aquatic organisms under site-specific conditions is a significant change from the previous Criterion Maximum Concentration (CMC) derivation methodology. Previous aquatic life criteria documents for copper (e.g., U.S. EPA, 1980, 1985, 1996) expressed the CMC as a function of water hardness. Now, EPA chooses to utilize the BLM to update its freshwater acute criterion because the BLM accounts for all important inorganic and organic ligand interactions of copper while also considering competitive interactions that influence binding of copper at the site of toxicity, or the "biotic ligand." The BLM's ability to incorporate metal speciation reactions and organism interactions allows prediction of metal effect levels to a variety of organisms over a wide range of water quality conditions. Accordingly, the BLM is an attractive tool for deriving water quality criteria. Application of the BLM has the potential to substantially reduce the need for site-specific modifications, such as Water Effect Ratio, to account for site-specific chemistry influences on metal toxicity.

The updated BLM-based WQC will in some cases be more stringent and in other cases less stringent than the hardness based WQC. As there is not a single WQC value to use for comparison purposes, it will only be possible to provide illustrative examples of each situation. It is the judgement of the EPA that the BLM-based WQC for Cu will provide an improved framework for evaluating a level of protection (LOP) that is consistent with the LOP that was intended by the 1985 Guidelines (i.e., a 1-in-3 year exceedance frequency that will be protective of 95% of the genera).

While the BLM is currently considered appropriate for use to derive an updated freshwater CMC for the acute WQC, further development is required before it will be suitable for use to evaluate a saltwater CMC or a Criterion Continuous Concentration (CCC) or chronic value (freshwater or saltwater WQC).

## 3.0 INCORPORATION OF THE BLM INTO CRITERIA DERIVATIONS PROCEDURES

### 3.1 *General Final Acute Value (FAV) Procedures*

Application of the acute copper BLM to the derivation of the copper FAV is analogous to procedures already described in the Guidelines for metals criteria using empirical hardness regressions. For these hardness-dependent metals criteria, LC50s at various hardness are normalized to a reference hardness using the regression slopes. The normalized LC50s for each biological species are averaged to derive Species Mean Acute Values (SMAVs) at the reference hardness. The SMAVs within each genus are then averaged to derive Genus Mean Acute Values (GMAVs) at the reference hardness. The Guidelines' procedures for estimating the fifth percentile of the GMAVs are then used to derive the FAV at the reference hardness. FAVs for other hardness can then be derived using the hardness regression slope, and these FAVs are used to calculate the Criterion Maximum Concentration (CMC) by dividing the FAV by 2.0 and the Final Chronic Values (FCV) by dividing the FAV by the Final Acute-Chronic Ratio (FACR). Following the Guidelines, the Criterion Continuous Concentration (CCC) is set to the FCV unless other data justifies a lower value.

Extending this procedure to apply the BLM simply involves normalizing the LC50s to a reference exposure condition that includes all the physicochemical exposure factors important to the BLM, not just hardness. For this normalization, the BLM provides the factors $f_C$ and $f_L$ discussed in Section 2.3, these factors serving the same purpose as the hardness regression slope described above. Each LC50 to be used in criteria derivation would be normalized to the reference exposure conditions by the equation:

$$LC50_R = LC50_A \cdot \frac{f_{C,R} \cdot f_{L,R}}{f_{C,A} \cdot f_{L,A}} \qquad \text{Equation 6}$$

where the subscript A refers to the exposure conditions for the observed LC50 and the subscript R refers to the reference exposure conditions to which the LC50 is being normalized. These normalized LC50s are then used to derive the SMAVs, GMAVs, and FAV at the reference exposure condition as described above for the hardness-corrected criteria. The BLM is then used to derive FAVs at other exposures by the equation:

$$FAV_B = FAV_R \cdot \frac{f_{C,B} \cdot f_{L,B}}{f_{C,R} \cdot f_{L,R}} \qquad \text{Equation 7}$$

where the subscript B refers to the exposure conditions for which an FAV is desired. These BLM-derived FAVs are then used to derive CMCs and CCCs following standard Guidelines procedures.

For the criteria in this document, the reference exposure conditions to which LC50s are normalized and at which the reference FAV is calculated are as follows (see also footnote f in Table 1). The water chemistry used in the normalization was based on the EPA formulation for moderately-hard reconstituted water, but any other water chemistry could have been used. In this formulation the parameters included: temperature = 20ºC, pH = 7.5, DOC = 0.5 mg/L, Ca = 14.0 mg/L, Mg = 12.1 mg/L, Na = 26.3 mg/L, K = 2.1 mg/L, $SO_4$ =81.4 mg/L, Cl = 1.90 mg/L, Alkalinity = 65.0 mg/L and S = 0.0003 mg/L.

### 3.2 *BLM Input Parameters*

For applying an LC50 to criteria derivations and for determining an FAV at exposure conditions of interest, the necessary water quality input parameters for BLM calculations are temperature, pH, dissolved organic carbon, major geochemical cations (calcium, magnesium, sodium, and potassium), dissolved inorganic carbon (DIC, the sum of dissolved carbon dioxide, carbonic acid, bicarbonate, and carbonate), and other major geochemical anions (chloride, sulfate). DIC measurements are typically not made in the environment, and an alternative input parameter is alkalinity, which can be used with pH and temperature to estimate DIC. There is some evidence that other metals such as iron and aluminum can have an effect on copper toxicity to aquatic organisms, which might be due to interactions of these metals with the biotic ligand, effects of these metals on organic carbon complexation of copper, or adsorption of copper to iron and aluminum colloids which are present in filtrates used to measure dissolved copper. These metals are not currently included in routine BLM inputs, but users are encouraged to measure dissolved iron and aluminum as part of monitoring efforts to support possible future criteria applications.

A number of fixed parameters are also used in the BLM but are not required user inputs in criteria derivations. These include the variety of equilibrium constants used in copper speciation calculations, and also the binding constants for copper and various cations to the biotic ligand. The values for these constants were obtained from work by Playle and coworkers (Playle et al., 1992, 1993a,b) and also by inference from the relationship of toxicity to various water quality characteristics. More information about these parameters can be obtained from the technical support document.

### 3.3 *Data Screening Procedures*

To use a toxicity test in the derivation of BLM-based criteria, information must be available for the various water quality parameters described in Section 3.2. This is in contrast to past metals criteria, for which the only necessary water quality parameter was hardness. Many of these parameters are not routinely measured in toxicity tests and, if measured, are not necessarily reported in the primary literature for the test, especially for older toxicity tests. However, this information might be available from supplemental sources or be estimated based on other information. Therefore, in addition to reviewing the primary sources for relevant information, additional efforts were made to obtain or estimate the necessary water quality parameters for as many of the available LC50s as possible.

A detailed description of these efforts is provided in Appendix C, Estimation of Water Chemistry Parameters for Acute Copper Toxicity Tests, and are summarized as follows. Reports of acute copper toxicity tests identified in literature searches were reviewed to identify LC50s for possible inclusion in the criteria derivation. In addition to test acceptability standards specified in the Guidelines, the current effort also required that the LC50s be based on measured copper concentrations. LC50s based on nominal concentrations have been used in previous criteria, but there are enough measured LC50s for copper that this was considered to be no longer warranted, especially considering the more advanced bioavailability assessments represented by the BLM. For the identified LC50s, the primary reports were reviewed to record all reported information on dilution and test water chemistry. Any additional references specified by the authors were also obtained and reviewed. If test waters were synthetically prepared based on specified formulas, these were used to estimate parameters as appropriate. When critical water chemistry parameters were not available, authors were contacted regarding unpublished information or to measure missing water chemistry parameters in dilution source waters. If primary or corresponding authors could not be contacted, an attempt was made to contact secondary authors or personnel from the laboratories where the studies were conducted. Where actual water chemistry data were unavailable, data from other studies with the same water source were used as surrogate values if appropriate. Absent this, the U.S. Geological Survey's National Stream Quality Accounting Network (NASQAN) and the EPA STOrage and RETrieval (STORET) were used to obtain data for ambient surface waters which were the source of water for a test. In some instances other available sources were contacted to obtained water chemistry data (e.g., city drinking water treatment personnel). The acquired data were scrutinized for representativeness and usefulness for estimating surrogate values to complete the water quality information for the dilution and/or test water that was used in the original studies. When the above sources could not be used, geochemical ion inputs were based on reported hardness measurements and regressions relationships constructed for the relationship of various ions to hardness from NASQAN data.

As with any modeling effort, the reliability of model output depends on the reliability of model inputs. Although the input data have been closely scrutinized, the reliability of the BLM-normalized LC50s are subject to the uncertainties of the estimation procedures described above. Therefore, a ranking system was devised to rank the quality of the chemical characterization of the test water. Studies with a rank of 1 contain all of the necessary parameters for BLM input based on measurements from either the test chambers or the water source. In general, studies in which the BLM input parameters were reported for test chamber samples take precedence over studies in which the parameters were reported only for the source water. A characterization ranking of 2 denotes those studies where not all parameters were measured, but reliable estimates of the requisite concentrations could be made. Similarly, a rank of 3 denotes studies in which all parameters except DOC were measured, but reliable estimates of DOC could be made. For the majority of the tests, a chemical characterization of 4+ was assigned because hardness, alkalinity, and pH were measured, and the ionic composition could be reliably estimated or calculated. A 4- was assigned to those studies conducted using standard reconstituted water in which hardness, alkalinity, or pH was either measured or referenced, and the recipe for the water is known (ASTM, 2000; U.S. EPA, 1993). The chemical characterization rank of 5 was ascribed to studies in which one of the key parameters (DOC, Ca, pH, alkalinity) was not measured, and when it could not be reliably estimated. If two or more key parameters (DOC, Ca, pH, alkalinity) were not measured and could not be reliably estimated, a study was given a chemical characterization rank of 6. Studies receiving a quality rating of greater than 4+ (i.e., higher than 4) were not used in the criteria development procedures because the estimates for some of the key input parameters were not thought to be reliable, all other studies were used.

### 3.4 *Conversion Factors*

The LC50s used in deriving previous EPA metals criteria were based on total metal concentration (measured or nominal) and the criteria were consequently for total metals concentration. EPA afterwards made the decision that metals criteria should be based on dissolved metal because it was thought to better represent the bioavailable fraction of the metal (U.S. EPA, 1993). It was thus necessary to convert the criteria to a dissolved concentration basis. However, at that time, most toxicity tests reported only total concentration, so that a procedure was necessary to estimate the likely fractions of metals that were dissolved in typical toxicity tests. Studies were therefore conducted to determine these fractions under a variety of test conditions that mimicked the conditions in the tests used to derive the metals criteria (University of Wisconsin-Superior, 1995). These tests demonstrated high fractions of dissolved copper and resulted in a conversion factor (CF) of 0.96 for converting both the CMC and CCC for copper from a total to dissolved basis (Stephan, 1995). The BLM-derived criteria developed here also uses dissolved copper as the basis for criteria, assuming a negligible bioavailability for particulate copper. The conversion factor of 0.96 was also used to convert total to dissolved copper for any toxicity test for which dissolved copper measurements were not available.

### 3.5 *Final Chronic Value (FCV) Procedures*

Because the minimum eight family data requirements for chronic toxicity data were not met in order to calculate the FCV by the fifth percentile method used for the FAV and because insufficient information was available to develop a chronic BLM, EPA derived the CCC utilizing the Acute to Chronic Ratio (ACR) approach from the Guidelines (Stephan et al., 1985). To calculate the FCV at a specific water chemistry, the FAV at that chemistry is divided by the FACR. This entails the assumption that the acute BLM reasonably approximates the bioavailability relationships for chronic toxicity. Limited data available regarding effects of water chemistry on sublethal effects and chronic lethality do show substantial effects of organic matter, alkalinity, pH, and sodium (Winner, 1985; Erickson et al., 1996 a,b) similar to those in the acute BLM used here. For hardness, apparent effects are limited and uncertain, but the use of the acute BLM does not introduce major uncertainties in this regard because the effects of hardness by itself in the acute BLM are also limited.

## 4.0 DATA SUMMARY AND CRITERIA CALCULATION

### 4.1 *Summary of Acute Toxicity to Freshwater Animals and Criteria Calculation*

The screening procedure outlined in Sec. 3.3 (high quality data = 1, low quality data > 4, e.g. 4+) identified approximately 600 acute freshwater toxicity tests with aquatic organisms and copper potentially acceptable for deriving criteria. Of these tests, approximately 100 were eliminated from the criteria derivation process because they did not report measured copper concentrations. Nearly 150 additional tests were eliminated from the calculation of the FAV because they received a quality rating of greater than 4 in the quality rating scheme described in section 3.3 described above.

Data from approximately 350 tests were used to derive normalized LC50 values, including 15 species of invertebrates, 22 species of fish, and 1 amphibian species (Table 1), representing 27 different genera. Species Mean Acute Values (SMAVs) at the reference chemistry were calculated from the normalized LC50s and Genus Mean Acute Values (GMAVs) at the normalization chemistry were calculated from the SMAVs.

SMAVs ranged from 2.37 µg/L for the most sensitive species, *Daphnia pulicaria*, to 107,860 µg/L for the least sensitive species, *Notemigonus crysoleucas*. Cladocerans were among the most sensitive species, with *D. pulicaria, D. magna*, *Ceriodaphnia dubia*, and *Scapholeberis sp.* being four out of the six most sensitive species. Invertebrates in general were more sensitive than fish, representing the 10 lowest SMAVs.

The 27 GMAVs calculated from the above-mentioned SMAVs ranged from 4.05 µg/L for *Daphnia* to 107,860 µg/L for *Notemigonus* (Table 3a). Nine of the 10 most sensitive genera were invertebrates. The salmonid genus *Oncorhynchus* was the most sensitive fish genus, with a GMAV of 29.1 µg/L and an overall GMAV ranking of 10.

The ranked GMAVs are presented in Figure 4. Pursuant to procedures used to calculate the FAV, a FAV of 4.67 µg/L was derived from the four GMAVs with cumulative probabilities closest to the 5th percentile toxicity value for all the tested genera (Table 3b). The presumption is that this

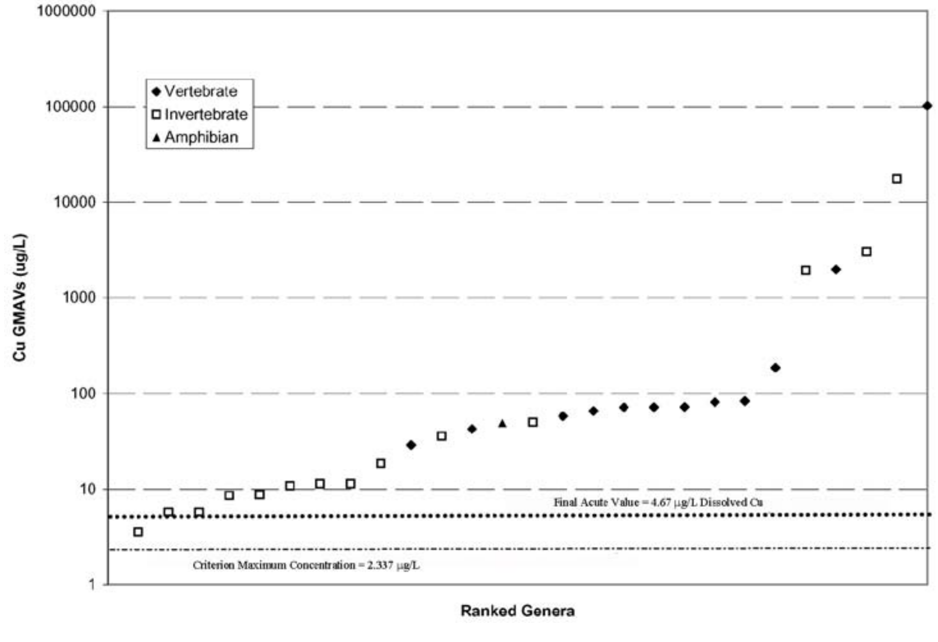


**Figure 4. Ranked Freshwater Genus Mean Acute Values (GMAVs)**

acute toxicity value represents the LC50 for an organism that is sensitive at the 5th percentile of the GMAV distribution. The CMC is the FAV divided by two. Therefore, the freshwater dissolved copper CMC for the reference chemistry presented is 2.337 µg/L.

Site-water chemistry parameters are needed to evaluate a criterion. This is analogous to the situation that previously existed for the hardness-based WQC, where a hardness concentration was necessary in order to derive a criterion. Examples of CMC calculations at various water chemistry conditions are presented in Figure 5 and Appendix G.

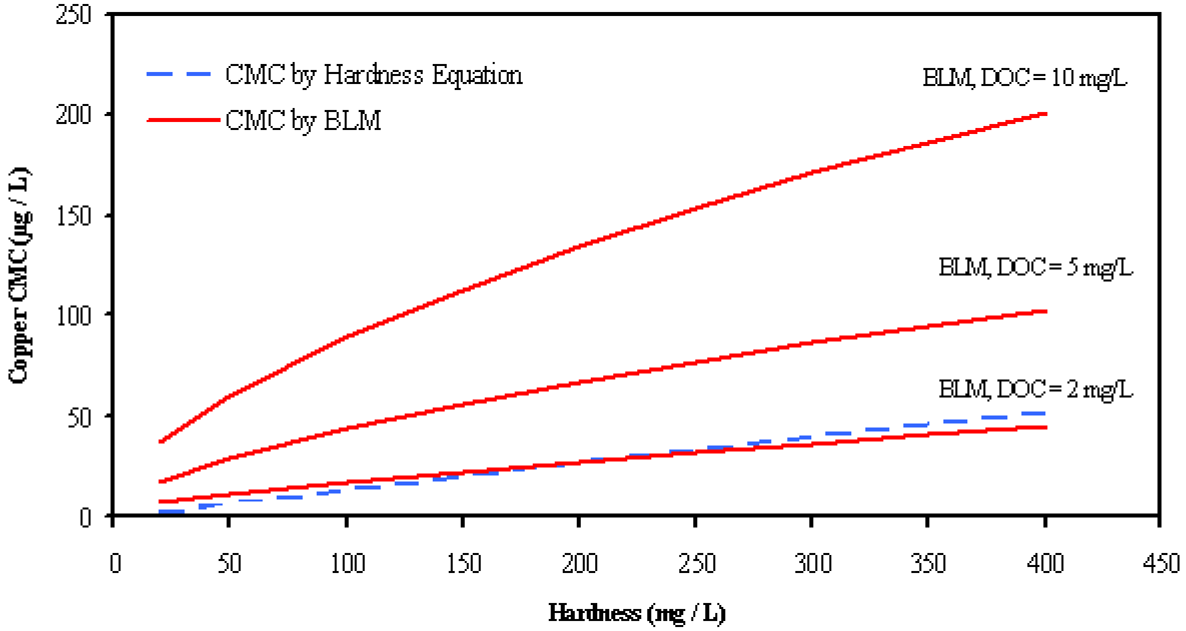


**Figure 5. Comparison of CMC calculated by BLM or Hardness Equation Alkalinity (11 - 245 mg CaCO3/L) and pH (7.3 - 8.7) Covary with Hardness**

### 4.1.1 *Comparison With Earlier Hardness-Adjusted Criteria*

EPA's earlier freshwater copper criteria recommendations were hardness-dependent values. One would expect a BLM-based criterion calculation procedure to yield the more appropriate criterion—appropriate in the sense that it accounts for the important water chemistry factors that affect toxicity, including DOC complexation, where the hardness correction does not. Application of the BLM in field situations where DOC is expected to be present at higher concentrations than those observed in laboratory studies would likely improve the performance of the BLM compared with the hardness adjustment. The reason is that the BLM would reasonably account for the typically observed increase in effect levels under such conditions, while the hardness-based approach would not (Figure 5).

As a comparison between the hardness typical of the previous copper criterion and this revised criterion using the BLM, both procedures were used to calculate criterion values for waters with a range in hardness as specified by the standard EPA recipes (U.S. EPA, 1993). The EPA formulations specify the concentration of various salts and reagents to be used in the synthesis of laboratory test waters with specific hardness values (e.g., very soft, soft, moderately hard, hard, or very hard). As the water hardness increases in these recipes, pH and alkalinity also increase. This has implications for the BLM because the bioavailability of copper would be expected to decrease with increasing pH and alkalinity due to the increasing degree of complexation of copper with hydroxides and carbonates and decreasing proton competition with the metal at both DOM and biotic ligand binding sites. The BLM criterion for these waters agrees very well with that calculated by the hardness equation used in previous copper criterion documents (Figure 5). However, alkalinity and pH change as hardness changes in the EPA recipes. The BLM prediction is taking all of these changes in water quality into account.

It is possible to use the BLM to look only at the change in predicted WQC with changes in hardness (e.g., alkalinity and pH remaining constant). The hardness equation is based on waters where changes in hardness are accompanied by changes in pH and alkalinity. However, there are many possible natural waters where changes in hardness are not accompanied by changes in pH and alkalinity (such as water draining a region rich in gypsum). In these cases, the hardness equation based criterion will still assume a response that is characteristic of waters where hardness, alkalinity, and pH co-vary, and will likely be underprotective relative to the level of protection intended by the Guidelines, in high hardness waters. Conversely, in waters where the covariation between hardness, pH, and alkalinity is greater than is typical for data in Table 1, the hardness equation based criteria may be overprotective. Appendix G shows representative water quality criteria values using both the BLM and the hardness equation approaches for waters with a range in pH, hardness, and DOC concentrations. The hardness approach does not consider pH and DOC while the BLM approach takes those water quality parameters into consideration.

## 4.2 Formulation of the CCC

### 4.2.1 *Evaluation of Chronic Toxicity Data*

In aquatic toxicity tests, chronic values are usually defined as the geometric mean of the highest concentration of a toxic substance at which no adverse effect is observed (highest no observed adverse effect concentration, or NOAEC) and the lowest concentration of the toxic substance that causes an adverse effect (lowest observed adverse effect concentration, or LOAEC). The significance of the observed effects is determined by statistical tests comparing responses of organisms exposed to low-level and control concentrations of the toxic substance against responses of organisms exposed to elevated concentrations. Analysis of variance is the most common test employed for such comparisons. This approach, however, has the disadvantage of resulting in marked differences between the magnitudes of the effects corresponding to the individual chronic values, because of variation in the power of the statistical tests used, the concentrations tested, and the size and variability of the samples used (Stephan and Rogers, 1985).

An alternative approach to calculating chronic values focuses on the use of point estimates such as from regression analysis to define the dose-response relationship. With a regression equation or probit analysis, which defines the level of adverse effects as a function of increasing concentrations of the toxic substance, it is possible to determine the concentration that causes a specific small effect, such as a 5 to 30 percent reduction in response. To make chronic values reflect a uniform level of effect, regression and probit analyses were used, where possible, both to demonstrate that a significant concentration-effect relationship was present and to estimate chronic values with a consistent level of effect. The most precise estimates of effect concentrations can generally be made for 50 percent reduction (EC50); however, such a major reduction is not necessarily consistent with criteria providing adequate protection. In contrast, a concentration that causes a low level of reduction, such as an EC5 or EC10, might not be statistically significantly different from the control treatment. As a compromise, the EC20 is used here to represent a low level of effect that is generally significantly different from the control treatment across the useful chronic datasets that are available for copper. The EC20 was also viewed as providing a level of protection similar to the geometric mean of the NOEC and LOEC. Since the EC20 is not directly dependent on the tested dilution series, similar EC20s should be expected irrespective of the tested concentrations, provided that the range of tested concentrations is appropriate.

Regression or probit analysis was utilized to evaluate a chronic dataset only in cases where the necessary data were available and the dataset met the following conditions: (1) it contained a control treatment (or low exposure data point) to anchor the curve at the low end, (2) it contained at least three concentrations, and (3) two of the data points had effect variable values below the control and above zero (i.e., "partial effects"). Control concentrations of copper were estimated in cases where no measurements were reported. These analyses were performed using the Toxicity Relationship Analysis Program software (version 1.0; U.S. EPA, Mid-Continental Ecology Division, Duluth, MN, USA). Additional detail regarding the aforementioned statistical procedures is available in the cited program.

When the data from an acceptable chronic test met the conditions for the logistic regression or probit analysis, the EC20 was the preferred chronic value. When data did not meet the conditions the chronic value was usually set to the geometric mean of the NOAEC and the LOAEC. However, when no treatment concentration was an NOAEC, the chronic value is reported as less than the lowest tested concentration.

For life-cycle, partial life-cycle, and early life stage tests, the toxicological variable used in chronic value analyses was survival, reproduction, growth, emergence, or intrinsic growth rate. If copper apparently reduced both survival and growth (weight or length), the product of variables (biomass) was analyzed, rather than analyzing the variables separately. The most sensitive of the toxicological variables was generally selected as the chronic value for the particular study.

A species-by-species discussion of each acceptable chronic test on copper evaluated for this document is presented in Appendix F. Figures that present the data and regression/probability distribution line for each of the acceptable chronic test which contained sufficient acceptable data are also provided in Appendix F.

### 4.2.2 *Calculation of Freshwater CCC*

Acceptable freshwater chronic toxicity data from early life stage tests, partial life-cycle tests, and full life-cycle tests were available for 29 tests including data for 6 invertebrate species and 10 fish species (Table 2a). The 17 chronic values for invertebrate species range from 2.83 (*D. pulex)* to 34.6 µg/L (*C. dubia*); and the 12 chronic values for the fish species range from <5 (brook trout) to 60.4 µg/L (northern pike). Of the 29 chronic tests, comparable acute values are available for 18 of the tests (Table 2c). The relationship between acute toxicity values and ACRs is presented in Figure 6. The supporting acute and chronic test values for the ACRs and the species mean ACRs are presented in Table 2c. For the 11 tests in Table 2a with chronic values both from a regression EC20 and the geometric mean of the NOAEC and LOAEC, the EC20 averaged 81% of the geometric mean, demonstrating the similar level of protection for the two approaches.

Overall, individual ACRs varied from <1 (0.55) for *C. dubia* (Oris et al., 1991) to 191.6 for the snail, *Campeloma decisum* (Arthur and Leonard, 1970). Species mean acute-chronic ratios ranged from 1.48 in saltwater for the sheepshead minnow (Hughes et al., 1989) to 171.2 in freshwater for the snail, *C. decisum*. Pursuant to the Guidelines (Stephan et al., 1985), consideration was given to calculating the FACR based on all ACRs within a factor of 10, but because there appeared to be a relationship between acute sensitivity and ACRs (Figure 6), the FACR was derived from data for species whose SMAVs were close to the FAV. The FACR of 3.22 was calculated as the geometric mean of the ACRs for sensitive freshwater species, *C. dubia, D. magna, D. pulex, O. tshawytscha*, and *O. mykiss* along with the one saltwater ACR for *C. variegatus* (Table 2b). Based on the normalization water chemistry conditions used for illustrative purposes in the document, the freshwater site specific FAV value is 4.67 µg/L, which divided by the FACR of 3.22 results in a freshwater FCV of 1.45 µg/L dissolved Cu.

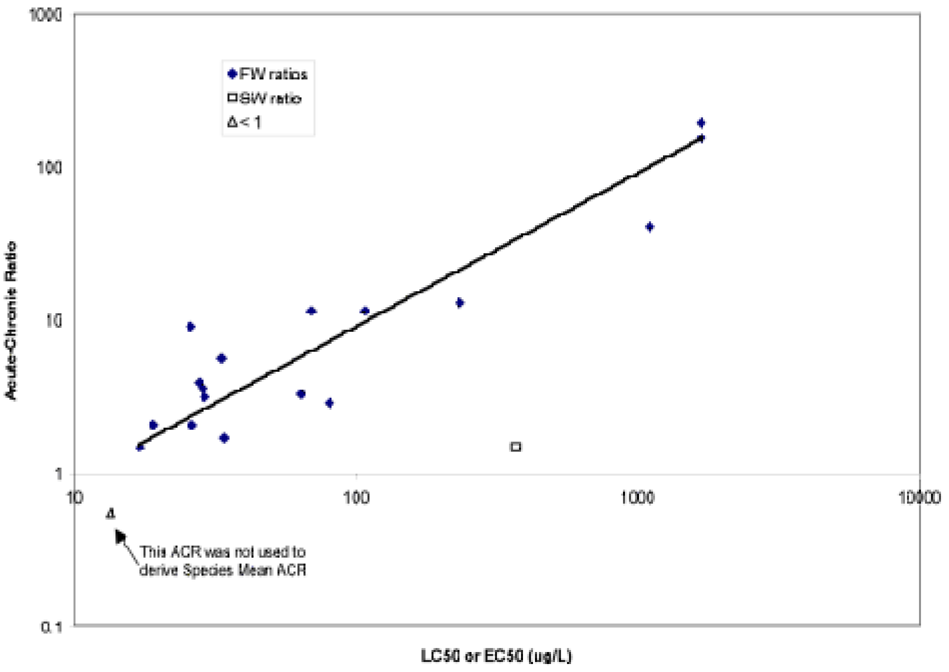


**Figure 6. Relationship Between Freshwater Acute Copper Sensitivity (LC50 or EC50) and Acute- Chronic Ratios**

## 5.0 PLANT DATA

Copper has been widely used as an algicide and herbicide for nuisance aquatic plants (McKnight et al., 1983). Although copper is known as an inhibitor of photosynthesis and plant growth, toxicity data on individual species suitable for deriving aquatic life criteria (Table 4) are not numerous.

The relationship of copper toxicity to the complexing capacity of the water or the culture medium is now widely recognized (Gächter et al., 1973; Petersen, 1982), and several studies have used algae to "assay" the copper complexing capacity of both fresh and salt waters (Allen et al., 1983; Lumsden and Florence, 1983; Rueter, 1983). It has also been shown that algae are capable of excreting complexing substances in response to copper stress (McKnight and Morel, 1979; Swallow et al., 1978; van den Berg et al., 1979). Foster (1982) and Stokes and Hutchinson (1976) have identified resistant strains and/or species of algae from copper (or other metal) impacted environments. A portion of this resistance probably results from induction of the chelate-excretion mechanism. Chelate excretion by algae may also serve as a protective mechanism for other aquatic organisms in eutrophic waters; that is, where algae are capable of maintaining free copper activities below harmful concentrations.

Copper concentrations from 1 to 8,000 µg/L have been shown to inhibit growth of various freshwater plant species. Very few of these tests, though, were accompanied by analysis of actual copper exposure concentrations. Notable exceptions are freshwater tests with green alga including *Chlamydomonas reinhardtii* (Schafer et al., 1993; Winner and Owen, 1991b), which is the only flow-through, measured test with an aquatic plant, *Chlorella vulgaris* and *Selenastrum capricornutum* (Blaylock et al., 1985). There is also a measured test with duckweed, *Lemna minor* (Taraldsen and Norberg-King, 1990).

A direct comparison between the freshwater plant data and the BLM derived criteria is difficult to make without a better understanding of the composition of the algal media used for different studies (e.g., DOC, hardness, and pH) because these factors influence the applicable criteria comparison. BLM derived criteria for certain water conditions, such as low to mid-range pH, hardness up to 100 mg/L as $CaCO_3$, and low DOC are in the range of, if not lower than, the lowest reported toxic endpoints for freshwater algal species and would therefore appear protective of plant species. In other water quality conditions BLM-derived criteria may be significantly higher (see Figure 5).

Two publications provide data for the red algae *Champia parvula* that indicate that reproduction of this species is especially sensitive to copper. The methods manual (U.S. EPA 1988) for whole effluent toxicity (WET) testing contains the results of six experiments showing nominal reproduction LOECs from 48-hr exposures to 1.0 to 2.5 µg/L copper (mean 2.0 µg/L); these tests used a mixture of 50 percent sterile seawater and 50 percent GP2 medium copper. The second study by Morrison et al. (1989) evaluated interlaboratory variation of the 48-hr WET test procedure; this six-test study gave growth EC50 values from 0.8 to 1.9 µg/L (mean 1.0 µg/L). Thus, there are actually 12 tests that provide evidence of significant reproductive impairment in *C. parvula* at nominal copper concentrations between 0.8 and 2.5 µg/L. For these studies though, the dilution water source was not identified.

One difficulty in assessing these data is the uncertainty of the copper concentration in the test solutions, primarily with respect to any background copper that might be found in the dilution water, especially with solutions compounded from sea salts or reagents. Thus, with a CCC of 1.9 µg/L dissolved copper, the significance of a 1 or 2 µg/L background copper level to a 1 to 3 µg/L nominal effect level can be considerable.

The reproduction of other macroalgae appears to be generally sensitive to copper, but not to the extent of *Champia*. Many of these other macroalgae appear to have greater ecological significance than *Champia*, several forming significant intertidal and subtidal habitats for other saltwater organisms, as well as being a major food source for grazers. Reproductive and growth effects on the other species of macroalgae sometimes appear to occur at copper concentrations between 5 and 10 µg/L (Appendix B, Other Data). Thus, most major macrophyte groups seem to be adequately protected by the CMC and CCC, but appear similar in sensitivity to some of the more sensitive groups of saltwater animals.

## 6.0 OTHER DATA

Many of the data identified for this effort are listed in Appendix B, Other Data, for various reasons, including exposure durations other than 96 hours with the same species reported in Table 1, and some exposures lasting up to 30 days. Acute values for test durations less than 96 hours are available for several species not shown in Table 1. Still, these species have approximately the same sensitivities to copper as species in the same families listed in Table 1. Reported LC50s at 200 hours for chinook salmon and rainbow trout (Chapman, 1978) differ only slightly from 96-hour LC50s reported for these same species in the same water.

A number of other acute tests in Appendix B were conducted in dilution waters that were not considered appropriate for criteria development. Brungs et al. (1976) and Geckler et al. (1976) conducted tests with many species in stream water that contained a large amount of effluent from a sewage treatment plant. Wallen et al. (1957) tested mosquitofish in a turbid pond water. Until chemical measurements that correlate well with the toxicity of copper in a wide variety of waters are identified and widely used, results of tests in unusual dilution waters, such as those in Appendix B, will not be very useful for deriving water quality criteria.

Appendix B also includes tests based on physiological effects, such as changes in appetite, blood parameters, stamina, etc. These were included in Appendix B because they could not be directly interpreted for derivation of criteria. For the reasons stated in this section above, data in Appendix B was not used for criteria derivation.

A direct comparison of a particular test result to a BLM-derived criterion is not always straightforward, particularly if complete chemical characterization of the test water is not available. Such is the case for a number of studies included in Appendix B. While there are some test results with effect concentrations below the example criteria concentrations presented in this document, these same effect concentrations could be above criteria derived for other normalization chemistries, raising the question as to what is the appropriate comparison to make. For example, Appendix B includes an EC50 for *D. Pulex* of 3.6 µg/L (Koivisto et al., 1992) at an approximate hardness of 25 mg/L (33 mg/L as $CaCO_3$). Yet, example criteria at a hardness of 25 mg/L (as $CaCO_3$) (including those in Figure 6) range from 0.23 µg/L (DOC = 0.1 mg/L) to 4.09 µg/L (DOC = 2.3 mg/L) based on the DOC concentration selected for the synthetic water recipe. The chemical composition for the Koivisto et al. (1992) study would dictate what the appropriate BLM criteria comparison should be.

Based on the expectation that many of the test results presented in Appendix B were conducted in laboratory dilution water with low levels of DOC, the appropriate comparison would be to the criteria derived from low DOC waters. Comparing many of the values in Appendix B to the example criteria presented in this document, it appears that a large proportion of Appendix B values are above these concentration levels. This is a broad generalization though and as stated previously, all important water chemistry variables that affect toxicity of copper to aquatic organisms should be considered before making these types of comparisons.

Studies not considered suitable for criteria development were placed in Appendix G, Unused Data.

## 7.0 NATIONAL CRITERIA STATEMENT

The available toxicity data, when evaluated using the procedures described in the “Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses” indicate that freshwater aquatic life should be protected if the 24-hour average and four-day average concentrations do not respectively exceed the acute and chronic criteria concentrations calculated by the Biotic Ligand Model.

A return interval of 3 years between exceedances of the criterion continues to be EPA's general recommendation. However, the resilience of ecosystems and their ability to recover differ greatly. Therefore, scientific derivation of alternative frequencies for exceeding criteria may be appropriate.

## 8.0 IMPLEMENTATION

The use of water quality criteria in designing waste treatment facilities and appropriate effluent limits involves the use of an appropriate wasteload allocation model. Although dynamic models are preferred for application of these criteria, limited data or other factors may make their use impractical, in which case one should rely on a steady-state model. EPA recommends the interim use of 1B3 or 1Q10 for criterion maximum concentration stream design flow and 4B3 or 7Q10 for the criterion continuous concentration design flow in steady-state models. These matters are discussed in more detail in the Technical Support Document for Water Quality-Based Toxics Control (U.S. EPA, 1991).

With regard to BLM-derived freshwater criteria, to develop a site-specific criterion for a stream reach, one is faced with determining what single criterion is appropriate even though a BLM criterion calculated for the event corresponding to the input water chemistry conditions will be time-variable. This is not a new problem unique to the BLM—hardness-dependent metals criteria are also time-variable values. Although the variability of hardness over time can be characterized, EPA has not provided guidance on how to calculate site-specific criteria considering this variability. Multiple input parameters for the BLM could complicate the calculation of site-specific criteria because of their combined effects on variability. Another problem arise from potential scarcity of data from small stream reaches with small dischargers. The EPA is currently exploring two approaches to fill data gaps in such situations. One potential approach is the selection of values based on geography, the second approach is based on correlations between measured parameters and missing parameter measurements. A companion document in the form of Supplementary Training Materials, addressing issues related to data requirements, implementation, permitting, and monitoring will be released via EPA's website following the publication of this criteria document.

## Table 1.  Acute Toxicity of Copper to Freshwater Animals

| Species[a] | Organism Age, Size, or Lifestage | Method[b] | Chemical[c] | Reported LC50 or EC50 (total µg/L)[d] | Reported LC50 or EC50 (Diss. µg/L)[e] | BLM Data Label | BLM Normalized LC50 or EC50 (µg/L)[f] | Species Mean Acute Value (µg/L)[g] | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Worm, | adult (mixed age) | S,M,T | N | 130 | --- | LUVA01S | 37.81 | 48.41 | Schubauer-Berigan et al. 1993 |
| *Lumbriculus variega* | adult (mixed age) | S,M,T | N | 270 | --- | LUVA02S | 55.39 | | Schubauer-Berigan et al. 1993 |
| | adult (mixed age) | S,M,T | N | 500 | --- | LUVA03S | 54.18 | | Schubauer-Berigan et al. 1993 |
| Snail, | 1.1-2.7 cm | F,M,T | S | 2000 | --- | CADE01F | 4319 | 3573 | Arthur and Leonard 1970 |
| *Campeloma* | 1.1-2.7 cm | F,M,T | S | 1400 | --- | CADE02F | 2956 | | Arthur and Leonard 1970 |
| Snail, *Juga plicifera* | adult | F,M,T | C | 15 | --- | JUPL01F | 12.31 | 12.31 | Nebeker et al. 1986b |
| Snail, *Lithoglyphus virens* | adult | F,M,T | C | 8 | --- | LIVI01F | 6.67 | 6.67 | Nebeker et al. 1986b |
| Snail, | 0.4-0.7 cm | F,M,T | S | 41 | --- | PHIN01F | 21.81 | 20.41 | Arthur and Leonard 1970 |
| *Physa integra* | 0.4-0.7 cm | F,M,T | S | 37 | --- | PHIN02F | 19.09 | | Arthur and Leonard 1970 |
| Freshwater mussel, | juvenile | S,M,T | S | 27 | --- | ACPE01S | 10.36 | 11.33 | Keller unpublished |
| *Actinonaias* | juvenile | S,M,T | S | <29 | --- | ACPE02S | 12.39 | | Keller unpublished |
| Freshwater mussel, | 1-2 d juv | S,M,T | S | 86 | --- | UTIM01S | 177.9 | 52.51 | Keller and Zam 1991 |
| *Utterbackia imbecilli* | 1-2 d juv | S,M,T | S | 199 | --- | UTIM02S | 172.3 | | Keller and Zam 1991 |
| | juvenile | S,M,T | N | 76 | --- | UTIM03S | 40.96 | | Keller unpublished |
| | juvenile | S,M,T | N | 85 | --- | UTIM04S | 43.22 | | Keller unpublished |
| | juvenile | S,M,T | N | 41 | --- | UTIM05S | 24.12 | | Keller unpublished |
| | juvenile | S,M,T | S | 79 | --- | UTIM06S | 39.04 | | Keller unpublished |
| | juvenile | S,M,T | S | 72 | --- | UTIM07S | 39.96 | | Keller unpublished |
| | juvenile | S,M,T | S | 38 | --- | UTIM08S | 28.31 | | Keller unpublished |
| Cladoceran, | <4 h | S,M,T | C | 19 | --- | CEDU01S | 10.28 | 5.93 | Carlson et al. 1986 |
| *Ceriodaphnia dubia* | <4 h | S,M,T | C | 17 | --- | CEDU02S | 9.19 | | Carlson et al. 1986 |
| | <12 h | S,M,D | --- | - | 25 | CEDU03S | 7.98 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 17 | CEDU04S | 5.25 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 30 | CEDU05S | 9.80 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 24 | CEDU06S | 7.63 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 28 | CEDU07S | 9.06 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 32 | CEDU08S | 10.56 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 23 | CEDU09S | 7.28 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 20 | CEDU10S | 6.25 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 19 | CEDU11S | 5.91 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 26 | CEDU12S | 3.10 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 21 | CEDU13S | 2.46 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 27 | CEDU14S | 3.24 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 37 | CEDU15S | 4.66 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 34 | CEDU16S | 4.22 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 67 | CEDU17S | 5.50 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 38 | CEDU18S | 2.72 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 78 | CEDU19S | 6.74 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 81 | CEDU20S | 7.10 | | Belanger et al. 1989 |
| | <12 h | S,M,D | --- | - | 28 | CEDU21S | 4.10 | | Belanger and Cherry 1990 |

## Table 1. Acute Toxicity of Copper to Freshwater Animals

| Species[a] | Organism Age, Size, or Lifestage | Method[b] | Chemical[c] | Reported LC50 or EC50 (total µg/L)[d] | Reported LC50 or EC50 (Diss. µg/L)[e] | BLM Data Label | BLM Normalized LC50 or EC50 (µg/L)[f] | Species Mean Acute Value (µg/L)[g] | Reference |
|---|---|---|---|---|---|---|---|---|---|
|  | <12 h | S,M,D | --- | - | 84 | CEDU22S | 10.74 |  | Belanger and Cherry 1990 |
|  | <12 h | S,M,T | S | 13.4 | --- | CEDU23S | 6.19 |  | Oris et al. 1991 |
|  | <24 h | R,M,T,D | S | 6.98 | 5.54 | CEDU24R | 5.03 |  | Diamond et al. 1997b |
| Cladoceran, *Daphnia magna* | 1 d | S,M,T | C | 9.1 | --- | DAMA01S | 3.42 | 6.00 | Nebeker et al. 1986a |
|  | 1 d | S,M,T | C | 11.7 | --- | DAMA02S | 4.43 |  | Nebeker et al. 1986a |
|  | <2 h | S,M,T | C | 6.6 | --- | DAMA03S | 2.50 |  | Nebeker et al. 1986a |
|  | <2 h | S,M,T | C | 9.9 | --- | DAMA04S | 3.78 |  | Nebeker et al. 1986a |
|  | 1 d | S,M,T | C | 11.7 | --- | DAMA05S | 13.46 |  | Nebeker et al. 1986a |
|  | <4 h | S,M,T | C | 6.7 | --- | DAMA06S | 8.21 |  | Nebeker et al. 1986a |
|  | 1 d | S,M,T | C | 9.1 | --- | DAMA07S | 4.40 |  | Nebeker et al. 1986a |
|  | <2 h | S,M,T | C | 5.2 | --- | DAMA08S | 2.16 |  | Nebeker et al. 1986a |
|  | <24 h | S,M,T | S | 41.2 | --- | DAMA09S | 21.55 |  | Baird et al. 1991 |
|  | <24 h | S,M,T | S | 10.5 | --- | DAMA10S | 5.63 |  | Baird et al. 1991 |
|  | <24 h | S,M,T | S | 20.6 | --- | DAMA11S | 11.31 |  | Baird et al. 1991 |
|  | <24 h | S,M,T | S | 17.3 | --- | DAMA12S | 9.48 |  | Baird et al. 1991 |
|  | <24 h | S,M,T | S | 70.7 | --- | DAMA13S | 33.58 |  | Baird et al. 1991 |
|  | <24 h | S,M,T | S | 31.3 | --- | DAMA14S | 16.90 |  | Baird et al. 1991 |
|  | <24 h | S,M,I | S | 7.1 | --- | DAMA15S | 2.67 |  | Meador 1991 |
|  | <24 h | S,M,I | S | 16.4 | --- | DAMA16S | 4.26 |  | Meador 1991 |
|  | <24 h | S,M,I | S | 39.9 | --- | DAMA17S | 5.18 |  | Meador 1991 |
|  | <24 h | S,M,I | S | 18.7 | --- | DAMA18S | 3.39 |  | Meador 1991 |
|  | <24 h | S,M,I | S | 18.9 | --- | DAMA19S | 1.99 |  | Meador 1991 |
|  | <24 h | S,M,I | S | 39.7 | --- | DAMA20S | 3.04 |  | Meador 1991 |
|  | <24 h | S,M,I | S | 46 | --- | DAMA21S | 8.93 |  | Meador 1991 |
|  | <24 h | S,M,I | S | 71.9 | --- | DAMA22S | 9.97 |  | Meador 1991 |
|  | <24 h | S,M,I | S | 57.2 | --- | DAMA23S | 5.76 |  | Meador 1991 |
|  | <24 h | S,M,I | S | 67.8 | --- | DAMA24S | 4.16 |  | Meador 1991 |
|  | <24 h | S,M,T | C | 26 | --- | DAMA25S | 10.34 |  | Chapman et al. Manuscript |
|  | <24 h | S,M,T | C | 30 | --- | DAMA26S | 9.04 |  | Chapman et al. Manuscript |
|  | <24 h | S,M,T | C | 38 | --- | DAMA27S | 9.84 |  | Chapman et al. Manuscript |
|  | <24 h | S,M,T | C | 69 | --- | DAMA28S | 12.31 |  | Chapman et al. Manuscript |
|  | <24 h | S,M,T,D | S | 4.8 | --- | DAMA29S | 1.22 |  | Long's MS Thesis |
|  | <24 h | S,M,T,D | S | 7.4 | --- | DAMA30S | 16.29 |  | Long's MS Thesis |
|  | <24 h | S,M,T,D | S | 6.5 | --- | DAMA31S | 2.11 |  | Long's MS Thesis |
| Cladoceran, *Daphnia pulicaria* | --- | S,M,T | S | 11.4 | --- | DAPC01S | 1.63 | 2.73 | Lind et al. Manuscript (1978) |
|  | --- | S,M,T | S | 9.06 | --- | DAPC02S | 1.04 |  | Lind et al. Manuscript (1978) |
|  | --- | S,M,T | S | 7.24 | --- | DAPC03S | 0.88 |  | Lind et al. Manuscript (1978) |
|  | --- | S,M,T | S | 10.8 | --- | DAPC04S | 1.13 |  | Lind et al. Manuscript (1978) |
|  | --- | S,M,T | S | 55.4 | --- | DAPC05S | 8.81 |  | Lind et al. Manuscript (1978) |
|  | --- | S,M,T | S | 55.3 | --- | DAPC06S | 6.03 |  | Lind et al. Manuscript (1978) |
|  | --- | S,M,T | S | 53.3 | --- | DAPC07S | 4.12 |  | Lind et al. Manuscript (1978) |
|  | --- | S,M,T | S | 97.2 | --- | DAPC08S | 3.94 |  | Lind et al. Manuscript (1978) |

## Table 1. Acute Toxicity of Copper to Freshwater Animals

| Species[a] | Organism Age, Size, or Lifestage | Method[b] | Chemical[c] | Reported LC50 or EC50 (total µg/L)[d] | Reported LC50 or EC50 (Diss. µg/L)[e] | BLM Data Label | BLM Normalized LC50 or EC50 (µg/L)[f] | Species Mean Acute Value (µg/L)[g] | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | --- | S,M,T | S | 199 | --- | DAPC09S | 3.01 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 213 | --- | DAPC10S | 7.63 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 165 | --- | DAPC11S | 5.78 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 35.5 | --- | DAPC12S | 1.83 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 78.8 | --- | DAPC13S | 2.36 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 113 | --- | DAPC14S | 1.06 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 76.4 | --- | DAPC15S | 2.36 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 84.7 | --- | DAPC16S | 6.62 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 184 | --- | DAPC17S | 7.14 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 9.3 | --- | DAPC18S | 1.11 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 17.8 | --- | DAPC19S | 2.11 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 23.7 | --- | DAPC20S | 2.67 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 27.3 | --- | DAPC21S | 2.77 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 25.2 | --- | DAPC22S | 2.81 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 25.1 | --- | DAPC23S | 2.60 | | Lind et al. Manuscript (1978) |
| | --- | S,M,T | S | 25.1 | --- | DAPC24S | 2.31 | | Lind et al. Manuscript (1978) |
| Cladoceran, *Scapholeberis sp.* | adult | S,M,T | C | 18 | --- | SCSP01S | 9.73 | 9.73 | Carlson et al. 1986 |
| Amphipod, *Gammarus* | 1-3 d | F,M,T | S | 22 | --- | GAPS01F | 10.39 | 9.60 | Arthur and Leonard 1970 |
| | 1-3 d | F,M,T | S | 19 | --- | GAPS02F | 8.86 | | Arthur and Leonard 1970 |
| Amphipod, *Hyalella azteca* | 7-14 d | S,M,T | N | 17 | --- | HYAZ01S | 12.19 | 12.07 | Schubauer-Berigan et al. 1993 |
| | 7-14 d | S,M,T | N | 24 | --- | HYAZ02S | 9.96 | | Schubauer-Berigan et al. 1993 |
| | 7-14 d | S,M,T | N | 87 | --- | HYAZ03S | 15.77 | | Schubauer-Berigan et al. 1993 |
| | <7 d | S,M,T | S | 24.3 | --- | HYAZ04S | 8.26 | | Welsh 1996 |
| | <7 d | S,M,T | S | 23.8 | --- | HYAZ05S | 8.09 | | Welsh 1996 |
| | <7 d | S,M,T | S | 8.2 | --- | HYAZ06S | 15.49 | | Welsh 1996 |
| | <7 d | S,M,T | S | 10 | --- | HYAZ07S | 18.80 | | Welsh 1996 |
| Stonefly, *Acroneuria lycorias* | --- | S,M,T | S | 8300 | --- | ACLY01S | 20636 | 20636 | Warnick and Bell 1969 |
| Midge, *Chironomus* | 4th instar | S,M,T | S | 739 | --- | CHDE01S | 1987 | 1987 | Kosalwat and Knight 1987 |
| Shovelnose sturgeon, *Scaphirhynchus* | fry, 6.01 cm, 0.719 g | S,M,T | S | 160 | --- | SCPL01S | 69.63 | 69.63 | Dwyer et al. 1999 |
| Apache trout, *Oncorhynchus* | larval, 0.38 g | S,M,T | S | 70 | --- | ONAP01S | 32.54 | 32.54 | Dwyer et al. 1995 |
| Lahontan cutthroat *Oncorhynchus clarki henshawi* | larval, 0.34 g | S,M,T | S | 80 | --- | ONCL01S | 34.26 | 32.97 | Dwyer et al. 1995 |
| | larval, 0.57 g | S,M,T | S | 60 | --- | ONCL02S | 24.73 | | Dwyer et al. 1995 |

## Table 1.  Acute Toxicity of Copper to Freshwater Animals

| Species[a] | Organism Age, Size, or Lifestage | Method[b] | Chemical[c] | Reported LC50 or EC50 (total µg/L)[d] | Reported LC50 or EC50 (Diss. µg/L)[e] | BLM Data Label | BLM Normalized LC50 or EC50 (µg/L)[f] | Species Mean Acute Value (µg/L)[g] | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Cutthroat trout, | 7.4 cm, 4.2 g | F,M,T,D | C | 398.91 | 367 | ONCL03F | 67.30 |  | Chakoumakos et al. 1979 |
| *Oncorhynchus clarki* | 6.9 cm, 3.2 g | F,M,T,D | C | 197.87 | 186 | ONCL04F | 44.91 |  | Chakoumakos et al. 1979 |
|  | 8.8 cm, 9.7 g | F,M,T,D | C | 41.35 | 36.8 | ONCL05F | 21.87 |  | Chakoumakos et al. 1979 |
|  | 8.1 cm, 4.4 g | F,M,T,D | C | 282.93 | 232 | ONCL06F | 51.94 |  | Chakoumakos et al. 1979 |
|  | 6.8 cm, 2.7 g | F,M,T,D | C | 186.21 | 162 | ONCL07F | 111.3 |  | Chakoumakos et al. 1979 |
|  | 7.0 cm, 3.2 g | F,M,T,D | C | 85.58 | 73.6 | ONCL08F | 39.53 |  | Chakoumakos et al. 1979 |
|  | 8.5 cm, 5.2 g | F,M,T,D | C | 116.67 | 91 | ONCL09F | 19.63 |  | Chakoumakos et al. 1979 |
|  | 7.7 cm, 4.4 g | F,M,T,D | C | 56.20 | 44.4 | ONCL10F | 18.81 |  | Chakoumakos et al. 1979 |
|  | 8.9 cm, 5.7 g | F,M,T,D | C | 21.22 | 15.7 | ONCL11F | 10.60 |  | Chakoumakos et al. 1979 |
| Pink salmon, | alevin (newly hatched | F,M,T | S | 143 | --- | ONGO01F | 41.65 | 40.13 | Servizi and Martens 1978 |
| *Oncorhynchus gorbu* | alevin | F,M,T | S | 87 | --- | ONGO02F | 19.70 |  | Servizi and Martens 1978 |
|  | fry | F,M,T | S | 199 | --- | ONGO03F | 78.76 |  | Servizi and Martens 1978 |
| Coho salmon, | 6 g | R,M,T,I | --- | 164 | --- | ONKI01R | 106.09 | 22.93 | Buckley 1983 |
| *Oncorhynchus kisutc* | parr | F,M,T | C | 33 | --- | ONKI02F | 20.94 |  | Chapman 1975 |
|  | adult, 2.7 kg | F,M,T | C | 46 | --- | ONKI03F | 32.66 |  | Chapman and Stevens 1978 |
|  | fry | F,M,T,D,I | --- | 61 | 49 | ONKI04F | 12.67 |  | Mudge et al. 1993 |
|  | smolt | F,M,T,D,I | --- | 63 | 51 | ONKI05F | 13.19 |  | Mudge et al. 1993 |
|  | fry | F,M,T,D,I | --- | 86 | 58 | ONKI06F | 11.95 |  | Mudge et al. 1993 |
|  | parr | F,M,T,D,I | --- | 103 | 78 | ONKI07F | 22.98 |  | Mudge et al. 1993 |
| Rainbow trout, | larval, 0.67 g | S,M,T | S | 110 | --- | ONMY01S | 41.64 | 22.19 | Dwyer et al. 1995 |
| *Oncorhynchus mykis* | larval, 0.48 g | S,M,T | S | 50 | --- | ONMY02S | 25.26 |  | Dwyer et al. 1995 |
|  | larval, 0.50 g | S,M,T | S | 60 | --- | ONMY03S | 29.46 |  | Dwyer et al. 1995 |
|  | swim-up, 0.25 g | R,M,T,D | C | 46.7 | 40 | ONMY04R | 10.90 |  | Cacela et al. 1996 |
|  | swim-up, 0.25 g | R,M,T,D | C | 24.2 | 19 | ONMY05R | 9.04 |  | Cacela et al. 1996 |
|  | swim-up, 0.20-0.24 g | R,M,T,D | C | 0 | 3.4 | ONMY06R | 5.02 |  | Welsh et al. 2000 |
|  | swim-up, 0.20-0.24 g | R,M,T,D | C | 0 | 8.1 | ONMY07R | 11.97 |  | Welsh et al. 2000 |
|  | swim-up, 0.20-0.24 g | R,M,T,D | C | 0 | 17.2 | ONMY08R | 13.80 |  | Welsh et al. 2000 |
|  | swim-up, 0.20-0.24 g | R,M,T,D | C | 0 | 32 | ONMY09R | 23.84 |  | Welsh et al. 2000 |
|  | alevin | F,M,T | C | 28 | --- | ONMY10F | 20.30 |  | Chapman 1975, 1978 |
|  | swim-up, 0.17 g | F,M,T | C | 17 | --- | ONMY11F | 12.54 |  | Chapman 1975, 1978 |
|  | parr, 8.6 cm, 6.96 g | F,M,T | C | 18 | --- | ONMY12F | 9.87 |  | Chapman 1975, 1978 |
|  | smolt, 18.8 cm, 68.19 | F,M,T | C | 29 | --- | ONMY13F | 22.48 |  | Chapman 1975, 1978 |
|  | 1 g | F,M,T,D | C | - | 169 | ONMY14F | 23.41 |  | Chakoumakos et al. 1979 |
|  | 4.9 cm | F,M,T,D | C | - | 85.3 | ONMY15F | 10.20 |  | Chakoumakos et al. 1979 |
|  | 6.0 cm, 2.1 g | F,M,T,D | C | - | 83.3 | ONMY16F | 9.93 |  | Chakoumakos et al. 1979 |
|  | 6.1 cm, 2.5 g | F,M,T,D | C | - | 103 | ONMY17F | 12.71 |  | Chakoumakos et al. 1979 |
|  | 2.6 g | F,M,T,D | C | - | 274 | ONMY18F | 44.54 |  | Chakoumakos et al. 1979 |
|  | 4.3 g | F,M,T,D | C | - | 128 | ONMY19F | 16.51 |  | Chakoumakos et al. 1979 |
|  | 9.2 cm, 9.4 g | F,M,T,D | C | - | 221 | ONMY20F | 33.33 |  | Chakoumakos et al. 1979 |
|  | 9.9 cm, 11.5 g | F,M,T,D | C | - | 165 | ONMY21F | 22.70 |  | Chakoumakos et al. 1979 |
|  | 11.8 cm, 18.7 g | F,M,T,D | C | - | 197 | ONMY22F | 28.60 |  | Chakoumakos et al. 1979 |
|  | 13.5 cm, 24.9 g | F,M,T,D | C | - | 514 | ONMY23F | 99.97 |  | Chakoumakos et al. 1979 |

## Table 1. Acute Toxicity of Copper to Freshwater Animals

| Species[a] | Organism Age, Size, or Lifestage | Method[b] | Chemical[c] | Reported LC50 or EC50 (total µg/L)[d] | Reported LC50 or EC50 (Diss. µg/L)[e] | BLM Data Label | BLM Normalized LC50 or EC50 (µg/L)[f] | Species Mean Acute Value (µg/L)[g] | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | 13.4 cm, 25.6 g | F,M,T,D | C | - | 243 | ONMY24F | 37.88 | | Chakoumakos et al. 1979 |
| | 6.7 cm, 2.65 g | F,M,T | C | 2.8 | --- | ONMY25F | 7.00 | | Cusimano et al. 1986 |
| | parr | F,M,T,D,I | --- | 90 | 68 | ONMY26F | 19.73 | | Mudge et al. 1993 |
| | swim-up, 0.29 g | F,M,T,D | C | 19.6 | 18 | ONMY27F | 8.10 | | Cacela et al. 1996 |
| | swim-up, 0.25 g | F,M,T,D | C | 12.9 | 12 | ONMY28F | 32.15 | | Cacela et al. 1996 |
| | swim-up, 0.23 g | F,M,T,D | C | 5.9 | 5.7 | ONMY29F | 24.80 | | Cacela et al. 1996 |
| | swim-up, 0.23 g | F,M,T,D | C | 37.8 | 35 | ONMY30F | 16.16 | | Cacela et al. 1996 |
| | swim-up, 0.26 g | F,M,T,D | C | 25.1 | 18 | ONMY31F | 37.66 | | Cacela et al. 1996 |
| | swim-up, 0.23 g | F,M,T,D | C | 17.2 | 17 | ONMY32F | 24.19 | | Cacela et al. 1996 |
| | 0.64 g, 4.1 cm | F,M,T,D | C | 101 | --- | ONMY33F | 39.73 | | Hansen et al. 2000 |
| | 0.35 g, 3.4 cm | F,M,T,D | C | 308 | --- | ONMY34F | 85.83 | | Hansen et al. 2000 |
| | 0.68 g, 4.2 cm | F,M,T,D | C | 93 | --- | ONMY35F | 95.9 | | Hansen et al. 2000 |
| | 0.43 g, 3.7 cm | F,M,T,D | C | 35.9 | --- | ONMY36F | 50.83 | | Hansen et al. 2000 |
| | 0.29 g, 3.4 cm | F,M,T,D | C | 54.4 | --- | ONMY37F | 47.69 | | Hansen et al. 2000 |
| Sockeye salmon,<br>*Oncorhynchus nerka* | alevin (newly hatched | F,M,T | S | 190 | --- | ONNE01F | 71.73 | 54.82 | Servizi and Martens 1978 |
| | alevin | F,M,T | S | 200 | --- | ONNE02F | 79.52 | | Servizi and Martens 1978 |
| | alevin | F,M,T | S | 100 | --- | ONNE03F | 23.74 | | Servizi and Martens 1978 |
| | alevin | F,M,T | S | 110 | --- | ONNE04F | 27.22 | | Servizi and Martens 1978 |
| | alevin | F,M,T | S | 130 | --- | ONNE05F | 35.36 | | Servizi and Martens 1978 |
| | fry | F,M,T | S | 150 | --- | ONNE06F | 45.37 | | Servizi and Martens 1978 |
| | smolt, 5.5 g | F,M,T | S | 210 | --- | ONNE07F | 87.77 | | Servizi and Martens 1978 |
| | smolt, 5.5 g | F,M,T | S | 170 | --- | ONNE08F | 57.53 | | Servizi and Martens 1978 |
| | smolt, 5.5 g | F,M,T | S | 190 | --- | ONNE09F | 71.73 | | Servizi and Martens 1978 |
| | smolt, 4,8 g | F,M,T | S | 240 | --- | ONNE10F | 114.4 | | Servizi and Martens 1978 |
| Chinook salmon,<br>*Oncorhynchus tshaw* | alevin, 0.05 g | F,M,T | C | 26 | --- | ONTS01F | 14.48 | 25.02 | Chapman 1975, 1978 |
| | swim-up, 0.23 g | F,M,T | C | 19 | --- | ONTS02F | 10.44 | | Chapman 1975, 1978 |
| | parr, 9.6 cm, 11.58 g | F,M,T | C | 38 | --- | ONTS03F | 28.30 | | Chapman 1975, 1978 |
| | smolt, 14.4 cm, 32.46 | F,M,T | C | 26 | --- | ONTS04F | 20.09 | | Chapman 1975, 1978 |
| | 3 mo, 1.35 g | F,M,T,I | C | 10.2 | --- | ONTS05F | 19.41 | | Chapman and McCrady 1977 |
| | 3 mo, 1.35 g | F,M,T,I | C | 24.1 | --- | ONTS06F | 30.91 | | Chapman and McCrady 1977 |
| | 3 mo, 1.35 g | F,M,T,I | C | 82.5 | --- | ONTS07F | 32.74 | | Chapman and McCrady 1977 |
| | 3 mo, 1.35 g | F,M,T,I | C | 128.4 | --- | ONTS08F | 20.66 | | Chapman and McCrady 1977 |
| | swim-up, 0.36-0.45 g | F,M,T,D | C | 0 | 7.4 | ONTS09F | 36.49 | | Welsh et al. 2000 |
| | swim-up, 0.36-0.45 g | F,M,T,D | C | 0 | 12.5 | ONTS10F | 30.85 | | Welsh et al. 2000 |
| | swim-up, 0.36-0.45 g | F,M,T,D | C | 0 | 14.3 | ONTS11F | 31.49 | | Welsh et al. 2000 |
| | swim-up, 0.36-0.45 g | F,M,T,D | C | 0 | 18.3 | ONTS12F | 48.56 | | Welsh et al. 2000 |

## Table 1. Acute Toxicity of Copper to Freshwater Animals

| Species[a] | Organism Age, Size, or Lifestage | Method[b] | Chemical[c] | Reported LC50 or EC50 (total µg/L)[d] | Reported LC50 or EC50 (Diss. µg/L)[e] | BLM Data Label | BLM Normalized LC50 or EC50 (µg/L)[f] | Species Mean Acute Value (µg/L)[g] | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Bull trout,<br>*Salvelinus confluent* | 0.130 g, 2.6 cm | F,M,T,D | C | 228 | --- | SACO01F | 69.70 | 68.31 | Hansen et al. 2000 |
| | 0.555 g, 4.0 cm | F,M,T,D | C | 207 | --- | SACO02F | 63.62 | | Hansen et al. 2000 |
| | 0.774 g, 4.5 cm | F,M,T,D | C | 66.6 | --- | SACO03F | 74.18 | | Hansen et al. 2000 |
| | 1.520 g, 5.6 cm | F,M,T,D | C | 50 | --- | SACO04F | 63.60 | | Hansen et al. 2000 |
| | 1.160 g, 5.2 cm | F,M,T,D | C | 89 | --- | SACO05F | 71.11 | | Hansen et al. 2000 |
| Chiselmouth,<br>*Acrocheilus* | 4.6 cm, 1.25 g | F,M,T | C | 143 | --- | ACAL01F | 216.3 | 216.3 | Andros and Garton 1980 |
| Bonytail chub,<br>*Gila elegans* | larval, 0.29 g | S,M,T | S | 200 | --- | GIEL01S | 63.22 | 63.22 | Dwyer et al. 1995 |
| Golden shiner,<br>*Notemigonus crysoleucas* | --- | F,M,T | C | 84600 | --- | NOCR01F | 107860 | 107860 | Hartwell et al. 1989 |
| Fathead minnow,<br>*Pimephales promela* | adult, 40 mm | S,M,T | S | 310 | --- | PIPR01S | 266.3 | 69.63 | Birge et al. 1983 |
| | adult, 40 mm | S,M,T | S | 120 | --- | PIPR02S | 105.61 | | Birge et al. 1983 |
| | adult, 40 mm | S,M,T | S | 390 | --- | PIPR03S | 207.3 | | Birge et al. 1983; Benson & Birge |
| | --- | S,M,T | C | 55 | --- | PIPR04S | 38.08 | | Carlson et al. 1986 |
| | --- | S,M,T | C | 85 | --- | PIPR05S | 70.71 | | Carlson et al. 1986 |
| | <24 h | S,M,T | N | 15 | --- | PIPR06S | 11.23 | | Schubauer-Berigan et al. 1993 |
| | <24 h | S,M,T | N | 44 | --- | PIPR07S | 18.03 | | Schubauer-Berigan et al. 1993 |
| | <24 h | S,M,T | N | >200 | --- | PIPR08S | 24.38 | | Schubauer-Berigan et al. 1993 |
| | <24 h, 0.68 mg | S,M,T | S | 4.82 | --- | PIPR09S | 8.87 | | Welsh et al. 1993 |
| | <24 h, 0.68 mg | S,M,T | S | 8.2 | --- | PIPR10S | 16.72 | | Welsh et al. 1993 |
| | <24 h, 0.68 mg | S,M,T | S | 31.57 | --- | PIPR11S | 25.15 | | Welsh et al. 1993 |
| | <24 h, 0.68 mg | S,M,T | S | 21.06 | --- | PIPR12S | 17.67 | | Welsh et al. 1993 |
| | <24 h, 0.68 mg | S,M,T | S | 35.97 | --- | PIPR13S | 21.24 | | Welsh et al. 1993 |
| | <24 h, 0.68 mg | S,M,T | S | 59.83 | --- | PIPR14S | 16.64 | | Welsh et al. 1993 |
| | <24 h, 0.68 mg | S,M,T | S | 4.83 | --- | PIPR15S | 5.92 | | Welsh et al. 1993 |
| | <24 h, 0.68 mg | S,M,T | S | 70.28 | --- | PIPR16S | 13.34 | | Welsh et al. 1993 |
| | <24 h, 0.68 mg | S,M,T | S | 83.59 | --- | PIPR17S | 8.22 | | Welsh et al. 1993 |
| | <24 h, 0.68 mg | S,M,T | S | 182 | --- | PIPR18S | 13.91 | | Welsh et al. 1993 |
| | larval, 0.32 g | S,M,T | S | 290 | --- | PIPR19S | 73.92 | | Dwyer et al. 1995 |
| | larval, 0.56 g | S,M,T | S | 630 | --- | PIPR20S | 157.9 | | Dwyer et al. 1995 |
| | larval, 0.45 g | S,M,T | S | 400 | --- | PIPR21S | 103.2 | | Dwyer et al. 1995 |
| | larval, 0.39 g | S,M,T | S | 390 | --- | PIPR22S | 161.7 | | Dwyer et al. 1995 |
| | 3.2-5.5 cm, 0.42-3.23 | S,M,T | S | 450 | --- | PIPR23S | 152.9 | | Richards and Beitinger 1995 |
| | 2.8-5.1 cm, 0.30-2.38 | S,M,T | S | 297 | --- | PIPR24S | 77.75 | | Richards and Beitinger 1995 |
| | 1.9-4.6 cm, 0.13-1.55 | S,M,T | S | 311 | --- | PIPR25S | 67.56 | | Richards and Beitinger 1995 |
| | 3.0-4.8 cm, 0.23-1.36 | S,M,T | S | 513 | --- | PIPR26S | 76.36 | | Richards and Beitinger 1995 |
| | <24 h | S,M,T,D | S | 62.23 | 53.96 | PIPR27S | 25.70 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 190.5 | 165.18 | PIPR28S | 87.89 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 68.58 | 59.46 | PIPR29S | 28.59 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 168.91 | 146.46 | PIPR30S | 89.18 | | Erickson et al. 1996a,b |

## Table 1.  Acute Toxicity of Copper to Freshwater Animals

| Species[a] | Organism Age, Size, or Lifestage | Method[b] | Chemical[c] | Reported LC50 or EC50 (total µg/L)[d] | Reported LC50 or EC50 (Diss. µg/L)[e] | BLM Data Label | BLM Normalized LC50 or EC50 (µg/L)[f] | Species Mean Acute Value (µg/L)[g] | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | <24 h | S,M,T,D | S | 94.62 | 82.04 | PIPR31S | 49.27 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 143.51 | 124.43 | PIPR32S | 104.90 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 120.65 | 103.76 | PIPR33S | 86.54 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 196.85 | 167.32 | PIPR34S | 122.0 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 133.35 | 120.02 | PIPR35S | 75.0 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 184.15 | 169.42 | PIPR36S | 122.2 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 304.8 | 268.22 | PIPR37S | 78.5 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 292.1 | 242.44 | PIPR38S | 201.5 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 133.35 | 113.35 | PIPR39S | 100.75 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 92.71 | 77.88 | PIPR40S | 72.95 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 152.4 | 128.02 | PIPR41S | 112.9 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 177.8 | 151.13 | PIPR42S | 136.3 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 203.2 | 166.62 | PIPR43S | 136.0 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 190.5 | 163.83 | PIPR44S | 147.7 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 196.85 | 157.48 | PIPR45S | 125.9 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 234.95 | 199.71 | PIPR46S | 157.4 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 146.05 | 128.52 | PIPR47S | 127.8 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 171.45 | 150.88 | PIPR48S | 153.9 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 152.4 | 131.06 | PIPR49S | 114.57 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 184.15 | 160.21 | PIPR50S | 131.3 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 203.2 | 182.88 | PIPR51S | 130.9 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 203.2 | 180.85 | PIPR52S | 105.76 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 203.2 | 176.78 | PIPR53S | 128.8 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 222.25 | 188.91 | PIPR54S | 122.1 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 146.05 | 125.60 | PIPR55S | 111.87 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 139.7 | 117.35 | PIPR56S | 85.45 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 139.7 | 114.55 | PIPR57S | 83.10 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 152.4 | 126.49 | PIPR58S | 85.82 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 203.2 | 172.72 | PIPR59S | 110.0 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 196.85 | 167.32 | PIPR60S | 106.46 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 266.7 | 226.70 | PIPR61S | 133.4 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 99.06 | 84.20 | PIPR62S | 138.0 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 111.13 | 97.79 | PIPR63S | 165.8 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 78.74 | 70.08 | PIPR64S | 114.8 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 92.71 | 81.58 | PIPR65S | 121.5 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 85.09 | 77.43 | PIPR66S | 106.69 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 123.19 | 110.87 | PIPR67S | 124.7 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 165.1 | 151.89 | PIPR68S | 114.24 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 190.5 | 175.26 | PIPR69S | 89.93 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 165.1 | 145.29 | PIPR70S | 140.2 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 127 | 111.76 | PIPR71S | 100.16 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 92.08 | 79.18 | PIPR72S | 58.74 | | Erickson et al. 1996a,b |

### Table 1. Acute Toxicity of Copper to Freshwater Animals

| Species[a] | Organism Age, Size, or Lifestage | Method[b] | Chemical[c] | Reported LC50 or EC50 (total µg/L)[d] | Reported LC50 or EC50 (Diss. µg/L)[e] | BLM Data Label | BLM Normalized LC50 or EC50 (µg/L)[f] | Species Mean Acute Value (µg/L)[g] | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | <24 h | S,M,T,D | S | 66.68 | 60.01 | PIPR73S | 37.67 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 393.70 | 370.08 | PIPR74S | 163.3 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 317.50 | 292.10 | PIPR75S | 252.2 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 107.95 | 101.47 | PIPR76S | 169.6 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 67.95 | 62.51 | PIPR77S | 146.5 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 45.72 | 42.06 | PIPR78S | 126.3 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 177.80 | 172.47 | PIPR79S | 197.6 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 13.97 | 12.43 | PIPR80S | 28.13 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 304.80 | 271.27 | PIPR81S | 149.2 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 71.12 | 71.12 | PIPR82S | 105.76 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 83.82 | 79.63 | PIPR83S | 108.41 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 104.78 | 99.54 | PIPR84S | 114.7 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 139.70 | 132.72 | PIPR85S | 137.8 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 152.40 | 137.16 | PIPR86S | 114.8 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 260.35 | 182.25 | PIPR87S | 114.8 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 488.95 | 268.92 | PIPR88S | 122.1 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 203.20 | 188.98 | PIPR89S | 147.5 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 704.85 | 662.56 | PIPR90S | 185.0 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 952.50 | 904.88 | PIPR91S | 197.1 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 1244.60 | 995.68 | PIPR92S | 188.3 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 1485.90 | 891.54 | PIPR93S | 135.5 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 781.05 | 757.62 | PIPR94S | 181.4 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 476.25 | 404.81 | PIPR95S | 172.5 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 273.05 | 262.13 | PIPR96S | 191.4 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 22.23 | 20.45 | PIPR97S | 59.14 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 24.13 | 23.16 | PIPR98S | 64.08 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 36.83 | 34.99 | PIPR99S | 97.49 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 27.94 | 27.94 | PIPR100S | 78.99 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 26.67 | 26.67 | PIPR101S | 72.86 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 20.32 | 20.32 | PIPR102S | 50.73 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 26.67 | 26.67 | PIPR103S | 68.24 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 190.50 | 182.88 | PIPR104S | 146.6 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 109.86 | 96.67 | PIPR105S | 93.76 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 203.20 | 182.88 | PIPR106S | 128.86 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 209.55 | 190.69 | PIPR107S | 113.0 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 146.05 | 127.06 | PIPR108S | 101.01 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 165.10 | 148.59 | PIPR109S | 120.9 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 254.00 | 223.52 | PIPR110S | 137.6 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 311.15 | 283.15 | PIPR111S | 142.9 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 165.10 | 150.24 | PIPR112S | 106.74 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 920.75 | 644.53 | PIPR113S | 131.9 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 1073.15 | 697.55 | PIPR114S | 116.5 | | Erickson et al. 1996a,b |

## Table 1. Acute Toxicity of Copper to Freshwater Animals

| Species[a] | Organism Age, Size, or Lifestage | Method[b] | Chemical[c] | Reported LC50 or EC50 (total µg/L)[d] | Reported LC50 or EC50 (Diss. µg/L)[e] | BLM Data Label | BLM Normalized LC50 or EC50 (µg/L)[f] | Species Mean Acute Value (µg/L)[g] | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | <24 h | S,M,T,D | S | 1003.30 | 752.48 | PIPR115S | 109.8 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 933.45 | 653.42 | PIPR116S | 123.2 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 742.95 | 646.37 | PIPR117S | 129.6 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 1879.60 | 939.80 | PIPR118S | 124.8 | | Erickson et al. 1996a,b |
| | <24 h | S,M,T,D | S | 266.70 | 253.37 | PIPR119S | 176.1 | | Erickson et al. 1996a,b |
| | --- | F,M,T | S | 114.00 | --- | PIPR120F | 17.99 | | Lind et al. Manuscript (1978) |
| | --- | F,M,T | S | 121.00 | --- | PIPR121F | 19.70 | | Lind et al. Manuscript (1978) |
| | --- | F,M,T | S | 88.50 | --- | PIPR122F | 13.27 | | Lind et al. Manuscript (1978) |
| | --- | F,M,T | S | 436.00 | --- | PIPR123F | 78.50 | | Lind et al. Manuscript (1978) |
| | --- | F,M,T | S | 516.00 | --- | PIPR124F | 50.09 | | Lind et al. Manuscript (1978) |
| | --- | F,M,T | S | 1586.00 | --- | PIPR125F | 66.49 | | Lind et al. Manuscript (1978) |
| | --- | F,M,T | S | 1129.00 | --- | PIPR126F | 73.03 | | Lind et al. Manuscript (1978) |
| | --- | F,M,T | S | 550.00 | --- | PIPR127F | 42.76 | | Lind et al. Manuscript (1978) |
| | --- | F,M,T | S | 1001.00 | --- | PIPR128F | 34.39 | | Lind et al. Manuscript (1978) |
| | 30 d, 0.15 g | F,M,T,D | N | 96.00 | 88.32 | PIPR129F | 39.58 | | Spehar and Fiandt 1986 |
| | <24 h | F,M,T,D | S | 31.75 | 27.94 | PIPR130F | 8.69 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 117.48 | 105.73 | PIPR131F | 37.88 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 48.26 | 40.06 | PIPR132F | 10.80 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 73.03 | 64.26 | PIPR133F | 22.19 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 59.06 | 49.02 | PIPR134F | 20.32 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 78.74 | 67.72 | PIPR135F | 18.51 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 22.23 | 18.67 | PIPR136F | 13.61 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 6.99 | 6.15 | PIPR137F | 10.94 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 22.23 | 20.45 | PIPR138F | 17.70 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 107.32 | 93.36 | PIPR139F | 67.09 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 292.10 | 245.36 | PIPR140F | 17.75 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 81.28 | 72.34 | PIPR141F | 41.16 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 298.45 | 229.81 | PIPR142F | 16.18 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 241.30 | 195.45 | PIPR143F | 24.40 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 133.35 | 109.35 | PIPR144F | 21.07 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 93.98 | 78.00 | PIPR145F | 50.83 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 67.95 | 45.52 | PIPR146F | 23.18 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 4.76 | 4.38 | PIPR147F | 40.09 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 13.97 | 12.43 | PIPR148F | 45.37 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 29.85 | 26.86 | PIPR149F | 59.43 | | Erickson et al. 1996a,b |
| | <24 h | F,M,T,D | S | 59.69 | 51.33 | PIPR150F | 58.84 | | Erickson et al. 1996a,b |
| Northern squawfish, | larval, 0.32 g | S,M,T | S | 380 | --- | PTLU01S | 88.44 | 132.2 | Dwyer et al. 1995 |
| *Ptychocheilus orego* | larval, 0.34 g | S,M,T | S | 480 | --- | PTLU02S | 197.6 | | Dwyer et al. 1995 |

## Table 1. Acute Toxicity of Copper to Freshwater Animals

| Species[a] | Organism Age, Size, or Lifestage | Method[b] | Chemical[c] | Reported LC50 or EC50 (total μg/L)[d] | Reported LC50 or EC50 (Diss. μg/L)[e] | BLM Data Label | BLM Normalized LC50 or EC50 (μg/L)[f] | Species Mean Acute Value (μg/L)[g] | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Northern squawfish, | 5.0 cm, 1.33 g | F,M,T | C | 23 | --- | PTOR01F | 17.02 | 14.61 | Andros and Garton 1980 |
| *Ptychocheilus orego* | 7.2 cm, 3.69 g | F,M,T | C | 18 | --- | PTOR02F | 12.54 | | Andros and Garton 1980 |
| Razorback sucker, | larval, 0.31 g | S,M,T | S | 220 | --- | XYTE01S | 63.78 | 78.66 | Dwyer et al. 1995 |
| *Xyrauchen texanus* | larval, 0.32 g | S,M,T | S | 340 | --- | XYTE02S | 97.0 | | Dwyer et al. 1995 |
| Gila topminnow,<br>*Poeciliposis* | 2.72 cm, 0.219 g | S,M,T | S | 160 | --- | POAC01S | 56.15 | 56.15 | Dwyer et al. 1999 |
| Bluegill, | 3.58 cm, 0.63 g | R,M,D | C | - | 2200 | LEMA01R | 2202 | 2231 | Blaylock et al. 1985 |
| *Lepomis macrochiru* | 12 cm, 35 g | F,M,T | S | 1100 | --- | LEMA02F | 2305 | | Benoit 1975 |
| | 2.8-6.8 cm | F,M,T | C | 1000 | --- | LEMA03F | 4200 | | Cairns et al. 1981 |
| | 3.58 cm, 0.63 g | F,M,D | C | - | 1300 | LEMA04F | 1163 | | Blaylock et al. 1985 |
| Fantail darter, | 3.7 cm | S,M,T | S | 330 | --- | ETFL01S | 117.7 | 124.3 | Lydy and Wissing 1988 |
| *Etheostoma flabellar* | 3.7 cm | S,M,T | S | 341 | --- | ETFL02S | 121.1 | | Lydy and Wissing 1988 |
| | 3.7 cm | S,M,T | S | 373 | --- | ETFL03S | 122.8 | | Lydy and Wissing 1988 |
| | 3.7 cm | S,M,T | S | 392 | --- | ETFL04S | 136.6 | | Lydy and Wissing 1988 |
| Greenthroat darter,<br>*Etheostoma* | 2.26 cm, 0.133 g | S,M,T | S | 260 | --- | ETLE01S | 82.80 | 82.80 | Dwyer et al. 1999 |
| Johnny darter, | 3.9 cm | S,M,T | S | 493 | --- | ETNI01S | 167.3 | 178.3 | Lydy and Wissing 1988 |
| *Etheostoma nigrum* | 3.9 cm | S,M,T | S | 483 | --- | ETNI02S | 164.2 | | Lydy and Wissing 1988 |
| | 3.9 cm | S,M,T | S | 602 | --- | ETNI03S | 200.1 | | Lydy and Wissing 1988 |
| | 3.9 cm | S,M,T | S | 548 | --- | ETNI04S | 183.9 | | Lydy and Wissing 1988 |
| Fountain darter,<br>*Etheostoma rubrum* | 2.02 cm, 0.062 g | S,M,T | S | 60 | --- | ETRU01S | 22.74 | 22.74 | Dwyer et al. 1999 |
| Boreal toad,<br>*Bufo boreas* | tadpole, 0.012 g | S,M,T | S | 120 | --- | BUBO01S | 47.49 | 47.49 | Dwyer et al. 1999 |

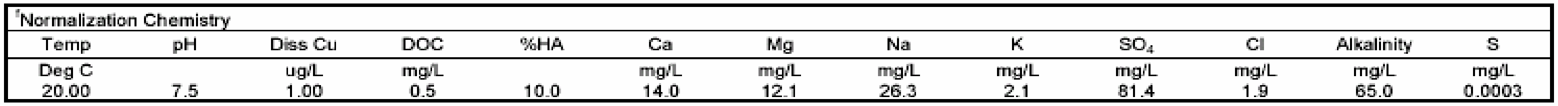
[a] Species appear in order taxonomically, with invertebrates listed first, fish, and an amphibian listed last. Species within each genus are ordered alphabetically. Within each species, tests are ordered b test method (static, renewal, flow-through) and date.

[b] S = static, R = renewal, F = flow-through, U = unmeasured, M = measured, T = exposure concentrations were measured as total copper, D = exposure concentrations were measured as dissolved copper.

[c] S = copper sulfate, N = copper nitrate, C = copper chloride.

[d] Values in this column are total copper LC50 or EC50 values as reported by the author.

[e] Values in this column are dissolved copper LC50 or EC50 values either reported by the author or if the author did not report a dissolved value then a conversion factor (CF) was applied to the total copper LC50 to estimate dissolved copper values.



[f]Normalization Chemistry

| Temp | pH | Diss Cu | DOC | %HA | Ca | Mg | Na | K | $SO_4$ | Cl | Alkalinity | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Deg C | | ug/L | mg/L | | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L |
| 20.00 | 7.5 | 1.00 | 0.5 | 10.0 | 14.0 | 12.1 | 26.3 | 2.1 | 81.4 | 1.9 | 65.0 | 0.0003 |

g Underlined LC50s or EC50s not used to derive SMAV because considered extreme value.

* Table updated as of March 2, 2007

# Table 2a. Chronic Toxicity of Copper to Freshwater Animals

| Species | Test[a] | Chemical | Endpoint | Hardness (mg/L as CaCO3) | Chronic Limits (µg/L) | Chronic Values | | Species Mean Chronic Value (Total µg/L) | Genus Mean Chronic Value (Total µg/L) | ACR | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Chronic Value[b] (µg/L) | EC20[b] (µg/L) | | | | |
| Rotifer, *Brachionus calyciflorus* | LC,T | Copper sulfate | Intrinsic growth rate | 85 | 2.5-5.0 | 3.54 | - | 3.54 | 3.54 | | Janssen et al. 1994 |
| Snail, *Campeloma decisum (Test 1)* | LC,T | Copper sulfate | Survival | 35-55 | 8-14.8 | 10.88 | 8.73 | 9.77 | 9.77 | 191.6 | Arthur and Leonard 1970 |
| Snail, *Campeloma decisum (Test 2)* | LC,T | Copper sulfate | Survival | 35-55 | 8-14.8 | 10.88 | 10.94 | | | 153.0 | Arthur and Leonard 1970 |
| Cladoceran, *Ceriodaphnia dubia (New River)* | LC,D | - | Reproduction | 179 | 6.3-9.9 | 7.90[c]<br>(8.23) | - | 19.3 | 19.3 | 3.599 | Belanger et al. 1989 |
| Cladoceran, *Ceriodaphnia dubia (Cinch River)* | LC,D | - | Reproduction | 94.1 | <19.3-19.3 | <19.3 | 19.36[c]<br>(20.17) | | | 3.271 | Belanger et al. 1989 |
| Cladoceran, *Ceriodaphnia dubia* | LC,T | Copper sulfate | Survival and reproduction | 57 | - | 24.50 | - | | | 0.547 | Oris et al. 1991 |
| Cladoceran, *Ceriodaphnia dubia* | LC,T | Copper sulfate | Survival and reproduction | 57 | - | 34.60 | - | | | | Oris et al. 1991 |
| Cladoceran, *Ceriodaphnia dubia* | LC,T,D | Copper chloride | Reproduction | | 12-32 | 19.59 | 9.17 | | | 2.069 | Carlson et al. 1986 |
| Cladoceran, *Daphnia magna* | LC,T | Copper chloride | Reproduction | 85 | 10-30 | 17.32 | - | 14.1 | 8.96 | | Blaylock et al. 1985 |
| Cladoceran, *Daphnia magna* | LC,T | Copper chloride | Carapace length | 225 | 12.6-36.8 | 21.50 | - | | | | van Leeuwen et al. 1988 |
| Cladoceran, *Daphnia magna* | LC,T | Copper chloride | Reproduction | 51 | 11.4-16.3 | 13.63 | 12.58 | | | 2.067 | Chapman et al. Manuscript |
| Cladoceran, *Daphnia magna* | LC,T | Copper chloride | Reproduction | 104 | 20-43 | 29.33 | 19.89 | | | 1.697 | Chapman et al. Manuscript |
| Cladoceran, *Daphnia magna* | LC,T | Copper chloride | Reproduction | 211 | 7.2-12.6 | 9.53 | 6.06 | | | 11.39 | Chapman et al. Manuscript |
| Cladoceran, *Daphnia pulex* | LC,T | Copper sulfate | Survival | 57.5 (No HA) | 4.0-6.0 | 4.90 | 2.83 | 5.68 | | 9.104 | Winner 1985 |
| Cladoceran, *Daphnia pulex* | LC,T | Copper sulfate | Survival | 115 (No HA) | 5.0-10.0 | 7.07 | | | | 3.904 | Winner 1985 |
| Cladoceran, *Daphnia pulex* | LC,T | Copper sulfate | Survival | 230 (0.15 HA) | 10-15 | 12.25 | 9.16 | | | 3.143 | Winner 1985 |

## Table 2a. Chronic Toxicity of Copper to Freshwater Animals

| Species | Test[a] | Chemical | Endpoint | Hardness (mg/L as CaCO3) | Chronic Limits (µg/L) | Chronic Values | | Species Mean Chronic Value (Total µg/L) | Genus Mean Chronic Value (Total µg/L) | ACR | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Chronic Value[b] (µg/L) | EC20[b] (µg/L) | | | | |
| Caddisfly,<br>*Clistoronia magnifica* | LC,T | Copper chloride | Emergence (adult 1st gen) | 26 | 8.3-13 | 10.39 | 7.67 | 7.67 | 7.67 | | Nebeker et al. 1984b |
| Rainbow trout,<br>*Oncorhynchus mykiss* | ELS,T continuous | Copper chloride | Biomass | 120 | | | 27.77 | 23.8 | 11.9 | 2.881 | Seim et al. 1984 |
| Rainbow trout,<br>*Oncorhynchus mykiss* | ELS,T | Copper sulfate | Biomass | 160-180 | 12-22 | 16.25 | 20.32 | | | | Besser et al. 2001 |
| Chinook salmon,<br>*Oncorhynchus tshawytscha* | ELS,T | Copper chloride | Biomass | 20-45 | <7.4 | <7.4 | 5.92 | 5.92 | | 5.594 | Chapman 1975, 1982 |
| Brown trout,<br>*Salmo trutta* | ELS,T | Copper sulfate | Biomass | 45.4 | 20.8-43.8 | 29.91 | - | 29.9 | 29.9 | | McKim et al. 1978 |
| Brook trout,<br>*Salvelinus fontinalis* | PLC,T | Copper sulfate | Biomass | 35.0 | <5 -5 | <5 | - | 12.5 | 19.7 | | Sauter et al. 1976 |
| Brook trout,<br>*Salvelinus fontinalis* | ELS,T | Copper sulfate | Biomass | 45.4 | 22.3-43.5 | 31.15 | - | | | | McKim et al. 1978 |
| Lake trout,<br>*Salvelinus namaycush* | ELS, T | Copper sulfate | Biomass | 45.4 | 22.0-43.5 | 30.94 | - | 30.9 | | | McKim et al. 1978 |
| Northern pike,<br>*Esox lucius* | ELS, T | Copper sulfate | Biomass | 45.4 | 34.9-104.4 | 60.36 | - | 60.4 | 60.4 | | McKim et al. 1978 |
| Bluntnose minnow<br>*Pimephales notatus* | LC,T | Copper sulfate | Egg production | 172-230 | <18-18 | 18.00 | - | 18.0 | 13.0 | 12.88 | Horning and Neiheisel 1979 |
| Fathead minnow,<br>*Pimephales promelas* | ELS,T,D | - | Biomass | 45 | | | 9.38 | 9.38 | | 11.40 | Lind et al. manuscript |
| White sucker,<br>*Catostomus commersoni* | ELS, T | Copper sulfate | Biomass | 45.4 | 12.9-33.8 | 20.88 | - | 20.9 | 20.9 | | McKim et al. 1978 |
| Bluegill (larval),<br>*Lepomis macrochirus* | ELS,T,D | Copper sulfate | Survival | 44-50 | 21-40 | 28.98 | 27.15 | 27.2 | 27.2 | 40.52 | Benoit 1975 |

[a] LC = life-cycle; PLC = partial life-cyle; ELS = early life state; T = total copper; D = dissolved copper.

[b] Results are based on copper, not the chemical.

[c] Chronic values based on dissolved copper concentration.

## Table 2b. Chronic Toxicity of Copper to Saltwater Animals

| Species | Test | Chemical | Salinity (g/kg) | Limits (µg/L) | Chronic Value (µg/L) | Chronic Value Dissolved (µg/L) | ACR | Reference |
|---|---|---|---|---|---|---|---|---|
| Sheepshead minnow, *Cyprinodon variegatus* | ELS | Copper chloride | 30 | 172-362 | 249 | 206.7 | 1.48 | Hughes et al. 1989 |

## Table 2c. Acute-Chronic Ratios

| Species | Hardness (mg/L as $CaCO_3$) | Acute Value (µg/L) | Chronic Value (µg/L) | Ratio | Reference | Overall Ratio for Species | |
|---|---|---|---|---|---|---|---|
| Snail, | 35-55 | 1673[a] | 8.73 | 191.61 | Arthur and Leonard 1970 | | |
| *Campeloma decisum* | 35-55 | 1673[a] | 10.94 | 152.95 | Arthur and Leonard 1970 | 171.19 | |
| Cladoceran, | 179 | 28.42[b] | 7.90 | 3.60 | Belanger et al. 1989 | | |
| *Ceriodaphnia dubia* | 94.1 | 63.33[b] | 19.36 | 3.27 | Belanger et al. 1989 | | |
| | 57 | 13.4 | 24.5 | 0.55 | Oris et al. 1991 | | |
| | -- | 17.974[c] | 9.17 | 1.96 | Carlson et al. 1986 | 2.85[g] | ✓ |
| Cladoceran, | 51 | 26 | 12.58 | 2.07 | Chapman et al. Manuscript | | |
| *Daphnia magna* | 104 | 33.76[d] | 19.89 | 1.70 | Chapman et al. Manuscript | | |
| | 211 | 69 | 6.06 | 11.39 | Chapman et al. Manuscript | 3.42 | ✓ |
| Cladoceran, | 57.5 | 25.737 | 2.83 | 9.10 | Winner 1985 | | |
| *Daphnia pulex* | 115 | 27.6 | 7.07 | 3.90 | Winner 1985 | | |
| | 230 | 28.79 | 9.16 | 3.14 | Winner 1985 | 4.82 | ✓ |
| Rainbow trout,<br>*Oncorhynchus mykiss* | 120 | 80 | 27.77 | 2.88 | Seim et al. 1984 | 2.88 | ✓ |
| Chinook salmon,<br>*Oncorhynchus tshawytscha* | 20-45 | 33.1 | 5.92 | 5.59 | Chapman 1975, 1982 | 5.59 | ✓ |
| Bluntnose minnow,<br>*Pimephales notatus* | 172-230 | 231.9[e] | 18 | 12.88 | Horning and Neiheisel 1979 | 12.88 | |
| Fathead minnow,<br>*Pimephales promelas* | 45 | 106.875[f] | 9.38 | 11.40 | Lind et al. 1978 | 11.40 | |
| Bluegill,<br>*Lepomis macrochirus* | 21-40 | 1100 | 27.15 | 40.52 | Benoit 1975 | 40.49 | |
| Sheepshead minnow,<br>*Cyprinodon variegatus* | - | 368 | 249 | 1.48 | Hughes et al. 1989 | 1.48 | ✓ |

[a] Geometric mean of two values from Arthur and Leonard (1970) in Table 1.

[b] Geometric mean of five values from Belanger et al. (1989) in Table 1. ACR is based on dissolved metal measurements.

[c] Geometric mean of two values from Carlson et al. (1986) in Table 1.

[d] Geometric mean of two values from Chapman manuscript in Table 1.

[e] Geometric mean of two values of three values from Horning and Neiheisel (1979) in Appendix C.

[f] Geometric mean of three values from Lind et al. (1978) in Table 1.

[g] ACR from Oris et al. (1991) not used in calculating overall ratio for species because it is <1.

FACR
Freshwater final acute-chronic ratio = 3.22
Saltwater final acute-chronic ratio = 3.22

* Table updated as of March 2, 2007

### Table 3a. Ranked Freshwater Genus Mean Acute Values with Species Mean Acute-Chronic Ratios

| Rank | GMAV | Species | SMAV (µg/L) | ACR |
|---|---|---|---|---|
| 27 | 102,000 | Golden shiner, *Notemigonus crysoleucas* | 102,000 | |
| 26 | 17,484 | Stonefly, *Acroneuria lycorias* | 17,484 | |
| 25 | 3,027 | Snail, *Campeloma decisum* | 3,027 | 171.19 |
| 24 | 1,968 | Bluegill sunfish, *Lepomis macrochirus* | 1,968 | 40.49 |
| 23 | 1,925 | Midge, *Chironomus decorus* | 1,925 | |
| 22 | 187.5 | Chiselmouth, *Acrocheilus alutaceus* | 187.5 | |
| 21 | 83.76 | Fantail darter, *Etheostoma flabellare* | 130.2 | |
| | | Greenthroat darter, *Etheostoma lepidum* | 86.34 | |
| | | Johnny darter, *Etheostoma nigrum* | 187.3 | |
| | | Fountain darter, *Etheostoma rubrum* | 23.38 | |
| 20 | 81.75 | Razorback sucker, *Xyrauchen texanus* | 81.75 | |
| 19 | 72.50 | Shovelnose sturgeon, *Scaphirhynchus platorynchus* | 72.50 | |
| 18 | 72.36 | Bull trout, *Salvelinus confluentus* | 72.36 | |
| 17 | 72.07 | Fathead minnow, *Pimephales promelas* | 72.07 | 11.40 |
| 16 | 65.62 | Bonytail chub, *Gila elegans* | 65.62 | |
| 15 | 58.32 | Gila topminnow, *Poeciliposis occidentalis* | 58.32 | |
| 14 | 50.12 | Worm, *Lumbriculus variegatus* | 50.12 | |
| 13 | 49.06 | Boreal toad, *Bufo boreas* | 49.06 | |
| 12 | 42.64 | Colorado squawfish, *Ptychocheilus lucius* | 138.2 | |
| | | Northern squawfish, *Ptychocheilus oregonensis* | 13.15 | |
| 11 | 35.97 | Freshwater mussel, *Utterbackia imbecillis* | 35.97 | |
| 10 | 29.11 | Apache trout, *Oncorhynchus apache* | 33.70 | |
| | | Cutthroat trout, *Oncorhynchus clarki* | 31.28 | |
| | | Pink salmon, *Oncorhynchus gorbuscha* | 37.30 | |
| | | Coho salmon, *Oncorhynchus kisutch* | 15.98 | |
| | | Rainbow trout, *Oncorhynchus mykiss* | 21.60 | 2.88 |
| | | Sockeye salmon, *Oncorhynchus nerka* | 50.83 | |
| | | Chinook salmon, *Oncorhynchus tshawytscha* | 25.68 | 5.59 |
| 9 | 18.60 | Snail, *Physa integra* | 18.60 | |
| 8 | 11.36 | Amphipod, *Hyalella azteca* | 11.36 | |
| 7 | 11.35 | Freshwater mussel, *Actinonaias pectorosa* | 11.35 | |
| 6 | 10.84 | Snail, *Juga plicifera* | 10.84 | |
| 5 | 8.77 | Cladoceran, *Scapholeberis sp.* | 8.77 | |
| 4 | 8.57 | Amphipod, *Gammarus pseudolimnaeus* | 8.57 | |
| 3 | 5.75 | Cladoceran, *Ceriodaphnia dubia* | 5.75 | 2.90 |
| 2 | 5.75 | Snail, *Lithoglyphus virens* | 5.75 | |
| 1 | 3.56 | Cladoceran, *Daphnia magna* | 4.98 | 3.42 |
| | | Cladoceran, *Daphnia pulicaria* | 2.54 | |

## Table 3b. Freshwater Final Acute Value (FAV) and Criteria Calculations

**Calculated Freshwater FAV based on 4 lowest values:** Total Number of GMAVs in Data Set = 27

| **Rank** | **GMAV** | **lnGMAV** | **(lnGMAV)$^2$** | **P = R/(n+1)** | **SQRT(P)** |
|---|---|---|---|---|---|
| 4 | 9.600 | 2.261 | 5.114 | 0.143 | 0.378 |
| 3 | 6.670 | 1.897 | 3.599 | 0.107 | 0.327 |
| 2 | 5.930 | 1.780 | 3.170 | 0.071 | 0.267 |
| 1 | 4.050 | 1.398 | 1.954 | 0.036 | 0.189 |
| **Sum:** | | **7.33671** | **13.83657** | **0.35714** | **1.16153** |
| S = | 4.374 | | | | |
| L = | 0.5641 | | | | |
| A = | 1.542 | | | | |
| **Calculated FAV =** | **4.674452** | | | | |
| **Calculated CMC =** | **2.337** | | | | |

Dissolved Copper Criterion Maximum Concentration (CMC) = 2.337 µg/L (for example normalization chemistry see Table 1, footnote f)
Criteria Lethal Accumulation (LA50) based on example normalization chemistry = 0.03395 nmol/g wet wt
Criterion Continuous Concentration (CCC) = 4.67445/3.22 = 1.4516932 µg/L (for example normalization chemistry see Table 1, footnote f)

S = Scale parameter or slope
L = Location parameter or intercept
P = Cumulative probability
A = lnFAV

* Table updated as of March 2, 2007

## Table 4. Toxicity of Copper to Freshwater Plants

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Result[b] (Total µg/L) | Reference |
|---|---|---|---|---|---|---|---|
| Blue-green alga,<br>*Anabaena flos-aqua* | S,U | Copper sulfate | 65.2 | 96 hr | EC75<br>(cell density) | 200 | Young and Lisk 1972 |
| Bllue-green alga,<br>*Anabaena variabilis* | S,U | Copper sulfate | 65.2 | - | EC85<br>(wet weight) | 100 | Young and Lisk 1972 |
| Blue-green alga,<br>*Anabaena* strain 7120 | - | - | - | - | Lag in growth | 64 | Laube et al. 1980 |
| Blue-green alga,<br>*Chroococcus paris* | S,U | Copper nitrate | 54.7 | 10 days | Growth reduction | 100 | Les and Walker 1984 |
| Blue-green alga,<br>*Microcystis aeruginosa* | S,U | Copper sulfate | 54.9 | 8 days | Incipient inhibition | 30 | Bringmann 1975; Bringmann and Kuhn 1976, 1978a,b |
| Alga,<br>*Ankistrodesmus braunii* | - | - | - | - | Growth reduction | 640 | Laube et al. 1980 |
| Green alga,<br>*Chlamydomonas* sp. | S,U | Copper sulfate | 68 | 10 days | Growth inhibition | 8,000 | Cairns et al. 1978 |
| Green alga,<br>*Chlamydomonas reinhardtii* | S,M,T | - | 90 - 133 | 72 hr | NOEC<br>(deflagellation) | 12.2-49.1 | Winner and Owen 1991a |
| Green alga,<br>*Chlamydomonas reinhardtii* | S,M,T | - | 90 - 133 | 72 hr | NOEC<br>(cell density) | 12.2-43.0 | Winner and Owen 1991a |
| Green alga,<br>*Chlamydomonas reinhardtii* | F,M,T | - | 24 | 10 days | EC50<br>(cell density) | 31.5 | Schafer et al. 1993 |
| Green alga,<br>*Chlorella pyrenoidosa* | S,U | - | - | 96 hr | ca. 12 hr lag in growth | 1 | Steeman-Nielsen and Wium-Andersen 1970 |
| Green alga,<br>*Chlorella pyrenoidosa* | S,U | - | 54.7 | - | Growth inhibition | 100 | Steeman-Nielsen and Kamp-Nielsen 1970 |
| Green alga,<br>*Chlorella pyrenoidosa* | S,U | Copper sulfate | 365 | 14 days | EC50<br>(dry weight) | 78-100 | Bednarz and Warkowska-Dratnal 1985 |
| Green alga,<br>*Chlorella pyrenoidosa* | S,U | Copper sulfate | 36.5 | 14 days | EC50<br>(dry weight) | 78-100 | Bednarz and Warkowska-Dratnal 1985 |
| Green alga,<br>*Chlorella pyrenoidosa* | S,U | Copper sulfate | 3.65 | 14 days | EC50<br>(dry weight) | 78-100 | Bednarz and Warkowska-Dratnal 1983/1984 |
| Green alga,<br>*Chlorella saccharophila* | S,U | Copper chloride | - | 96 hr | 96-h EC50 | 550 | Rachlin et al. 1982 |
| Green alga,<br>*Chlorella vulgaris* | S,U | Copper sulfate | 2,000 | 96 hr | Growth inhibition | 200 | Young and Lisk 1972 |
| Green alga,<br>*Chlorella vulgaris* | S,U | Copper chloride |  | 33 days | EC20<br>(growth) | 42 | Rosko and Rachlin 1977 |
| Green alga,<br>*Chlorella vulgaris* | F,U | Copper sulfate | - | 96 hr | EC50 or EC50<br>(cell numbers) | 62 | Ferard et al. 1983 |
| Green alga,<br>*Chlorella vulgaris* | S,M,D | Copper sulfate | - | 96 hr | IC50 | 270 | Ferard et al. 1983 |
| Green alga,<br>*Chlorella vulgaris* | S,M,T | Copper chloride | - | 96 hr | EC50<br>(cell density) | 200 | Blaylock et al. 1985 |
| Green alga,<br>*Chlorella vulgaris* | S,U | Copper sulfate | 17.1 | 7 days | 15% reduction in cell density | 100 | Bilgrami and Kumar 1997 |

## Table 4.  Toxicity of Copper to Freshwater Plants

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Result[b] (Total µg/L) | Reference |
|---|---|---|---|---|---|---|---|
| Green alga,<br>*Scenedesmus quadricauda* | S,U | Copper sulfate | 68 | 10 days | Growth reduction | 8,000 | Cairns et al. 1978 |
| Green alga,<br>*Scenedesmus quadricauda* | S,U | Copper sulfate | 181 | 7 days | LOEC (growth) | 1,100 | Bringmann and Kuhn 1977a, 1978a,b, 1979, 1980a |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper chloride | 14.9 | 14 days | EC50 (cell volume) | 85 | Christensen et al. 1979 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper chloride | 14.9 | 7 days | LOEC (growth) | 50 | Bartlett et al. 1974 |
| Green alga,<br>*Selenastrum capricornutum* | S,M,T | Copper chloride | 24.2 | 96 hr | EC50 (cell count) | 400 | Blaylock et al. 1985 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 9.3 | 96 hr | EC50 (cell count) | 48.4 | Blaise et al. 1986 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 9.3 | 96 hr | EC50 (cell count) | 44.3 | Blaise et al. 1986 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 9.3 | 96 hr | EC50 (cell count) | 46.4 | Blaise et al. 1986 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper chloride | 15 | 2-3 wk | EC50 (biomass) | 53.7 | Turbak et al. 1986 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 14.9 | 5 days | Growth reduction | 58 | Nyholm 1990 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 9.3 | 96 hr | EC50 (cell count) | 69.9 | St. Laurent et al. 1992 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 9.3 | 96 hr | EC50 (cell count) | 65.7 | St. Laurent et al. 1992 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 24.2 | 96 hr | EC50 (cell count) | 54.4 | Radetski et al. 1995 |
| Green alga,<br>*Selenastrum capricornutum* | R,U | Copper sulfate | 24.2 | 96 hr | EC50 (cell count) | 48.2 | Radetski et al. 1995 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 16 | 96 hr | EC50 (cell density) | 38 | Chen et al. 1997 |
| Algae,<br>mixed culture | S,U | Copper sulfate | - | - | Significant reduction in blue-green algae and nitrogen fixation | 5 | Elder and Horne 1978 |
| Diatom,<br>*Cyclotella meneghiniana* | S,U | Copper sulfate | 68 | 10 days | Growth inhibition | 8,000 | Cairns et al. 1978 |
| Diatom,<br>*Navicula incerta* | S,U | Copper chloride | - | 96 hr | EC50 | 10,429 | Rachlin et al. 1983 |
| Diatom,<br>*Nitzschia linearis* | - | - | - | 5 day | EC50 | 795-815 | Academy of Natural Sciences 1960; Patrick et al. 1968 |
| Diatom,<br>*Nitzschia palea* | - | - | - | - | Complete growth inhibition | 5 | Steeman-Nielsen and Wium-Andersen 1970 |
| Duckweed,<br>*Lemna minor* | F | - | - | 7 day | EC50 | 119 | Walbridge 1977 |
| Duckweed,<br>*Lemna minor* | S,U | Copper sulfate | - | 28 days | Significant plant damage | 130 | Brown and Rattigan 1979 |

## Table 4. Toxicity of Copper to Freshwater Plants

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Result[b] (Total µg/L) | Reference |
|---|---|---|---|---|---|---|---|
| Duckweed,<br>*Lemna minor* | S,U | - | 0 | 96 hr | EC50<br>(frond number) | 1,100 | Wang 1986 |
| Duckweed,<br>*Lemna minor* | S,U | Copper sulfate | 78 | 96 hr | EC50<br>(chlorophyll a reduction) | 250 | Eloranta et al. 1988 |
| Duckweed,<br>*Lemna minor* | R,M,T | Copper nitrate | 39 | 96 hr | Reduced chlorophyll production | 24 | Taraldsen and Norberg-King 1990 |
| Eurasian watermilfoil,<br>*Myriophyllum spicatum* | S,U | - | 89 | 32 days | EC50<br>(root weight) | 250 | Stanley 1974 |

[a] S=Static; R=Renewal; F=Flow-through; M=Measured; U=Unmeasured; T=Total metal conc. measured; D=dissolved metal conc. measured.

[b] Results are expressed as copper, not as the chemical.

## 9.0 REFERENCES

Allen, H.E. and D.J. Hansen. 1996. The importance of trace metal speciation to water quality criteria. Water Environ. Res. 68:42-54.

Allen, H.E. et al. 1983. An algal assay method for determination of copper complexation capacities of natural waters. Bull. Environ. Contam. Toxicol. 30:448.

Arthur, J.W. and E.N. Leonard. 1970. Effects of copper on *Gammarus pseudolimnaeus, Physa integra*, and *Campeloma decisum* in soft water. J. Fish. Res. Board Can. 27:1277-1283.

ASTM. 2000. Standard guide for conducting acute toxicity tests on test materials with fishes, macroinvertebrates, and amphibians. E729-96. In: Annual book of ASTM standards. Section 11, Volume 5. American Society for Testing and Materials, Pennsylvania, PA.

Blaylock, B.G., M.L. Frank and J.F. McCarthy. 1985. Comparative toxicity of copper and acridine to fish, *Daphnia* and algae. Environ. Toxicol. Chem. 4(1):63-71.

Bowen, H.J.M. 1985. In D. Hutzinger (ed.), The Handbook of Environmental Chemistry, Vol. 1, Part D: The natural environment and biogeochemical cycles, Springer-Verlag, New York. p. 1-26.

Brown, P. L., and Markich, S. J. 2000. Evaluation of the free ion activity model of metal-organism interaction: Extension of the conceptual model. Aquatic Toxicology 51:177-194.

Brungs, W.A., J.R. Geckler and M. Gast. 1976. Acute and chronic toxicity of copper to the fathead minnow in a surface water of variable quality. Water Res. 10:37-43.

Bryan, S. E., Tipping, E., and Hamilton-Taylor, J. 2002. Comparison of measured and modelled copper binding by natural organic matter in freshwaters. Comparative Biochemistry and Physiology 133C:37-49.

Buckley, J. A., Yoshida, G. A., and Wells, N. R. 1984. A cupric ion-copper bioaccumulation relationship in coho salmon exposed to copper-containing treated sewage. Comparative Biochemistry and Physiology 78C:105-110.

Campbell, P.G.C. 1995. “Interactions Between Trace Metals and Aquatic Organisms: A Critique of the Free-ion Activity Model,” in *Metal Speciation and Bioavailability in Aquatic Systems*, A. Tessier and D.R. Turner, eds., John Wiley and Sons, New York, pp. 45-102.

Carlson, A.R., W.A. Brungs, G.A. Chapman and D.J. Hansen. 1984. Guidelines for deriving numerical aquatic site-specific water quality criteria by modifying national criteria. EPA-600/3-84-099, U.S. Environmental Protection Agency, Environmental Research Laboratory, Duluth, Minnesota, USA.

Chakoumakos, C., R.C. Russo and R.V. Thurston. 1979. The toxicity of copper to cutthroat trout (*Salmo clarki*) under different conditions of alkalinity, pH, and hardness. Environ. Sci. Technol. 13:213-219.

Chapman, G.A. 1978. Toxicities of cadmium, copper, and zinc to four juvenile stages of chinook salmon and steelhead. Trans. Am. Fish. Soc. 107:841-847.

Davis, A. and D. Ashenberg. 1989. The aqueous geochemistry of the Berkeley Pit, Butte, Montana, U.S.A. Appl. Geochem. Vol (4):23-36.

Di Toro, D.M. et al. 2001. The persistence and availability of metals in aquatic environments. International council on metals and the environment. Ottawa, Ontario, Canada.

Erickson, R.J., D.A. Benoit and V.R. Mattson. 1996a. A prototype toxicity factors model for site-specific copper water quality criteria. U.S. EPA, Duluth, Minnesota.

Erickson, R.J., D.A. Benoit, V.R. Mattson, H.P. Nelson, Jr. and E.N. Leonard. 1996b. The effects of water chemistry on the toxicity of copper to fathead minnows. Environ. Toxicol. Chem. 15(2):181-193.

Erickson, R.J., D.A. Benoit and V.R. Mattson, 1987. "A Prototype Toxicity Factors Model ForSite-Specific Copper Water Quality Criteria," revised September 5, 1996, United States Environmental Protection Agency, Environmental Research Laboratory-Duluth, Duluth, MN.

Foster, P.L. 1982. Metal resistances of chlorophyta from rivers polluted by heavy metals. Freshwater Biol. 12:41.

Gächter, R., K. Lum-Shue-Chan and Y.K Chau. 1973. Complexing capacity of the nutrient medium and its relation to inhibition of algal photosynthesis by copper. Schweiz. Z. Hydrol. 35:252.

Geckler, J.R., W.B. Horning, T.M. Neiheisel, Q.H. Pickering, E.L. Robinson and C.E. Stephan. 1976. Validity of laboratory tests for predicting copper toxicity in streams. EPA-600/3-76-116. National Technical Information Service, Springfield, VA.

Hem, J.D. 1989. Study and interpretation of the chemical characteristics of natural water, 3rd ed. U.S. Geological Survey water-supply paper 2253. Government Printing Office.

Hughes, M.M., M.A. Heber, G.E. Morrison, S.C. Schimmel and W.J. Berry. 1989. An evaluation of a short-term chronic effluent toxicity test using sheepshead minnow (*Cyprinodon variegatus*) larvae. Environ. Pollut. 60(1):1-14.

Hunt, D. T. E. 1987. Trace Metal Speciation and Toxicity to Aquatic Organisms - A Review. TR 247, Water Research Centre, Marlow, Bucks, United Kingdom.

Inglis, A. and E.L. Davis. 1972. Effects of water hardness on the toxicity of several organic and inorganic herbicides to fish. Technical Paper No. 67. U.S. Fish and Wildlife Service, Washington, D.C.

Janes, N., Playle, R.C. 1995. Modeling silver binding to gills of rainbow trout (*Oncorhynchus mykiss*). Env. Toxicol. Chem. 14, 1847-1858.

Kapustka, L.A., W.H. Clements, L. Ziccardi, P.R. Paquin, M. Sprenger and D. Wall, August 19, 2004. "Issue Paper on the Ecological Effects of Metals," Submitted by ERG to U.S. Environmental Protection Agency, Risk Assessment Forum, Washington, DC.

Koivisto, S., M. Ketola and M. Walls. 1992. Comparison of five cladoceran species in short- and long-term copper exposure. Hydrobiol. 248(2):125-136.

Kramer, J. R., Allen, H. E., Davison, W., Godtfredsen, K. L., Meyer, J. S., Perdue, E. M., Tipping, E., van der Meent, D., and Westall, J. C. 1997. Chemical speciation and metal toxicity in surface freshwater. In Bergman, H. L., and Dorward-King, E. J. (eds.) Reassessment of Metals Criteria for Aquatic Life Protection. Pensacola, FL: SETAC Press.

Lauren, D. J., and McDonald, D. G. 1986. Influence of water hardness, pH, and alkalinity on the mechanisms of copper toxicity in juvenile rainbow trout, *Salmo gairdneri*. Canadian Journal of Fisheries and Aquatic Sciences 43:1488-1496.

Lopez, J.M., Lee, G.F. 1977. Water, Air and Soils Pollut. Vol. (8): 373.

Lumsden, B.R. and T.M. Florence. 1983. A new algal assay procedure for the determination of the toxicity of copper species in seawater. Environ. Toxicol. Lett. 4:271.

MacRae, R.K., D.E. Smith, N. Swoboda-Colberg, J.S. Meyer and H.L. Bergman. 1999. Copper binding affinity of rainbow trout (*Oncorhynchus mykiss*) and brook trout (*Salvelinus fontinalis*) gills: Implications for assessing bioavailable metal. Environ. Toxicol. Chem. 18:1180-1189.

McGeer JC, Szebedinszky C, McDonald DG, and Wood CM. 2002. The role of dissolved organic carbon in moderating the bioavailability and toxicity of Cu to rainbow trout during chronic waterbrone exposure. Comp. Biochem. Physiol. C: Toxicol and Pharmacol. 133C:147-161.

McKnight, D.M. and F.M.M. Morel. 1979. Release of weak and strong copper-complexing agents by algae. Limnol. Oceanogr. 24:823.

McKnight, D.M. et al. 1983. CuSO4 treatment of nuisance algal blooms in drinking water reservoirs. Environ. Manage. 7:311.

Meyer, J.S., C.J. Boese and S.A. Collyard. 2002. Whole-body accumulation of copper predicts acute toxicity to an aquatic oligochaete (*Lumbriculus variegatus*) as pH and calcium are varied. Comp. Biochem. Physiol. Part C 133:99-109.

Meyer, J.S., R.C. Santore, J.P. Bobbitt, L.D. DeBrey, C.J. Boese, P.R. Paquin, H.E. Allen, H.L. Bergman and D.M. Di Toro. 1999. Binding of nickel and copper to fish gills predicts toxicity when water hardness varies, but free-ion activity does not. Environ. Sci. Technol. 33:913-916.

Miller, T.G. and W.C. MacKay. 1980. The effects of hardness, alkalinity and pH of test water on the toxicity of copper to rainbow trout (*Salmo gairdneri*). Water Res. 14:129-133.

Morel, F.M., 1983a. "Complexation: Trace Metals and Microorganisms," in Chapter 6 of *Principles of Aquatic Chemistry*, Wiley Interscience, New York, pp. 301-308.

Morel F.M.M. 1983b. Principles of Aquatic Chemistry. John Wiley and Sons, New York, NY.

Morrison, G., E. Torello, R. Comeleo, R. Walsh, A. Kuhn, R. Burgess, M. Tagliabue and W. Greene. 1989. Intralaboratory precision of saltwater short-term chronic toxicity tests. J. Water Pollut. Control Fed. 61(11-12):1707-1710.

Muramoto, S. 1980. Effect of complexants (EDTA, NTA and DTPA) on the exposure to high concentrations of cadmium, copper, zinc and lead. Bull Environ Contam Toxicol. 25(6):941-946.

National Research Council. 2003. Bioavailability of Contaminants in Soils and Sediments: Processes, Tools, and Applications. The National Academy of Sciences, Washington, DC, USA.

Nriagu, J.O. (Ed.) 1979. Copper in the Environment. Part I: Ecological Cycling; Part II: Health Effects. Wiley and Sons, Inc. New York, NY.

Oris, J.T., R.W. Winner and M.V. Moore. 1991. A four-day survival and reproduction toxicity test for *Ceriodaphnia dubia*. Environ. Toxicol. Chem. 10(2):217-224.

Pagenkopf, G.K. 1983. Gill surface interaction model for trace-metal toxicity to fishes: Role of complexation, pH, and water hardness. Environ. Sci. Technol. 17:342-347.

Paquin, P.R., J.W. Gorsuch, S. Apte, G.E. Batley, K.C. Bowles, P.G.C. Campbell, C.G. Delos, D.M. Di Toro, R.L. Dwyer, F. Galvez, R.W. Gensemer, G.G. Goss, C. Hogstrand, C.R. Janssen, J.C. McGeer, R.B. Naddy, R.C. Playle, R.C. Santore, U. Schneider, W.A. Stubblefield, C.M. Wood and K.B. Wu. 2002. The bitoic ligand model: A historical overview. Comp. Biochem. Physiol. Part C 133:3-35.

Patterson, J.W., R.A. Minear, E. Gasca and C. Petropoulou. 1998. Industrial discharges of metals to water. In: H.E. Allen, A.W. Garrison and G.W. Luther III (Eds.). Metals in Surface Waters. Ann Arbor Press, Chelsea, MI. pp. 37-66.

Petersen, R. 1982. Influence of copper and zinc on the growth of a freshwater algae, *Scenedesmus quadricauda*: The significance of speciation. Environ. Sci. Technol. 16:443.

Peterson, H. G., Healey, F. P., and Wagemann, R. 1984. Metal toxicity to algae: A highly pH dependent phenomenon. Canadian Journal of Fisheries and Aquatic Science 41:974-979.

Playle, R.C., D.G. Dixon and K. Burnison. 1993a. Copper and cadmium binding to fish gills: Estimates of metal-gill stability constants and modeling of metal accumulation. Can. J. Fish. Aquat. Sci. 50(12):2678-2687.

Playle, R.C., D.G. Dixon and K. Burnison. 1993b. Copper and cadmium binding to fish gills: Modification by dissolved organic carbon and synthetic ligands. Can. J. Fish. Aquat. Sci. 50(12):2667-2677.

Playle, R.C., R.W. Gensener and D.G. Dixon. 1992. Copper accumulation on gills of fathead minnows: Influence of water hardness, complexation and pH of the gill micro-environment. Environ. Toxicol. Chem. 11(3):381-391.

Reeve, W.R. et al. 1976. A controlled environmental pollution experiment (CEPEX) and its usefulness in the study of larger marine zooplankton under toxic stress. In: Effects of pollutants on aquatic organisms. Lockwood, P.M. (Ed.). Cambridge University Press, New York, NY. p. 145.

Robins, R.G., Berg, R.B., Dysinger, D.K., Duaime, T.E., Metesh, J.J., Diebold, F.E., Twidwell, L.G., Mitman, G.G., Chatham , W.H., Huang, H.H., Young, C.A. 1997. Chemical, physical and biological interactions at the Berkeley Pit, Butte, Montana. Tailings and Mine Waste 97. Bakeman, Rotterdam.

Rueter, J.G. 1983. Alkaline phosphatase inhibition by copper: Implications to phosphorus nutrition and use as a biochemical marker of toxicity. Limnol. Oceanogr. 28:743.

Santore, R.C., D.M. Di Toro and P.R. Paquin, H.E. Allen, and J.S. Meyer. 2001. "A Biotic Ligand Model of the Acute Toxicity of Metals. II. Application to Acute Copper Toxicity in Freshwater Fish and Daphnia," Environmental Toxicology and Chemistry. 20(10):2397-2402.

Schafer, H., A. Wentzel, U. Fritsche, G. Roderer and W. Trauspurger. 1993. Long-term effects of selected xenobiotica on freshwater green alga: Developmental of a flow-through test system. Sci. Total Environ. Suppl.:735-740.

Smith, D. S., Bell, R. A., and Kramer, J. R. 2002. Metal speciation in natural waters with emphasis on reduced sulfur groups as strong metal binding sites. Comparative Biochemistry and Physiology 133C:65-74.

Sprague, J.B. 1968. Avoidance reactions of rainbow trout to zinc sulphate solutions. Water Res.2(5):367-372.

Steemann-Nielsen, E. and L. Kamp-Nielsen. 1970. Influence of deleterious concentrations of copper on the growth of *Chlorella pyrenoidosa*. Physiol. Plant. 23:828-840.

Steemann-Nielsen, E. and S. Wium-Andersen. 1970. Copper ions as poison in sea and in freshwater. Mar. Biol. 6:93.

Stephan, C.E. 1995. Derivation of conversation factors for the calculation of dissolved freshwater aquatic life criteria for metals. Report. March 11, 1995. U.S. EPA, Duluth, MN.

Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman and W.A. Brungs. 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.

Stephan, C.E., and J.W. Rogers. 1985. Advantages of Using Regression Analysis to Calculate Results of Chronic Toxicity Tests. In: Aquatic Toxicology and Hazard Assessment: Eighth Symposium. R.C. Bahner and D.J. Hansen, Eds. ASTM STP 891. American Society for Testing and Materials, Philadelphia, PA. Pp. 328-338.

Stokes, P. and T.C. Hutchinson. 1976. Copper toxicity to phytoplankton, as affected by organic ligands, other cations and inherent tolerance of algae to copper. In: Toxicity to biota of metal forms in natural water. Andrew,

Swallow, K.C. et al. 1978. Potentiometric determination of copper complexation by phytoplankton exudates. Limnol. Oceanogr. 23:538.

Taraldsen, J.E. and T.J. Norberg-King. 1990. New method for determining effluent toxicity using duckweed (*Lemna minor*). Environ. Toxicol. Chem. 9(6):761-767.

Tipping, E., 1994. “WHAM--A Chemical Equilibrium Model and Computer Code for Waters, Sediments, and Soils Incorporating a Discrete Site/Electrostatic Model of Ion-Binding by Humic Substances,” *Computers and Geosciences*, 20(6): 973-1023.

U.S. EPA. 1980. Ambient water quality criteria for copper. EPA-440/4-80-036. National Technical Information Service, Springfield, VA.

U.S. EPA. 1983a. Methods for chemical analysis of water and wastes. EPA-600/4-79-020. National Technical Information Service, Springfield, VA.

U.S. EPA. 1983b. Water quality standards regulation. Federal Register 48:51400. November 8.

U.S. EPA. 1983c. Water quality standards handbook. Office of Water Regulations and Standards, Washington, D.C.

U.S. EPA. 1985. “Ambient Water Quality Criteria for Copper - 1984,” Office of Water Regulations and Standards, Criteria and Standards Division, Washington, DC.

U.S. EPA. 1986. Quality Criteria for Water 1986. EPA 440/5-86-001. Office of Water, Regulation and Standards, Washington, DC.

U.S. EPA. 1988. Short-term methods for estimating the chronic toxicity of effluents and receiving waters to marine and estuarine organisms. EPA/600/4-87-028. National Technical Information Service, Springfield, VA.

U.S. EPA. 1991. Technical support document for water quality-based toxics control. EPA-505/2-90-001. National Technical Information Service, Springfield, VA.

U.S. EPA. 1992. Interim guidance on interpretation and implementation of aquatic life criteria for metals. Health and Ecological Criteria Division, Office of Science and Technology, U.S. Environmental Protection Agency, Washington, District of Columbia, USA.

U.S. EPA. 1993. Methods for measuring the acute toxicity of effluents and receiving water to freshwater and marine organisms. Fourth Edition. EPA/600/4-90/027F. National Technical Information Service, Springfield, VA.

U.S. EPA. 1994. Water quality standards handbook. 2nd Edition. EPA-823-B94-005b.National Technical Information Service, Springfield, VA.

U.S. EPA. 1996 1995 Updates: Water Quality Criteria Documents for the Protection of Aquatic Life in Ambient Water. Office of Water. EPA-820-B-96-001.

University of Wisconsin-Superior. 1995. Results of freshwater simulation tests concerning dissolved metal. Report. March 10, 1995. U.S. EPA, Duluth, MN.

van den Berg, C.M.G., P.T.S. Wong and Y.K. Chan. 1979. Measurement of complexing materials excreted from algae and their ability to ameliorate copper toxicity. J. Fish. Res. Board Can. 36:901-905.

Wallen, I.E., W.C. Greer and R. Lasater. 1957. Toxicity to *Gambusia affinis* of certain pure chemicals in turbid waters. Sewage Ind. Wastes 29:695-711.

Winner, R.W. 1985. Bioaccumulation and toxicity of copper as affected by interactions between humic acid and water hardness. Water Res. 19(4):449-455.

Winner, R.W. and H.A. Owen. 1991b. Toxicity of copper to *Chlamydomonas reinhardtii* (Chlorophyceae) and *Ceriodaphnia dubia* (Crustacea) in relation to changes in water chemistry of a freshwater pond. Aquat. Toxicol. 21(3-4):157-169.

Wood, C. M. 1992. Flux measurements as indices of H+ and metal effects on freshwater fish. Aquatic Toxicology 22:239-264.

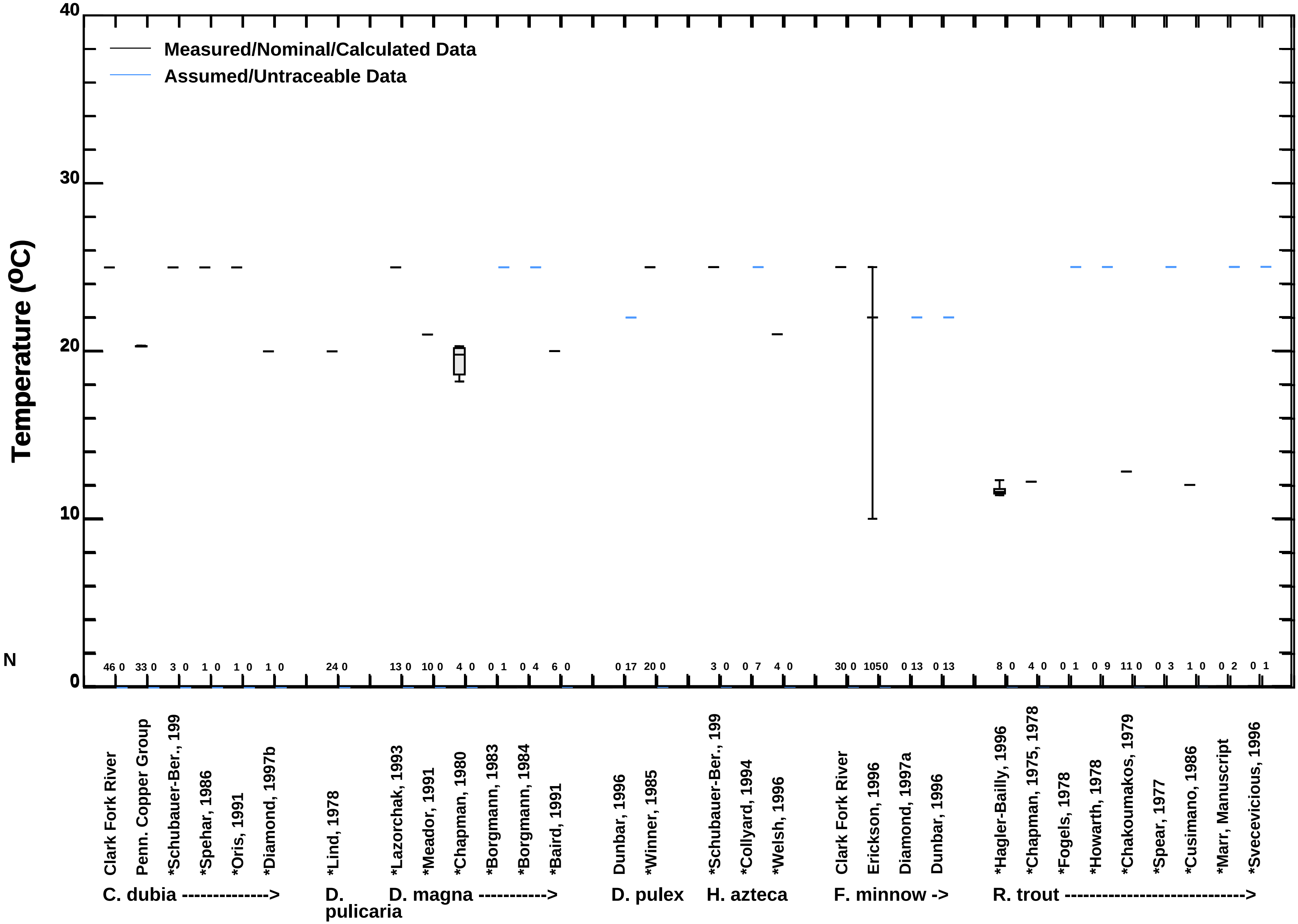
Wood, C. M., Adams, W. J., Ankley, G. T., DiBona, D. R., Luoma, W. N., Playle, R. C., Stubblefield, W. A., Bergman, H. L., Erickson, R. J., Mattice, J. S., and Schlekat, C. E. 1997. Environmental toxicology of metals. In Bergman, H. L., and Dorward-King, E. J. (eds.) Reassessment of Metals Criteria for Aquatic Life Protection. Pensacola, FL: SETAC Press.

Zitko, V. 1976. Toxicity to biota of metal forms in natural water. In Andrew, R. A., Hodson, P. V., and Konasewich, D. (eds.) Toxicity to Biota of Metal Forms in Natural Water. Proceedings of Workshop, October 1975, Duluth, MN. Windsor, Ontario: International Joint Commission.

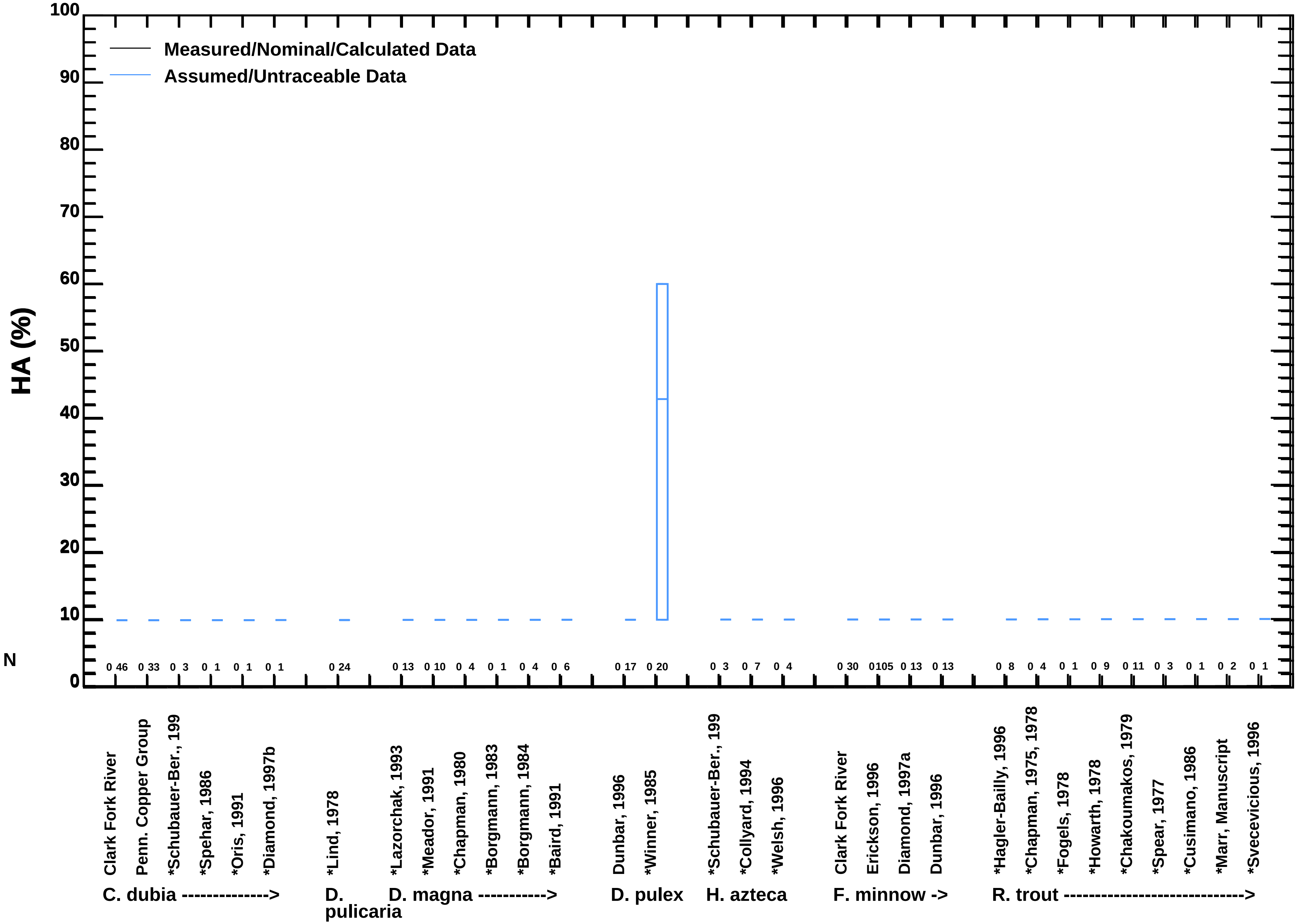
Zitko, V., and Carson, W. G. 1976. A mechanism of the effects of water hardness on the lethality of heavy metals to fish. Chemosphere 5:299-303.

# Appendices

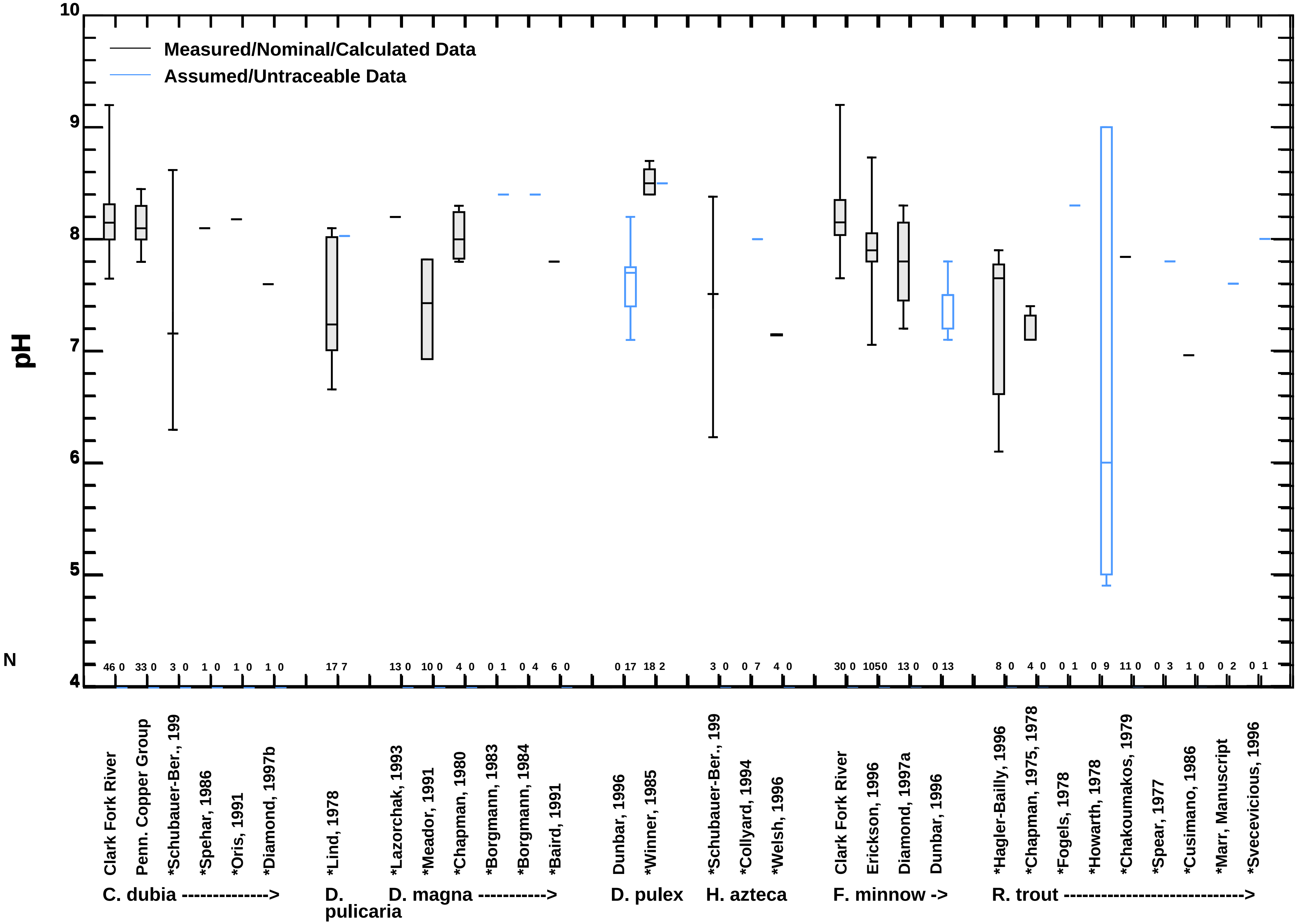
# Appendix A.  Ranges in Calibration and Application Data Sets



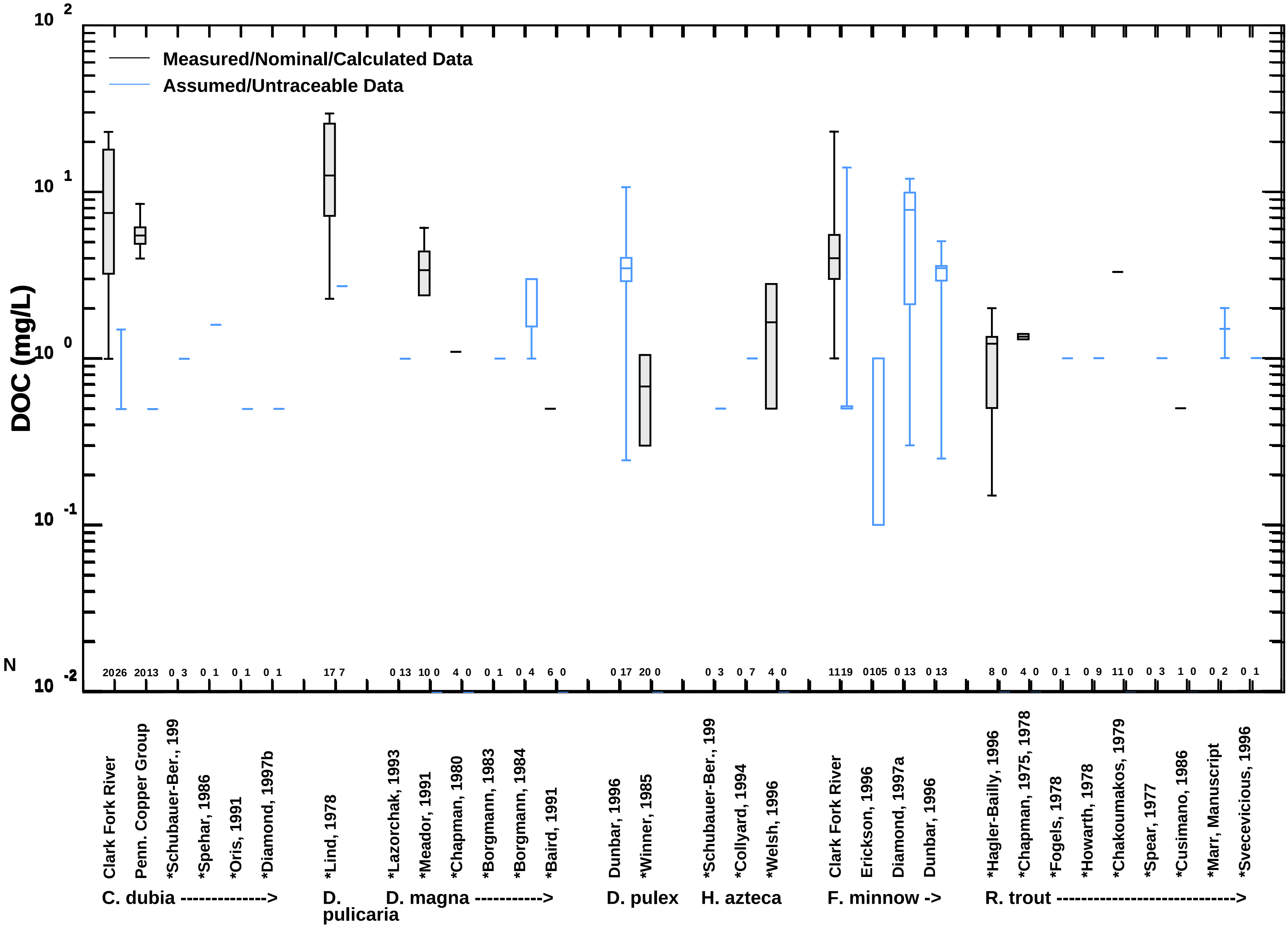
**Median, Range and Quartiles of Temperature in BLM Calibration and Application Datasets**
**(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)**



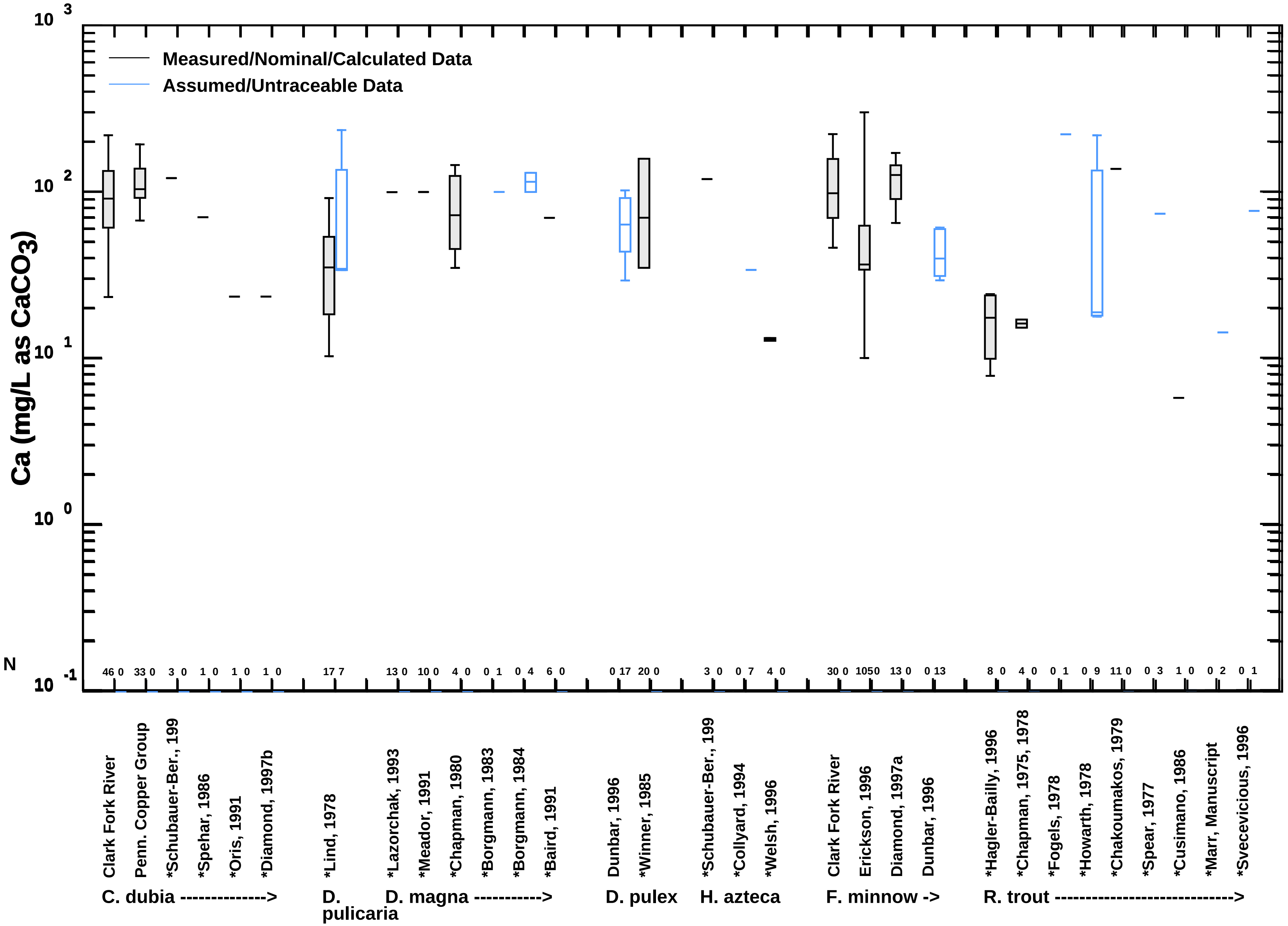
**Median, Range and Quartiles of HA in BLM Calibration and Application Datasets**
**(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)**



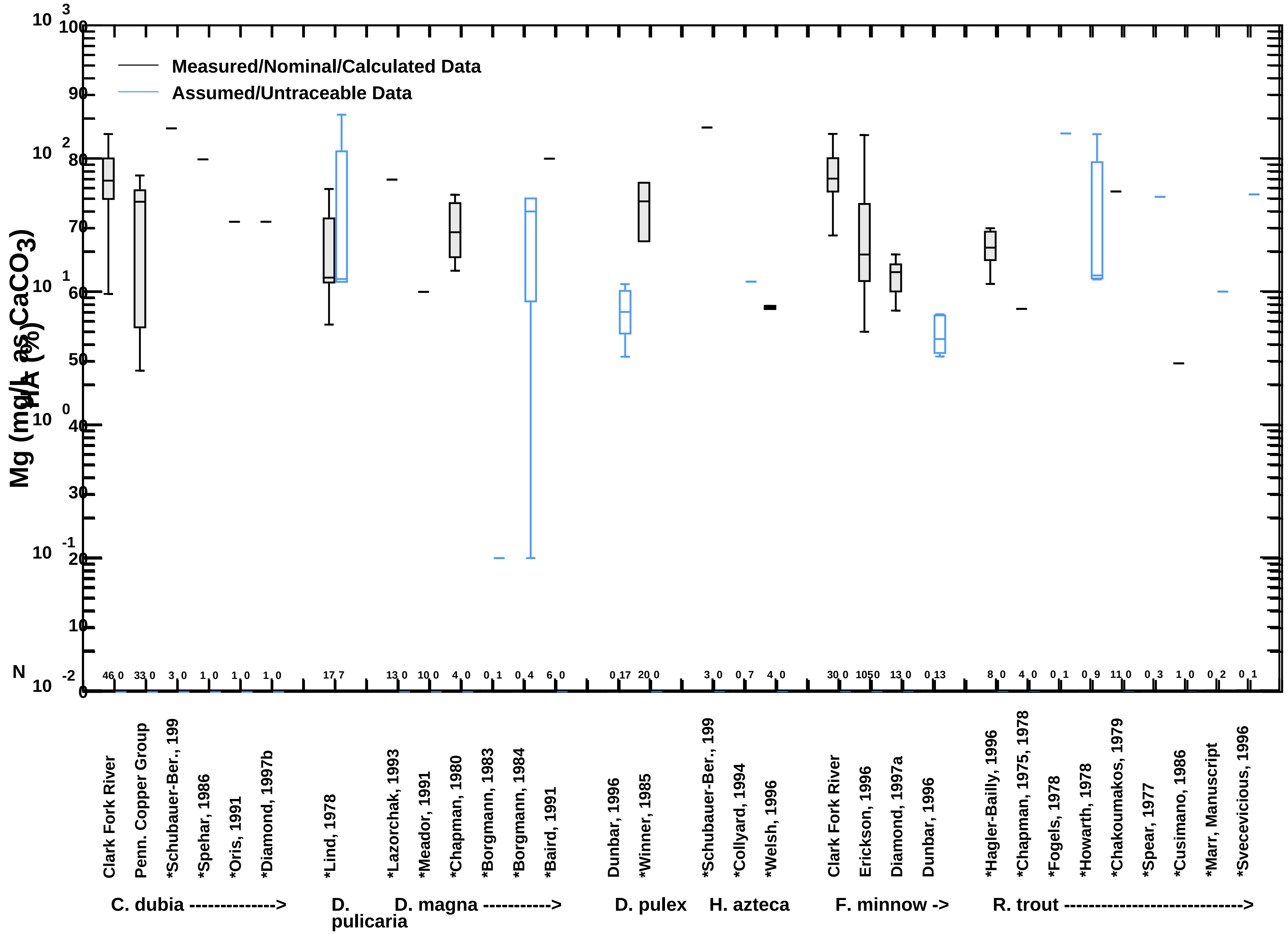
Median, Range and Quartiles of pH in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



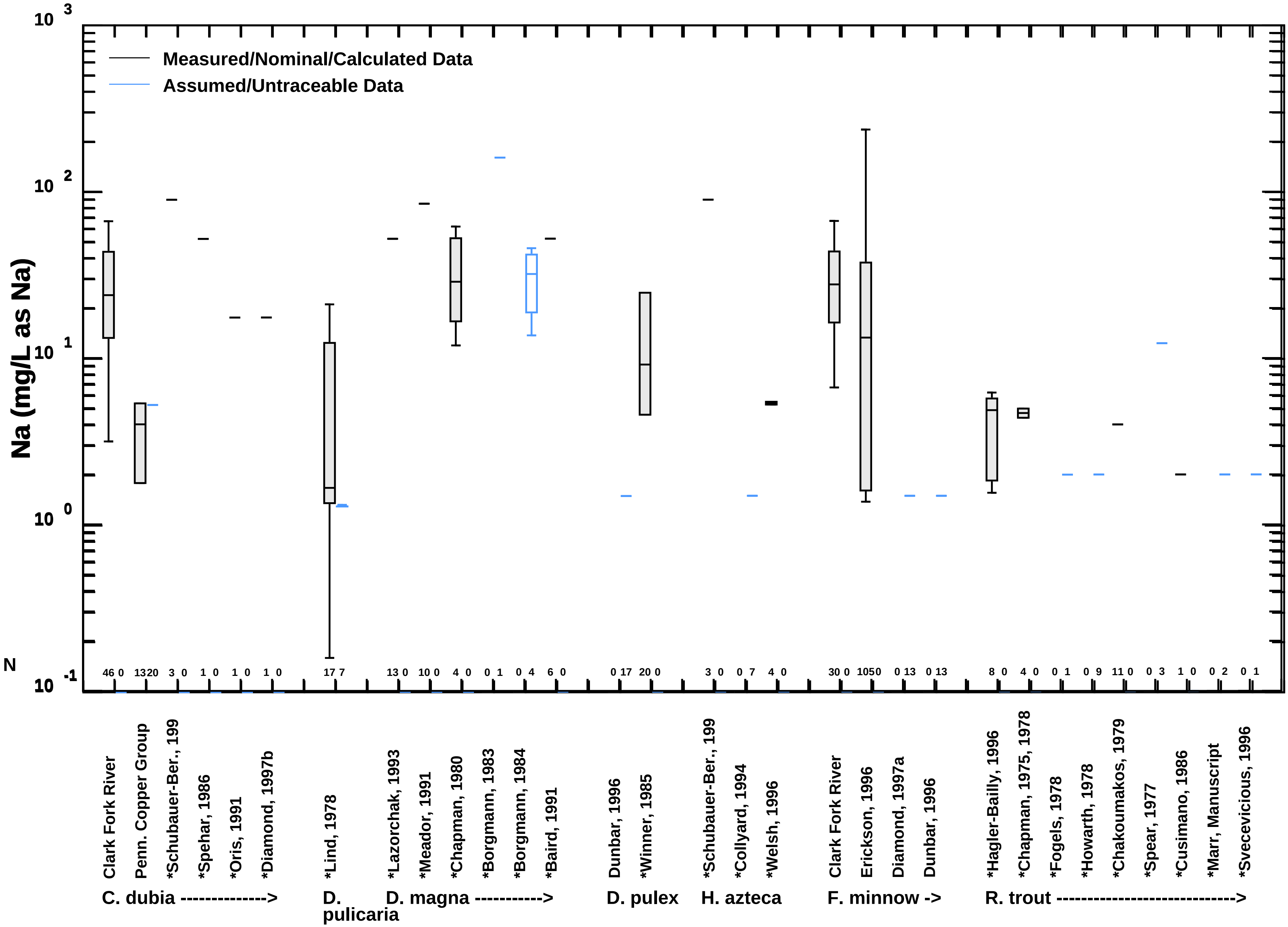
Median, Range and Quartiles of DOC in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



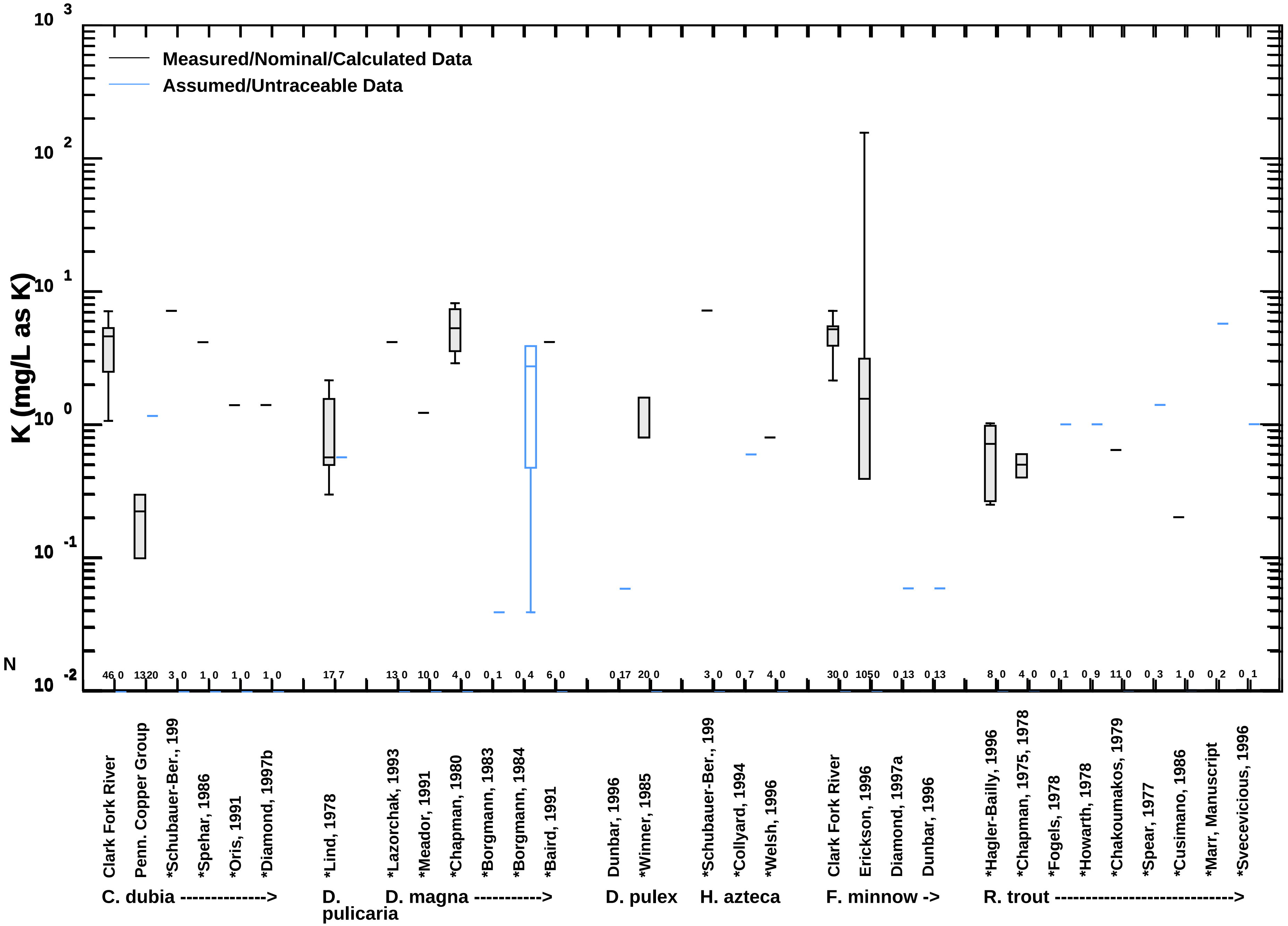
Median, Range and Quartiles of Ca in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



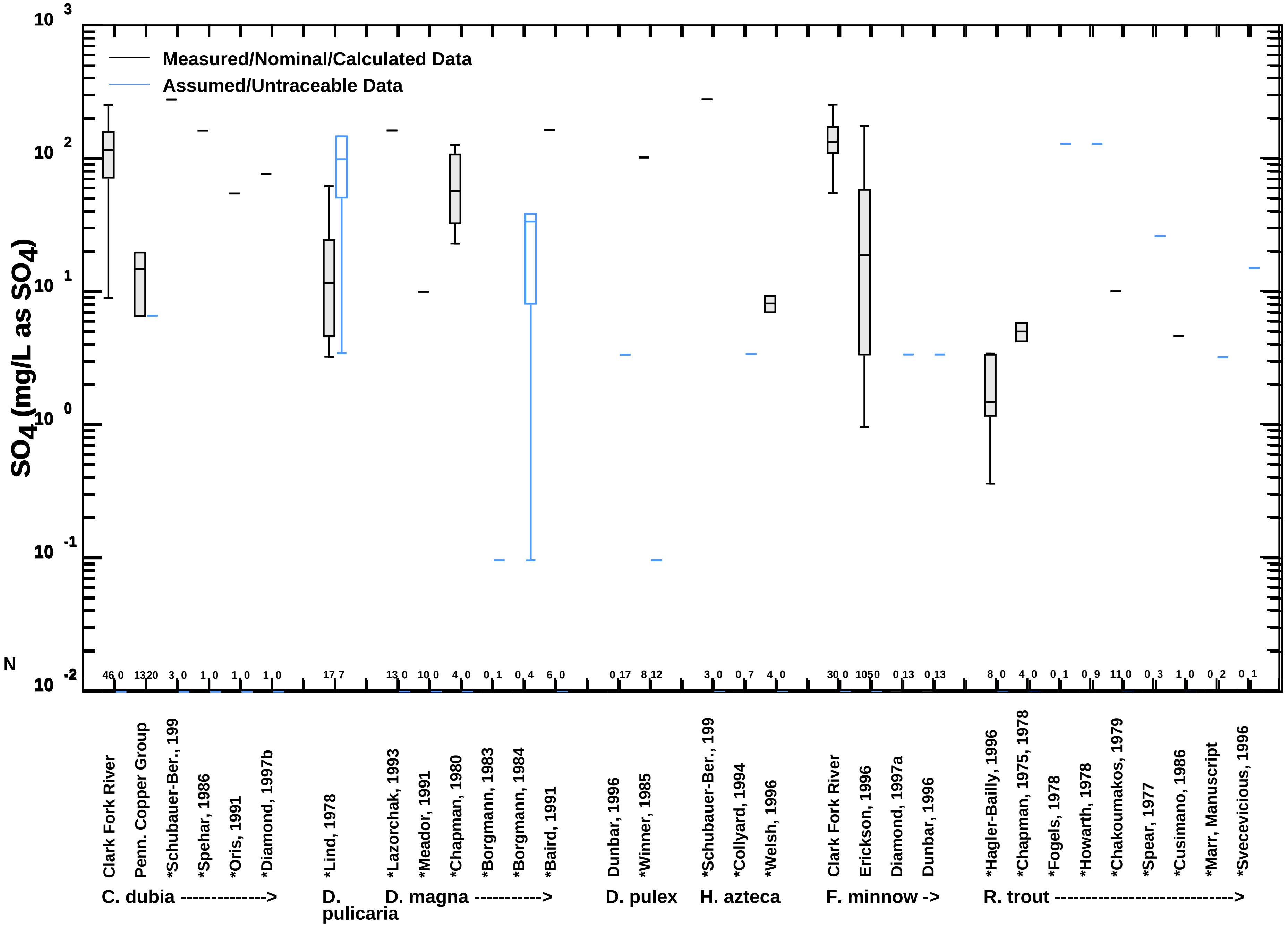
**Median, Range and Quartiles of HA in BLM Calibration and Application Datasets**
**(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)**



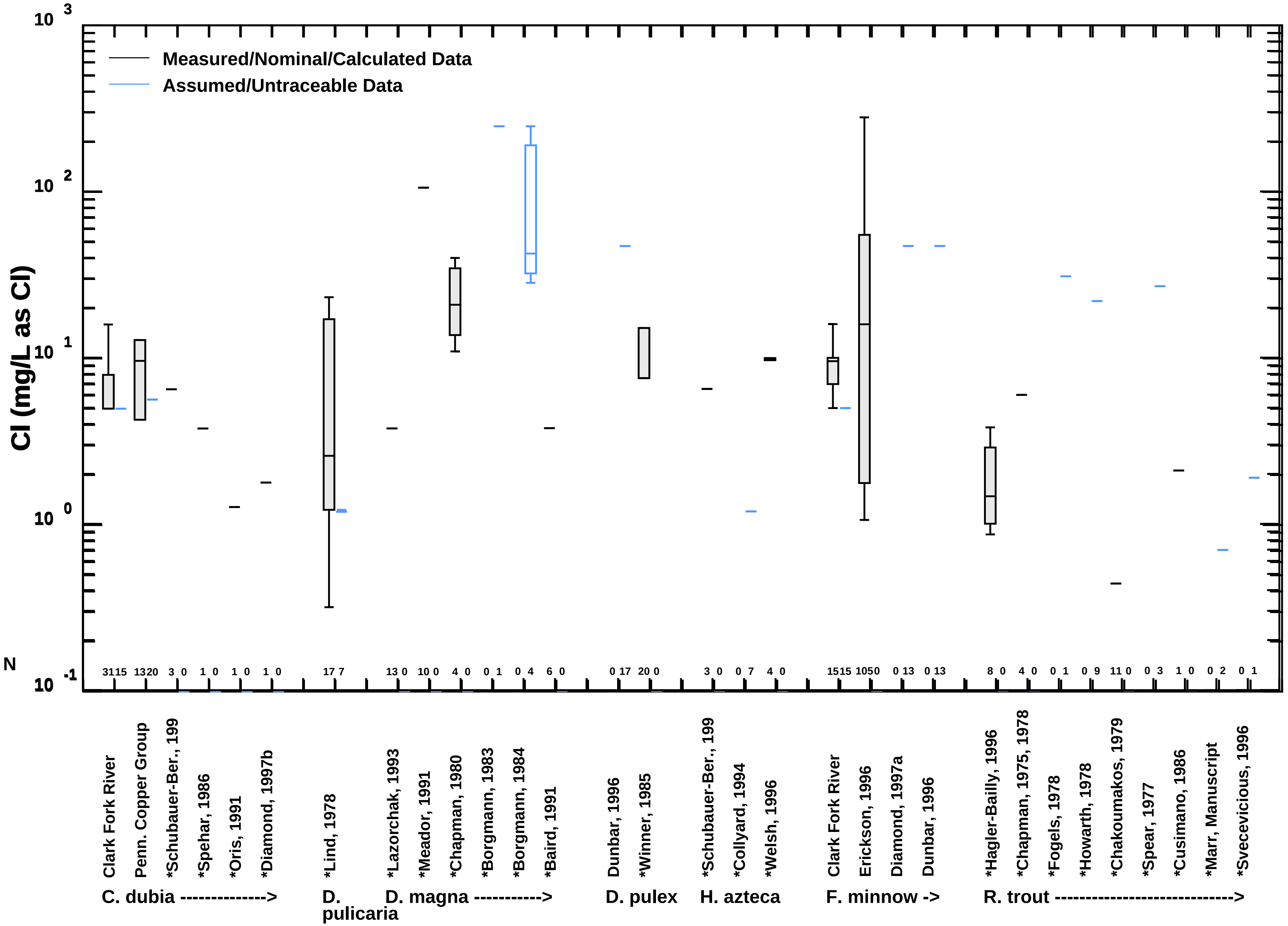
Median, Range and Quartiles of Na in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



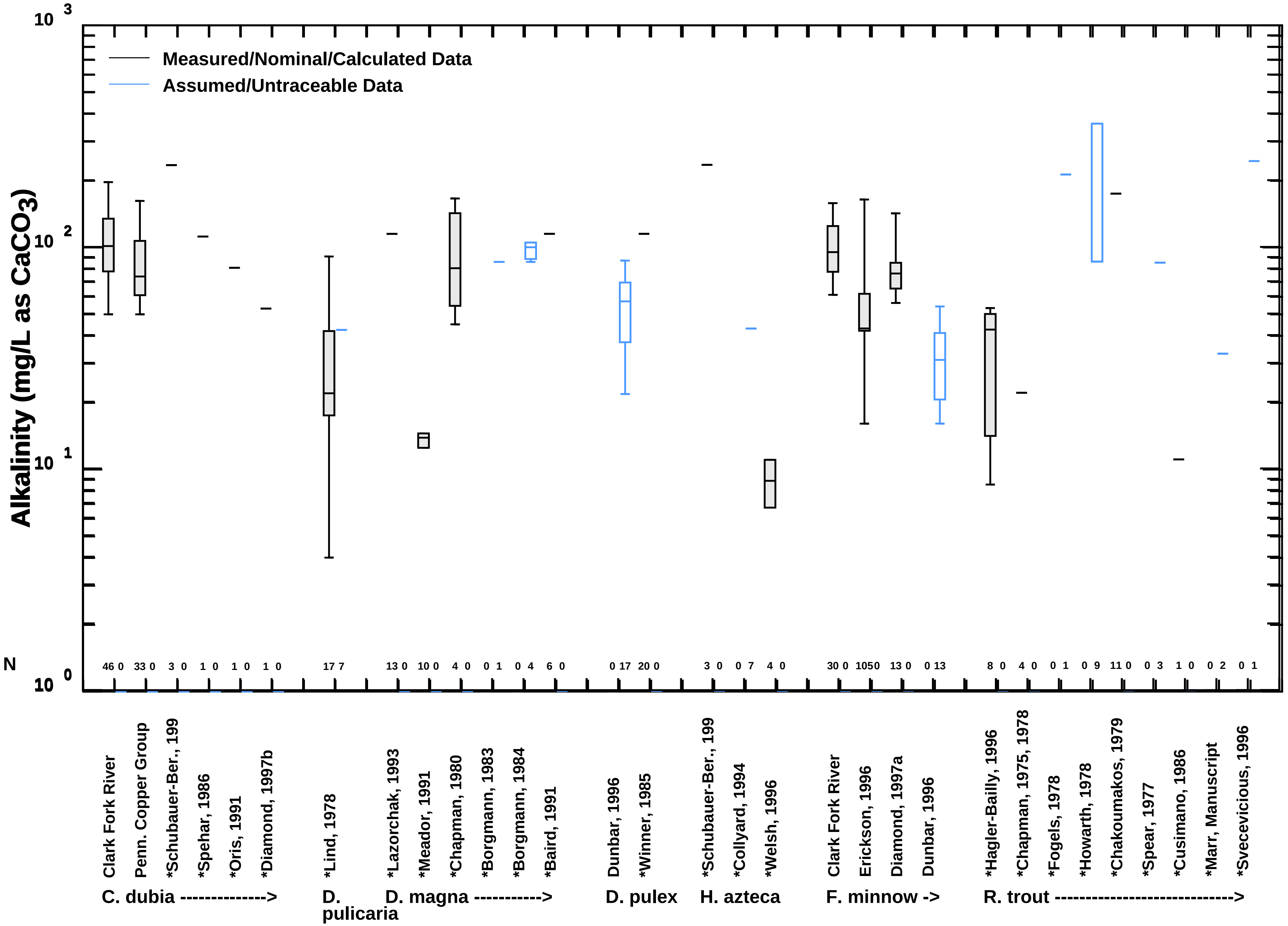
Median, Range and Quartiles of K in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



Median, Range and Quartiles of SO4 in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



Median, Range and Quartiles of Cl in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



Median, Range and Quartiles of Alkalinity in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as CaCO$_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Bacteria, *Escherichia coli* | S,U | Copper sulfate | - | 48 hr | Threshold of inhibited glucose use; measured by pH change in media | 80 | - | Bringmann and Kuhn 1959a |
| Bacteria, *Pseudomonas putida* | S,U | Copper sulfate | 81.1 | 16 hr | EC3 (cell numbers) | 30 | - | Bringmann and Kuhn 1976, 1977a, 1979, 1980a |
| Protozoan, *Entosiphon sulcatum* | S,U | Copper sulfate | 81.9 | 72 hr | EC5 (cell numbers) | 110 | - | Bringmann 1978;<br>Bringmann and Kuhn 1979, 1980a, |
| Protozoan, *Microrega heterostoma* | S,U | Copper sulfate | 214 | 28 hr | Threshold of decreased feeding rate | 50 | - | Bringmann and Kuhn 1959b |
| Protozoan, *Chilomonas paramecium* | S,U | Copper sulfate | - | 48 hr | Growth threshold | 3,200 | - | Bringmann and Kuhn 1980b, 1981 |
| Protozoan, *Uronema parduezi* | S,U | Copper sulfate | - | 20 hr | Growth threshold | 140 | - | Bringmann and Kuhn 1980b, 1981 |
| Protozoa, mixed species | - | - | - | 7 days | Reduced rate of colonization | 167 | - | Cairns et al. 1980 |
| Protozoa, mixed species | S,M,T | Copper sulfate | - | 15 days | Reduced rate of colonization | 100 | - | Buikema et al. 1983 |
| Green alga, *Cladophora glomerata* | Dosed stream | Copper sulfate | 226-310 | 10 mo | Decreased abundance from 21% down to 0% | 120 | - | Weber and McFarland 1981 |
| Green alga, *Chlamydomonas reinhardtii* | - | Copper sulfate | 76 | 72 hr | Deflagellation | 6.7 | - | Garvey et al. 1991 |
| Green alga, *Chlamydomonas reinhardtii* | - | Copper sulfate | 76 | 72 hr | Deflagellation | 6.7 | - | Garvey et al. 1991 |
| Green alga, *Chlamydomonas reinhardtii* | - | Copper sulfate | 76 | 72 hr | Deflagellation | 16.3 | - | Garvey et al. 1991 |
| Green alga, *Chlamydomonas reinhardti* | - | Copper sulfate | 76 | 72 hr | Deflagellation | 25.4 | - | Garvey et al. 1991 |
| Green alga, *Chlorella* sp. | S,U | Copper nitrate | - | 28 hr | Inhibited photosynthesis | 6.3 | - | Gachter et al. 1973 |
| Green alga, *Chlorella pyrenoidosa* | S,U | - | 29.4 | 72 hr | IC50 (cell division rate) | 16 | - | Stauber and Florence 1989 |
| Green alga, *Chlorella pyrenoidosa* | S,U | - | 14.9 | 72 hr | IC50 (cell division rate) | 24 | - | Stauber and Florence 1989 |
| Green alga, *Chlorella pyrenoidosa* | S,U | Copper sulfate | 82 | 4 hr | Disturbed photosystem II | 25 | - | Vavilin et al. 1995 |
| Green alga, *Eudorina californica* | S,U | Copper sulfate | 19.1 | - | Decrease in cell density | 5,000 | - | Young and Lisk 1972 |
| Green alga (flagellate cells), *Haematococcus* sp. | S,U | Copper sulfate | 2 | 24 hr | Inhibited growth during 96 hr recovery period | 50 | - | Pearlmutter and Buchheim 1983 |
| Green alga, *Scenedesmus quadricauda* | S,U | Copper sulfate | 214 | 96 hr | Threshold of effect on cell numbers | 150 | - | Bringmann and Kuhn 1959b |
| Green alga, *Scenedesmus quadricauda* | S,U | Copper sulfate | 60 | 72 hr | EC3 (cell numbers) | 1,100 | - | Bringmann and Kuhn 1980a |
| Green alga, *Scenedesmus quadricauda* | S,U | Copper sulfate | 34.8 | 24 hr | EC50 (photosynthesis) | 100 | - | Starodub et al. 1987 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Green alga,<br>*Scenedesmus quadricauda* | S,U | Copper sulfate | 34.8 | 24 hr | NOEC<br>(growth) | 50 | - | Starodub et al. 1987 |
| Green alga,<br>*Scenedesmus quadricauda* | S,U | Copper sulfate | 34.8 | 24 hr | NOEC<br>(growth) | 50 | - | Starodub et al. 1987 |
| Green alga,<br>*Scenedesmus quadricauda* | S,U | Copper sulfate | 34.8 | 24 hr | NOEC<br>(growth) | >200 | - | Starodub et al. 1987 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper chloride | 14.9 | 7 days | Growth reduction | 50 | - | Bartlett et al.1974 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 29.3 | 72 hr | EC50<br>(cell count) | 19 | - | Vasseur et al. 1988 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 24.2 | 72 hr | EC50<br>(cell count) | 41 | - | Vasseur et al. 1988 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 24.2 | 72 hr | EC50<br>(cell count) | 28 | - | Vasseur et al. 1988 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 14.9 | 72 hr | EC50<br>(cell count) | 60 | - | Vasseur et al. 1988 |
| Green alga,<br>*Selenastrum capricornutum* | S,U | Copper sulfate | 24.2 | 72 hr | EC50<br>(cell count) | 28.5 | - | Benhra et al. 1997 |
| Green alga,<br>*Selenastrum capricornutum* | F,U | Copper sulfate | 15 | 24 hr | EC50<br>(cell density) | 21 | - | Chen et al. 1997 |
| Diatom,<br>*Cocconeis placentula* | Dosed stream | Copper sulfate | 226-310 | 10 mo | Decreased abundance from 21% dow to <1% | 120 | - | Weber and McFarland 1981 |
| Phytoplankton,<br>mixed species | S,U | - | - | 124 hr | Averaged 39% reduction in primary production | 10 | - | Cote 1983 |
| Macrophyte,<br>*Elodea canadensis* | S,U | Copper sulfate | - | 24 hr | EC50<br>(photosynthesis) | 150 | - | Brown and Rattigan 1979 |
| Microcosm | F,M,T,D | Copper sulfate | 200 | 32 wk | LOEC<br>(primary production) | 9.3 | - | Hedtke 1984 |
| Microcosm | F,M,T,D | Copper sulfate | 200 | 32 wk | NOEC<br>(primary production) | 4 | - | Hedtke 1984 |
| Microcosm | F,M,T | Copper sulfate | 76.7 | 96 hr | Significant drop in no. of taxa and no. of individuals | 15 | - | Clements et al. 1988 |
| Microcosm | F,M,T | Copper sulfate | 58.5 | 10 days | Significant drop in no. of individuals | 2.5 | - | Clements et al. 1989 |
| Microcosm | F,M,T | Copper sulfate | 151 | 10 days | 58% drop in no. of individuals | 13.5 | - | Clements et al. 1989 |
| Microcosm | F,M,T | Copper sulfate | 68 | 10 days | Significant drop in species richness and no. of individuals | 11.3 | - | Clements et al. 1990 |
| Microcosm | F,M,T | Copper sulfate | 80 | 10 days | Significant drop in species richness and no. of individuals | 10.7 | - | Clements et al. 1990 |
| Microcosm | S,M,T | Copper sulfate | 102 | 5 wk | 14-28% drop in phytoplankton species richness | 20 | - | Winner and Owen 1991b |
| Microcosm | F,M,T | - | 160 | 28 days | LOEC<br>(species richness) | 19.9 | - | Pratt and Rosenberger 1993 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Dosed stream | F,M,D | Copper sulfate | 56 | 1 yr | Shifts in periphyton species abundance | 5.208 | - | Leland and Carter 1984 |
| Dosed stream | F,M,D | Copper sulfate | 56 | 1 yr | Reduced algal production | 5.208 | - | Leland and Carter 1985 |
| Sponge,<br>*Ephydatia fluviatilis* | S,U | Copper sulfate | 200 | 10 days | Reduced growth by 33% | 6 | - | Francis and Harrison 1988 |
| Sponge,<br>*Ephydatia fluviatilis* | S,U | Copper sulfate | 200 | 10 days | Reduced growth by 100% | 19 | - | Francis and Harrison 1988 |
| Rotifer,<br>*Philodina acuticornis* | S,U | Copper sulfate | 45 | 48 hr | LC50<br>($5^{0}$ C) | 1,300 | - | Cairns et al. 1978 |
| Rotifer,<br>*Philodina acuticornis* | S,U | Copper sulfate | 45 | 48 hr | LC50<br>($10^{0}$ C) | 1,200 | - | Cairns et al. 1978 |
| Rotifer,<br>*Philodina acuticornis* | S,U | Copper sulfate | 45 | 48 hr | LC50<br>($15^{0}$ C) | 1,130 | - | Cairns et al. 1978 |
| Rotifer,<br>*Philodina acuticornis* | S,U | Copper sulfate | 45 | 48 hr | LC50<br>($20^{0}$ C) | 1,000 | - | Cairns et al. 1978 |
| Rotifer,<br>*Philodina acuticornis* | S,U | Copper sulfate | 45 | 48 hr | LC50<br>($25^{0}$ C) | 950 | - | Cairns et al. 1978 |
| Rotifer,<br>*Brachionus calyciflorus* | S, U | Copper sulfate | 39.8 | 24 hr | EC50<br>(mobility) | 200 | - | Couillard et al. 1989 |
| Rotifer (2 hr),<br>*Brachionus calyciflorus* | S,U | Copper sulfate | - | 2 hr | LOEC<br>(swimming activity) | 12.5 | - | Charoy et al. 1995 |
| Rotifer,<br>*Brachionus calyciflorus* | S,U | Copper sulfate | 90 | 24 hr | EC50<br>(mobility) | 76 | - | Ferrando et al. 1992 |
| Rotifer (2 hr),<br>*Brachionus calyciflorus* | S,U | Copper sulfate | 90 | 5 hr | EC50<br>(filtration rate) | 34 | - | Ferrando et al. 1993a |
| Rotifer (2 hr),<br>*Brachionus calyciflorus* | S,U | Copper sulfate | 90 | 6 days | LOEC<br>(reproduction decreased 26%) | 5 | - | Janssen et al. 1993 |
| Rotifer (2 hr),<br>*Brachionus calyciflorus* | S,U | Copper sulfate | 90 | 5 hr | LOEC<br>(reduced swimming speed) | 12 | - | Janssen et al. 1993 |
| Rotifer (2 hr),<br>*Brachionus calyciflorus* | S,U | Copper sulfate | 85 | 3 days | LOEC<br>(reproduction decreased 27%) | 5 | - | Janssen et al. 1994 |
| Rotifer (2 hr),<br>*Brachionus calyciflorus* | S,U | Copper sulfate | 85 | 3 days | LOEC<br>(reproduction decreased 29%) | 5 | - | Janssen et al. 1994 |
| Rotifer (2 hr),<br>*Brachionus calyciflorus* | S,U | Copper sulfate | 85 | 8 days | LOEC<br>(reproduction decreased 47%) | 5 | - | Janssen et al. 1994 |
| Rotifer (2 hr),<br>*Brachionus calyciflorus* | S,U | Copper chloride | 170 | 35 min | LOEC<br>(food ingestion rate) | 100 | - | Juchelka and Snell 1994 |
| Rotifer (2 hr),<br>*Brachionus calyciflorus* | S,U | Copper sulfate | 63.2 | 24 hr | EC50<br>(mobility) | 9.4 | - | Porta and Ronco 1993 |
| Rotifer (2 hr),<br>*Brachionus calyciflorus* | S,U | - | 90 | 2 days | LOEC<br>(reproduction decreased 100%) | 30 | - | Snell and Moffat 1992 |
| Rotifer (<2 hr),<br>*Brachionus calyciflorus* | S, U | - | 85 | 24 hr | EC50<br>(mobility) | 26 | - | Snell et al. 1991b |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method$^a$ | Chemical | Hardness (mg/L as CaCO$_3$) | Duration | Effect | Total Concentration (µg/L)$^b$ | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Rotifer (<2 hr),<br>*Brachionus calyciflorus* | S, U | - | 85 | 24 hr | EC50<br>(mobility; 10$^0$ C) | 18 | - | Snell 1991;<br>Snell et al. 1991b |
| Rotifer (<2 hr),<br>*Brachionus calyciflorus* | S, U | - | 85 | 24 hr | EC50<br>(mobility; 15$^0$ C) | 31 | - | Snell 1991;<br>Snell et al. 1991b |
| Rotifer (<2 hr),<br>*Brachionus calyciflorus* | S, U | - | 85 | 24 hr | EC50<br>(mobility; 20$^0$ C) | 31 | - | Snell 1991;<br>Snell et al. 1991b |
| Rotifer (<2 hr),<br>*Brachionus calyciflorus* | S, U | - | 85 | 24 hr | EC50<br>(mobility; 25$^0$ C) | 26 | - | Snell 1991;<br>Snell et al. 1991b |
| Rotifer (<2 hr),<br>*Brachionus calyciflorus* | S, U | - | 85 | 24 hr | EC50<br>(mobility; 30$^0$ C) | 25 | - | Snell 1991;<br>Snell et al. 1991b |
| Rotifer (<3 hr),<br>*Brachionus rubens* | S, U | Copper sulfate | 90 | 24 hr | LC50 | 19 | - | Snell and Persoone 1989b |
| Rotifer,<br>*Keratella cochlearis* | S,U | Copper chloride | - | 24 hr | LC50 | 101 | - | Borgman and Ralph 1984 |
| Worm,<br>*Aeolosoma headleyi* | S,U | Copper sulfate | 45 | 48 hr | LC50<br>(5$^0$ C) | 2,600 | - | Cairns et al. 1978 |
| Worm,<br>*Aeolosoma headleyi* | S,U | Copper sulfate | 45 | 48 hr | LC50<br>(10$^0$ C) | 2,300 | - | Cairns et al. 1978 |
| Worm,<br>*Aeolosoma headleyi* | S,U | Copper sulfate | 45 | 48 hr | LC50<br>(15$^0$ C) | 2,000 | - | Cairns et al. 1978 |
| Worm,<br>*Aeolosoma headleyi* | S,U | Copper sulfate | 45 | 48 hr | LC50<br>(20$^0$ C) | 1,650 | - | Cairns et al. 1978 |
| Worm,<br>*Aeolosoma headleyi* | S,U | Copper sulfate | 45 | 48 hr | LC50<br>(50 C) | 1,000 | - | Cairns et al. 1978 |
| Worm (adult),<br>*Lumbriculus variegatus* | S,U | Copper sulfate | 30 | | LC50 | 150 | | Bailey and Liu, 1980 |
| Worm (7 mg),<br>*Lumbriculus variegatis* | F,M,T | Copper sulfate | 45 | 10 days | LC50 | 35 | - | West et al. 1993 |
| Tubificid worm,<br>*Limnodrilus hoffmeisteri* | S,U | Copper sulfate | 100 | | LC50 | 102 | | Wurtz and Bridges 1961 |
| Tubificid worm,<br>*Tubifex tubifex* | R, U | Copper sulfate | 245 | | LC50 | 158 | | Khangarot 1991 |
| Snail (11-27 mm),<br>*Campeloma decisum* | F,M,T | Copper sulfate | 45 | 6 wk | LOEC<br>(mortality) | 14.8 | - | Arthur and Leonard 1970 |
| Snail,<br>*Gyraulus circumstriatus* | S,U | Copper sulfate | 100 | | LC50 | 108 | | Wurtz and Bridges 1961 |
| Snail,<br>*Goniobasis livescens* | S,U | Copper sulfate | 154 | 48 hr | LC50 | 860 | - | Cairns et al. 1976 |
| Snail,<br>*Goniobasis livescens* | S,M,D | Copper sulfate | 154 | 96 hr | LC50 | - | 390 | Paulson et al. 1983 |
| Snail,<br>*Nitrocris* sp. | S,U | Copper sulfate | 45 | 48 hr | LC50<br>(5$^0$ C) | 3,000 | - | Cairns et al. 1978 |
| Snail,<br>*Nitrocris* sp. | S,U | Copper sulfate | 45 | 48 hr | LC50<br>(10$^0$ C) | 2,400 | - | Cairns et al. 1978 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Snail, *Nitrocris* sp. | S,U | Copper sulfate | 45 | 48 hr | LC50 (15$^0$ C) | 1,000 | - | Cairns et al. 1978 |
| Snail, *Nitrocris* sp. | S,U | Copper sulfate | 45 | 48 hr | LC50 (20$^0$ C) | 300 | - | Cairns et al. 1978 |
| Snail, *Nitrocris* sp. | S,U | Copper sulfate | 45 | 48 hr | LC50 (25$^0$ C) | 210 | - | Cairns et al. 1978 |
| Snail, *Lymnaea emarginata* | S,U | Copper sulfate | 154 | 48 hr | LC50 | 300 | - | Cairns et al. 1976 |
| Snail (adult), *Juga plicifera* | F,M,T | Copper chloride | 23 | 30 days | LC50 | 6 | - | Nebeker et al. 1986b |
| Snail (adult), *Lithoglyphus virens* | F,M,T | Copper chloride | 23 | 30 days | LC50 | 4 | - | Nebeker et al. 1986b |
| Snail, *Physa heterostropha* | S,U | Copper sulfate | 100 | | LC50 | 69 | | Wurtz and Bridges 1961 |
| Freshwater mussel (released glochidia), *Actinonaias pectorosa* | R,M | Copper sulfate | 140 | 24 hr | | 132 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Actinonaias pectorosa* | R,M | Copper sulfate | 150 | 24 hr | | 93 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Actinonaias pectorosa* | R,M | Copper sulfate | 170 | 24 hr | | 67 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Actinonaias pectorosa* | R,M | Copper sulfate | 140 | 24 hr | | 42 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Actinonaias pectorosa* | R,M | Copper sulfate | 170 | 48 hr | | 51 | | Jacobson et al. 1997 |
| Freshwater mussel (1-2 d), *Anodonta grandis* | S,M,T | Copper sulfate | 70 | 24 hr | LC50 | 44 | - | Jacobson et al. 1993 |
| Freshwater mussel (1-2 d), *Anodonta imbecilis* | S,M,T | Copper sulfate | 39 | 48 hr | LC50 | 171 | - | Keller and Zam 1991 |
| Freshwater mussel (1-2 d), *Anodonta imbecilis* | S,M,T | Copper sulfate | 90 | 48 hr | LC50 | 388 | - | Keller and Zam 1991 |
| Freshwater mussel (released glochidia), *Lampsilis fasciola* | R,M,T | Copper sulfate | 170 | 24 hr | | 48 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Lampsilis fasciola* | R,M,T | Copper sulfate | 160 | 24 hr | | 26 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Lampsilis fasciola* | R,M,T | Copper sulfate | 75 | 24 hr | | 46 | | Jacobson et al. 1997 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Freshwater mussel (released glochidia), *Lampsilis fasciola* | R,M,T | Copper sulfate | 170 | 48 hr | | 40 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Medionidus conradicus* | R,M,T | Copper sulfate | 185 | 24 hr | | 69 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Medionidus conradicus* | R,M,T | Copper sulfate | 185 | 24 hr | | 40 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Medionidus conradicus* | R,M,T | Copper sulfate | 185 | 24 hr | | 37 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Medionidus conradicus* | R,M,T | Copper sulfate | 170 | 24 hr | | 46 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Medionidus conradicus* | R,M,T | Copper sulfate | 160 | 24 hr | | 41 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Medionidus conradicus* | R,M,T | Copper sulfate | 150 | 24 hr | | 81 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Medionidus conradicus* | R,M,T | Copper sulfate | 170 | 48 hr | | 16 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Pygranodon grandis* | R,M,T | Copper sulfate | 170 | 24 hr | | >160 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Pygranodon grandis* | R,M,T | Copper sulfate | 170 | 24 hr | | 347 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Pygranodon grandis* | R,M,T | Copper sulfate | 50 | 24 hr | | 46 | | Jacobson et al. 1997 |
| Freshwater mussel (1-2 d), *Villosa iris* | S,M,T | Copper sulfate | 190 | 24 hr | LC50 | 83 | - | Jacobson et al. 1993 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 190 | 24 hr | | 80 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 190 | 24 hr | | 73 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 185 | 24 hr | | 65 | | Jacobson et al. 1997 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 185 | 24 hr | | 46 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 170 | 24 hr | | 75 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 160 | 24 hr | | 46 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 160 | 24 hr | | 36 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 155 | 24 hr | | 39 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 155 | 24 hr | | 37 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 150 | 24 hr | | 46 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 150 | 24 hr | | 46 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 55 | 24 hr | | 55 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 55 | 24 hr | | 38 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 50 | 24 hr | | 71 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 160 | 24 hr | | 46 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 170 | 48 hr | | 66 | | Jacobson et al. 1997 |
| Freshwater mussel (released glochidia), *Villosa iris* | R,M,T | Copper sulfate | 150 | 48 hr | | 46 | | Jacobson et al. 1997 |
| Zebra mussel (1.6-2.0 cm), *Dreissena polymorpha* | R,M,T | Copper chloride | 268 | 9 wk | EC50 +F106(filtration rate) | 43 | - | Kraak et al. 1992 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Zebra mussel (1.6-2.0 cm),<br>*Dreissena polymorpha* | R,M,T | Copper chloride | 268 | 10 wk | NOEC (filtration rate) | 13 | - | Kraak et al. 1993 |
| Asiatic clam (1.0-2.1 cm),<br>*Coprbicula fluminea* | S,M,T | Copper sulfate | 64 | 96 hr (24hr LC50 also reported) | LC50 | 40 | - | Rodgers et al. 1980 |
| Asiatic clam (1.0-2.1 cm),<br>*Coprbicula fluminea* | F,M,T | Copper sulfate | 64 | 96 hr (24 hr LC50 also reported) | LC50 | 490 | - | Rodgers et al. 1980 |
| Asiatic clam (juvenile),<br>*Corbicula fluminea* | F,M,D | Copper sulfate | 78 | 30 days | 43.3% mortality | 14.48 | - | Belanger et al. 1990 |
| Asiatic clam (juvenile),<br>*Corbicula fluminea* | F,M,D | Copper sulfate | 78 | 30 days | Stopped shell growth | 8.75 | - | Belanger et al. 1990 |
| Asiatic clam (adult),<br>*Corbicula fluminea* | F,M,D | Copper sulfate | 78 | 30 days | 13.3% mortality | 14.48 | - | Belanger et al. 1990 |
| Asiatic clam (adult),<br>*Corbicula fluminea* | F,M,D | Copper sulfate | 71 | 30 days | 25% mortality | 16.88 | - | Belanger et al. 1990 |
| Asiatic clam (adult),<br>*Corbicula fluminea* | F,M,D | Copper sulfate | 78 | 30 days | Inhibited shell growth | 8.75 | - | Belanger et al. 1990 |
| Asiatic clam (adult),<br>*Corbicula fluminea* | F,M,D | Copper sulfate | - | 15-16 days | LC50 | - | - | Belanger et al. 1991 |
| Asiatic clam (adult),<br>*Corbicula fluminea* | F,M,D | Copper sulfate | - | 19 days | LC100 | - | - | Belanger et al. 1991 |
| Asiatic clam (veliger larva),<br>*Corbicula manilensis* | S,M,T | Copper chloride | - | 24 hr | 34% mortality | 10 | - | Harrison et al. 1981, 1984 |
| Asiatic clam (juvenile),<br>*Corbicula manilensis* | S,M,T | Copper chloride | 17 | 24 hr | LC50 | 100 | - | Harrison et al. 1984 |
| Asiatic clam (veliger),<br>*Corbicula manilensis* | S,M,T | Copper chloride | 17 | 24 hr | LC50 | 28 | - | Harrison et al. 1984 |
| Asiatic clam (trochophore),<br>*Corbicula manilensis* | S,M,T | Copper chloride | 17 | 8 hr | LC100 | 7.7 | - | Harrison et al. 1984 |
| Asiatic clam (adult),<br>*Corbicula manilensis* | F,M,T | Copper chloride | 17 | 7 days | LC50 | 3,638 | - | Harrison et al. 1981, 1984 |
| Asiatic clam (adult),<br>*Corbicula manilensis* | F,M,T | Copper chloride | 17 | 42 days | LC50 | 12 | - | Harrison et al. 1981, 1984 |
| Asiatic clam (4.3 g adult),<br>*Corbicula manilensis* | F,M,T | Copper chloride | 17 | 30 days | LC50 | 11 | - | Harrison et al. 1984 |
| Cladoceran,<br>*Bosmina longirostrus* | S, U | Copper sulfate | 33.8 | | EC50 | 1.6 | | Koivisto et al. 1992 |
| Cladoceran (<24 hr),<br>*Daphnia ambigua* | S,U | Copper sulfate | 145 | 72 hr | LC50 | 86.5 | - | Winner and Farrell 1976 |
| Cladoceran (<24 hr),<br>*Daphnia ambigua* | S,U | Copper sulfate | 145 | Life span (ca. 5 wk) | Chronic limits (inst. rate of population growth) | 50 | - | Winner and Farrell 1976 |
| Cladoceran,<br>*Ceriodaphnia dubia* | S,U | Copper sulfate | 188 | | EC50 | 36.6 | | Bright 1995 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Cladoceran, *Ceriodaphnia dubia* | S,U | Copper sulfate | 204 | | EC50 | 19.1 | | Bright 1995 |
| Cladoceran, *Ceriodaphnia dubia* | S,U | Copper sulfate | 428 | | EC50 | 36.4 | | Bright 1995 |
| Cladoceran, *Ceriodaphnia dubia* | S,U | Copper sulfate | 410 | | EC50 | 11.7 | | Bright 1995 |
| Cladoceran, *Ceriodaphnia dubia* | S,U | Copper sulfate | 494 | | EC50 | 12.3 | | Bright 1995 |
| Cladoceran, *Ceriodaphnia dubia* | S,U | Copper sulfate | 440 | | EC50 | 12 | | Bright 1995 |
| Cladoceran, *Ceriodaphnia dubia* | S,U | Copper chloride | 90 | 1 hr | NOEC (ingestion) | 30 | - | Juchelka and Snell 1994 |
| Cladoceran (<24 hr), *Ceriodaphnia dubia* | S,M,D | Copper sulfate | 6-10 | 48 hr | LC50 | - | 2.72 | Suedel et al. 1996 |
| Cladoceran (<12 hr), *Ceriodaphnia dubia* | S,M,D | - | 113.6 | 48 hr | LC50 | - | 52 | Belanger and Cherry 1990 |
| Cladoceran (<12 hr), *Ceriodaphnia dubia* | S,M,D | - | 113.6 | 48 hr | LC50 | - | 76 | Belanger and Cherry 1990 |
| Cladoceran (<12 hr), *Ceriodaphnia dubia* | S,M,D | - | 113.6 | 48 hr | LC50 | - | 91 | Belanger and Cherry 1990 |
| Cladoceran (<48 h), *Ceriodaphnia dubia* | S,M,T | Copper nitrate | 280 - 300 | 48 hr | LC50 | 9.5 | - | Schubauer-Berigan et al. 1993 |
| Cladoceran (<48 h), *Ceriodaphnia dubia* | S,M,T | Copper nitrate | 280 - 300 | 48 hr | LC50 | 28 | - | Schubauer-Berigan et al. 1993 |
| Cladoceran (<48 h), *Ceriodaphnia dubia* | S,M,T | Copper nitrate | 280 - 300 | 48 hr | LC50 | 200 | - | Schubauer-Berigan et al. 1993 |
| Cladoceran (<24 hr), *Ceriodaphnia dubia* | S,M,T,D | Copper nitrate | 100 | 48 hr | LC50 | 66 | 60.72 | Spehar and Fiandt 1986 |
| Cladoceran, *Ceriodaphnia dubia* | R,U | Copper nitrate | 111 | 10 days | LC50 | 53 | - | Cowgill and Milazzo 1991a |
| Cladoceran, *Ceriodaphnia dubia* | R,U | Copper nitrate | 111 | 10 days | NOEC (reproduction) | 96 | - | Cowgill and Milazzo 1991a |
| Cladoceran, *Ceriodaphnia dubia* | R,U | Copper sulfate | 90 | - | LOEC (reproduction) | 44 | - | Zuiderveen and Birge 1997 |
| Cladoceran, *Ceriodaphnia dubia* | R,U | Copper sulfate | 90 | - | LOEC (reproduction) | 40 | - | Zuiderveen and Birge 1997 |
| Cladoceran, *Ceriodaphnia dubia* | R,M,T | - | 20 | - | IC50 (reproduction) | 5 | - | Jop et al. 1995 |
| Cladoceran (<24 hrs), *Ceriodaphnia reticulata* | S, U | Copper chloride | 240 | | EC50 | 23 | | Elnabarawy et al. 1986 |
| Cladoceran, *Ceriodubia reticulata* | S,U | - | 43-45 | | EC50 | 17 | | Mount and Norberg 1984 |
| Cladoceran, *Daphnia magna* | - | Copper sulfate | - | 72 hr | EC50 (mobility; $10^0$ C) | 61 | - | Braginskij and Shcherben 1978 |

## Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| cies | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Cladoceran,<br>*Daphnia magna* | - | Copper sulfate | - | 72 hr | EC50<br>(mobility; $15^0$ C) | 70 | - | Braginskij and Shcherben 1978 |
| Cladoceran,<br>*Daphnia magna* | - | Copper sulfate | - | 72 hr | EC50<br>(mobility; $20^0$ C) | 21 | - | Braginskij and Shcherben 1978 |
| Cladoceran,<br>*Daphnia magna* | - | Copper sulfate | - | 72 hr | EC50<br>(mobility; $30^0$ C) | 9.3 | - | Braginskij and Shcherben 1978 |
| Cladoceran,<br>*Daphnia magna* | S,U | Copper sulfate | - | 16 hr | EC 50<br>(mobility) | 38 | - | Anderson 1944 |
| Cladoceran (<8 hr),<br>*Daphnia magna* | S,U | Copper chloride | - | 64 hr | Immobilization threshold | 12.7 | - | Anderson 1948 |
| Cladoceran (1 mm),<br>*Daphnia magna* | S,U | Copper nitrate | 100 | 24 hr | EC 50<br>(mobility) | 50 | - | Bellavere and Gorbi 1981 |
| Cladoceran (1 mm),<br>*Daphnia magna* | S,U | Copper nitrate | 200 | 24 hr | EC 50<br>(mobility) | 70 | - | Bellavere and Gorbi 1981 |
| Cladoceran,<br>*Daphnia magna* | S,U | - | 100 | 48 hr | EC50<br>(mobility) | 254 | - | Borgmann and Ralph 1983 |
| Cladoceran,<br>*Daphnia magna* | S,U | - | 100 | 49 hr | EC50<br>(mobility) | 1,239 | - | Borgmann and Ralph 1983 |
| Cladoceran,<br>*Daphnia magna* | S,U | Copper sulfate | 45 | 48 hr | EC50<br>(mobility; $5^0$ C) | 90 | - | Cairns et al. 1978 |
| Cladoceran,<br>*Daphnia magna* | S,U | Copper sulfate | 45 | 48 hr | EC50<br>(mobility; $10^0$ C) | 70 | - | Cairns et al. 1978 |
| Cladoceran,<br>*Daphnia magna* | S,U | Copper sulfate | 45 | 48 hr | EC50<br>(mobility; $15^0$ C) | 40 | - | Cairns et al. 1978 |
| Cladoceran,<br>*Daphnia magna* | S,U | Copper sulfate | 45 | 48 hr | EC50<br>(mobility; $25^0$ C) | 7 | - | Cairns et al. 1978 |
| Cladoceran (4 days),<br>*Daphnia magna* | S,U | Copper sulfate | - | 24 hr | EC50<br>(filtration rate) | 59 | - | Ferrando and Andreu 1993 |
| Cladoceran (24-48 hr),<br>*Daphnia magna* | S,U | Copper sulfate | 90 | 24 hr | EC50<br>(mobility) | 380 | - | Ferrando et al. 1992 |
| Cladoceran,<br>*Daphnia magna* | S,U | Copper sulfate | 50 |  | EC50 | 7 |  | Oikari et al. 1992 |
| Cladoceran,<br>*Daphnia magna* | S,U | Copper sulfate | - | 48 hr | EC50<br>(mobility) | 45 | - | Oikari et al. 1992 |
| Cladoceran (<24 hr),<br>*Daphnia magna* | S,U | Copper sulfate | 145 | Life span<br>(ca. 18 wk) | Chronic limits<br>(inst. rate of population growth) | 70 | - | Winner and Farrell 1976 |
| Cladoceran (<24 hrs),<br>*Daphnia magna* | S,M,D | Copper sulfate | 72-80 | 48 hr | LC50 | - | 11.3 | Suedel et al. 1996 |
| Cladoceran (<24 hrs),<br>*Daphnia magna* | S,M,I | - | 180 | - | LC50 | 55.3 | - | Borgmann and Charlton 1984 |
| Cladoceran (<24 hr),<br>*Daphnia magna* | S,M,I | Copper sulfate | 100 | 48 hr | EC50<br>(mobility) | 46.0 | - | Meador 1991 |
| Cladoceran (<24 hr),<br>*Daphnia magna* | S,M,I | Copper sulfate | 100 | 48 hr | EC50<br>(mobility) | 57.2 | - | Meador 1991 |

## Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Cladoceran (<24 hr), *Daphnia magna* | S,M,I | Copper sulfate | 100 | 48 hr | EC50 (mobility) | 67.8 | - | Meador 1991 |
| Cladoceran (<24 hr), *Daphnia magna* | S,M,T | Copper sulfate | 100 | 72 hr | EC50 (mobility) | 52.8 | - | Winner 1984b |
| Cladoceran (<24 hr), *Daphnia magna* | S,M,T | Copper sulfate | 100 | 72 hr | EC50 (mobility) | 56.3 | - | Winner 1984b |
| Cladoceran (<24 hr), *Daphnia magna* | S,M,T | Copper chloride | 85 | 96 hr | EC50 (mobility) | 130 | - | Blaylock et al. 1985 |
| Cladoceran (24 hr), *Daphnia magna* | R,U | Copper sulfate | - | 48 hr | EC50 (mobility) | 18 | - | Kazlauskiene et al. 1994 |
| Cladoceran (<24 hr), *Daphnia parvula* | S,U | Copper sulfate | 145 | 72 hr | EC50 (mobility) | 72 | - | Winner and Farrell 1976 |
| Cladoceran (<24 hr), *Daphnia parvula* | S,U | Copper sulfate | 145 | 72 hr | EC50 (mobility) | 57 | - | Winner and Farrell 1976 |
| Cladoceran (<24 hr), *Daphnia parvula* | S,U | Copper sulfate | 145 | Life span (ca. 10 wk) | Chronic limits (inst. rate of population growth) | 50 | - | Winner and Farrell 1976 |
| Cladoceran, *Daphnia pulex* | S,U | Copper sulfate | 45 | | EC50 | 10 | | Cairns et al. 1978 |
| Cladoceran, *Daphnia pulex* | S,U | - | 45 | | EC50 | 53 | | Mount and Norberg 1984 |
| Cladoceran (<24 hrs), *Daphnia pulex* | S, U | Copper chloride | 240 | | EC50 | 31 | | Elnabarawy et al. 1986 |
| Cladoceran (<24 hrs), *Daphnia pulex* | S, U | Copper sulfate | 33.8 | | EC50 | 3.6 | | Koivisto et al. 1992 |
| Cladoceran (<24 hrs), *Daphnia pulex* | S,U | Copper chloride | 80-90 | | EC50 | 18 | | Roux et al. 1993 |
| Cladoceran (<24 hrs), *Daphnia pulex* | S,U | Copper chloride | 80-90 | | EC50 | 24 | | Roux et al. 1993 |
| Cladoceran (<24 hrs), *Daphnia pulex* | S,U | Copper chloride | 80-90 | | EC50 | 22 | | Roux et al. 1993 |
| Cladoceran (<24 hr), *Daphnia pulex* | S,U | Copper sulfate | 145 | 72 hr | EC50 (mobility) | 86 | - | Winner and Farrell 1976 |
| Cladoceran (<24 hr), *Daphnia pulex* | S,U | Copper sulfate | 145 | 72 hr | EC50 (mobility) | 54 | - | Winner and Farrell 1976 |
| Cladoceran (<24 hr), *Daphnia pulex* | S,U | Copper sulfate | 145 | Life span (ca. 7 wk) | Chronic limits (inst. rate of population growth) | 50 | - | Winner and Farrell 1976 |
| Cladoceran, *Daphnia pulex* | S,U | Copper sulfate | 45 | 48 hr | EC50 (mobility) | 70 | - | Cairns et al. 1978 |
| Cladoceran, *Daphnia pulex* | S,U | Copper sulfate | 45 | 48 hr | EC50 (mobility) | 60 | - | Cairns et al. 1978 |
| Cladoceran, *Daphnia pulex* | S,U | Copper sulfate | 45 | 48 hr | EC50 (mobility) | 20 | - | Cairns et al. 1978 |
| Cladoceran, *Daphnia pulex* | S,U | Copper sulfate | 45 | 48 hr | EC50 (mobility) | 56 | - | Cairns et al. 1978 |

## Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Cladoceran (<24 hr), *Daphnia pulex* | S,U | Copper sulfate | 200 | 24 hr | EC50 (mobility) | 37.5 | - | Lilius et al. 1995 |
| Cladoceran, *Daphnia pulex* | S,M,T | Copper sulfate | 106 | 48 hr | EC50 (mobility) | 29 | - | Ingersoll and Winner 1982 |
| Cladoceran, *Daphnia pulex* | S,M,T | Copper sulfate | 106 | 48 hr | EC50 (mobility) | 20 | - | Ingersoll and Winner 1982 |
| Cladoceran, *Daphnia pulex* | S,M,T | Copper sulfate | 106 | 48 hr | EC50 (mobility) | 25 | - | Ingersoll and Winner 1982 |
| Cladoceran, *Daphnia pulex* | R,U | Copper sulfate | 85 | 21 days | Reduced fecundity | 3 | - | Roux et al. 1993 |
| Cladoceran, *Daphnia pulex* | R,M,T | Copper sulfate | 106 | 70 days | Significantly shortened life span; reduced brood size | 20 | - | Ingersoll and Winner 1982 |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 31 | 48 hr | EC50 (mobility; TOC=14 mg/L) | 55.4 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 29 | 49 hr | EC50 (mobility; TOC=13 mg/L) | 55.3 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 28 | 50 hr | EC50 (mobility; TOC=13 mg/L) | 53.3 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 28 | 50 hr | EC50 (mobility; TOC=28 mg/L) | 97.2 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 100 | 51 hr | EC50 (mobility; TOC=34 mg/L) | 199 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 86 | 52 hr | EC50 (mobility; TOC=34 mg/L) | 627 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 84 | 53 hr | EC50 (mobility; TOC=32 mg/L) | 165 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 16 | 54 hr | EC50 (mobility; TOC=12 mg/L) | 35.5 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 151 | 55 hr | EC50 (mobility; TOC=13 mg/L) | 78.8 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 96 | 56 hr | EC50 (mobility; TOC=28 mg/L) | 113 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 26 | 57 hr | EC50 (mobility; TOC=25 mg/L) | 76.4 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 84 | 58 hr | EC50 (mobility; TOC=13 mg/L) | 84.7 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 92 | 59 hr | EC50 (mobility; TOC=21 mg/L) | 184 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | - | 106 | 60 hr | EC50 (mobility; TOC=34 mg/L) | 240 | - | Lind et al. manuscript |
| Cladoceran, *Daphnia pulicaria* | S,M,T | Copper sulfate | 106 | 48 hr | LC50 | 240 | - | Lind et al. manuscript |
| Cladoceran, *Simocephalus serrulatus* | S,M,T | Copper nitrate | 8 | 24 hr | EC50 (mobility; TOC=11 mg/L) | 12 | - | Giesy et al. 1983 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Cladoceran, *Simocephalus serrulatus* | S,M,T | Copper nitrate | 16 | 25 hr | EC50 (mobility; TOC=12.4 mg/L) | 7.2 | - | Giesy et al. 1983 |
| Cladoceran, *Simocephalus serrulatus* | S,M,T | Copper nitrate | 16 | 26 hr | EC50 (mobility; TOC=15.6 mg/L) | 24.5 | - | Giesy et al. 1983 |
| Cladoceran (<24 hr), *Simocephalus vetulus* | S,U | - | 45 | | | 57 | | Mount and Norberg 1984 |
| Cladoceran (life cycle), *Bosmina longirostris* | R,U | Copper sulfate | - | 13 days | LOEC (intrinsic rate of population increase) | 18 | - | Koivisto and Ketola 1995 |
| Copepods (mixed sp), Primarily *Acanthocyclops vernalis* and *Diacyclops thomasi* | R,M,I | Copper chloride | - | 1 wk | EC20 (growth) | 42 | - | Borgmann and Ralph 1984 |
| Copepod (adults and copepodids V), *Tropocyclops prasinus mexicanus* | S, U | Copper sulfate | 10 | | | 29 | | Lalande and Pinel-Alloul 1986 |
| Copepod (adults and copepodids V), *Tropocyclops prasinus mexicanus* | S, U | Copper sulfate | 10 | 96 hr | LC50 | 247 | - | Lalande and Pinel-Alloul 1986 |
| Amphipod (0.4 cm), *Crangonyx pseudogracilis* | R,U | Copper sulfate | 45-55 | | | 1290 | | Martin and Holdich 1986 |
| Amphipod (4 mm), *Crangonyx psuedogracilis* | R,U | Copper sulfate | 50 | 48 hr | LC50 | 2,440 | - | Martin and Holdich 1986 |
| Amphipod, *Gammarus fasciatus* | S,U | Copper sulfate | 206 | 48 hr | LC50 | 210 | - | Judy 1979 |
| Amphipod, *Gammarus lacustris* | S,U | Copper sulfate | - | 96 hr | LC50 | 1,500 | - | Nebeker and Gaufin 1964 |
| Amphipod (2-3 wk), *Hyallela azteca* | S,M,T | Copper sulfate | 6-10 | - | LC50 | 65.6 | - | Suedel et al. 1996 |
| Amphipod (0-1 wk), *Hyallela azteca* | R,M,T | Copper nitrate | 130 | 10 wk | Significant mortality | 25.4 | - | Borgmann et al. 1993 |
| Amphipod (7-14 days), *Hyallela azteca* | F,M,T | Copper sulfate | 46 | 10 days | LC50 | 31 | - | West et al. 1993 |
| Crayfish (intermoult adult, 19.6 g), *Cambarus robustus* | S,M,D | - | 10-12 | 96 hr | LC50 | - | 830 | Taylor et al. 1995 |
| Crayfish (1.9-3.2 cm), *Orconectes limosus* | S,M,T | Copper chloride | - | 96 hr | LC50 | 600 | - | Boutet and Chaisemartin 1973 |
| Crayfish (3.0-3.5 cm), *Orconectes rusticus* | F,U | Copper sulfate | 100-125 | | | 3,000 | | Hubschman 1967 |
| Crayfish (embryo), *Orconectes rusticus* | F,U | Copper sulfate | 113 | 2 wk | 52% mortality of newly hatched young | 250 | - | Hubschman 1967 |

## Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as CaCO$_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Crayfish (3.14 mg dry wt.), *Orconectes rusticus* | F,U | Copper sulfate | 113 | 2 wk | 23% reduction in growth | 15 | - | Hubschman 1967 |
| Crayfish (30-40 mm), *Orconectes* sp. | | - | 113 | 48 hr | LC50 | 2,370 | - | Dobbs et al. 1994 |
| Crayfish, *Procambarus clarkii* | F,M,T | Copper chloride | 17 | 1358 hr | LC50 | 657 | - | Rice and Harrison 1983 |
| Mayfly (6th-8th instar), *Stenonema* sp. | S,M,T | - | 110 | 48 hr | LC50 | 453 | - | Dobbs et al. 1994 |
| Mayfly, *Cloeon dipterium* | - | Copper sulfate | - | 72 hr | LC50 (10$^0$ C) | 193 | - | Braginskij and Shcherban 1978 |
| Mayfly, *Cloeon dipterium* | - | - | - | 72 hr | LC50 (15$^0$ C) | 95.2 | - | Braginskij and Shcherban 1978 |
| Mayfly, *Cloeon dipterium* | - | - | - | 72 hr | LC50 (25$^0$ C) | 53 | - | Braginskij and Shcherban 1978 |
| Mayfly, *Cloeon dipterium* | - | - | - | 72 hr | LC50 (30$^0$ C) | 4.8 | - | Braginskij and Shcherban 1978 |
| Mayfly, *Ephemerella grandis* | F,M,T | Copper sulfate | 50 | 14 days | LC50 | 180-200 | - | Nehring 1976 |
| Mayfly, *Ephemerella subvaria* | S,M | Copper sulfate | 44 | 48 hr | LC50 | 320 | - | Warnick and Bell 1969 |
| Mayfly (6th-8th instar), *Isonychia bicolor* | S,M,T | - | 110 | 48 hr | LC50 | 223 | - | Dobbs et al. 1994 |
| Stonefly, *Pteronarcys californica* | F,M,T | Copper sulfate | 50 | 14 days | LC50 | 12,000 | - | Nehring 1976 |
| Caddisfly, *Hydropsyche betteni* | S,M,T | Copper sulfate | 44 | 14 days | LC50 | 32,000 | - | Warnick and Bell 1969 |
| Midge (2nd instar), *Chironomus riparius* | S,M,T | - | 110 | 48 hr | LC50 | 1,170 | - | Dobbs et al. 1994 |
| Midge (1st instar), *Chironomus tentans* | S,U | Copper sulfate | 42.7 | | | 16.7 | | Gauss et al. 1985 |
| Midge (1st instar), *Chironomus tentans* | S,U | Copper sulfate | 109.6 | | | 36.5 | | Gauss et al. 1985 |
| Midge (1st instar), *Chironomus tentans* | S,U | Copper sulfate | 172.3 | | | 98.2 | | Gauss et al. 1985 |
| Midge (4th instar), *Chironomus tentans* | S,U | Copper sulfate | 42.7 | | | 211 | | Gauss et al. 1985 |
| Midge (4th instar), *Chironomus tentans* | S,U | Copper sulfate | 109.6 | | | 977 | | Gauss et al. 1985 |
| Midge (4th instar), *Chironomus tentans* | S,U | Copper sulfate | 172.3 | | | 1184 | | Gauss et al. 1985 |
| Midge, *Chironomus tentans* | S,U | Copper sulfate | 25 | | | 327 | | Khangarot and Ray 1989 |
| Midge (2nd instar), *Chironomus tentans* | S,M,T | Copper sulfate | 8 | 96 hr | LC50 | 630 | - | Suedel et al. 1996 |

## Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Midge (4th instar),<br>*Chironomus tentans* | F,M,T | Copper chloride | 36 | 20 days | LC50 | 77.5 | - | Nebeker et al. 1984b |
| Midge (embryo),<br>*Tanytarsus dissimilis* | S,M,T | Copper chloride | 46.8 | 10 days | LC50 | 16.3 | - | Anderson et al. 1980 |
| Midge,<br>Unidentified | F,M,T,D | Copper sulfate | 200 | 32 wk | Emergence | 30 | - | Hedtke 1984 |
| Bryozoan (2-3 day ancestrula),<br>*Lophopodella carteri* | S,U | - | 190-220 | | | 510 | | Pardue and Wood 1980 |
| Bryozoan (2-3 day ancestrula),<br>*Pectinatella magnifica* | S,U | - | 190-220 | | | 140 | | Pardue and Wood 1980 |
| Bryozoan (2-3 day ancestrula),<br>*Plumatella emarginata* | S,U | - | 190-220 | | | 140 | | Pardue and Wood 1980 |
| American eel (5.5 cm glass eel stage),<br>*Anguilla rostrata* | S,U | Copper sulfate | 40-48 | 96 hr | LC50 | 2,540 | | Hinton and Eversole 1978 |
| American eel (9.7 cm black eel stage),<br>*Anguilla rostrata* | S,U | Copper sulfate | 40-48 | 96 hr | LC50 | 3,200 | | Hinton and Eversole 1979 |
| American eel,<br>*Anguilla rostrata* | S,M,T | Copper nitrate | 53 | 96 hr | LC50 | 6,400 | - | Rehwoldt et al. 1971 |
| American eel,<br>*Anguilla rostrata* | S,M,T | Copper nitrate | 55 | 96 hr | LC50 | 6,000 | - | Rehwoldt et al. 1972 |
| Arctic grayling (larva),<br>*Thymallus arcticus* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 67.5 | | Buhl and Hamilton 1990 |
| Arctic grayling (larva),<br>*Thymallus arcticus* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 23.9 | | Buhl and Hamilton 1990 |
| Arctic grayling (larva),<br>*Thymallus arcticus* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 131 | | Buhl and Hamilton 1990 |
| Arctic grayling (swim-up),<br>*Thymallus arcticus* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 9.6 | | Buhl and Hamilton 1990 |
| Arctic grayling (0.20 g juvenile),<br>*Thymallus arcticus* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 2.7 | | Buhl and Hamilton 1990 |
| Arctic grayling (0.34 g juvenile),<br>*Thymallus arcticus* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 2.58 | | Buhl and Hamilton 1990 |
| Arctic grayling (0.81 g juvenile),<br>*Thymallus arcticus* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 49.3 | | Buhl and Hamilton 1990 |
| Arctic grayling (0.85 g juvenile),<br>*Thymallus arcticus* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 30 | | Buhl and Hamilton 1990 |
| Coho salmon (larva),<br>*Oncorhynchus kisutch* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 21 | | Buhl and Hamilton 1990 |
| Coho salmon (larva),<br>*Oncorhynchus kisutch* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 19.3 | | Buhl and Hamilton 1990 |
| Coho salmon (0.41 g juvenile),<br>*Oncorhynchus kisutch* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 15.1 | | Buhl and Hamilton 1990 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Coho salmon (0.47 g juvenile),<br>*Oncorhynchus kisutch* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 23.9 | | Buhl and Hamilton 1990 |
| Coho salmon (0.87 g juvenile),<br>*Oncorhynchus kisutch* | S,U | Copper sulfate | 41.3 | 96 hr | LC50 | 31.9 | | Buhl and Hamilton 1990 |
| Coho salmon (10 cm),<br>*Oncorhynchus kisutch* | S,U | Copper sulfate | - | 72 hr | LC50 | 280 | - | Holland et al. 1960 |
| Coho salmon (9.7 cm),<br>*Oncorhynchus kisutch* | S,U | Copper sulfate | - | 72 hr | LC50 | 190 | - | Holland et al. 1960 |
| Coho salmon (9.7 cm),<br>*Oncorhynchus kisutch* | S,U | Copper sulfate | - | 72 hr | LC50 | 480 | - | Holland et al. 1960 |
| Coho salmon (juvenile),<br>*Oncorhynchus kisutch* | R,M,T,I | - | 33 | 96 hr | LC50<br>(TOC=7.3 mg/L) | 164 | - | Buckley 1983 |
| Coho salmon (juvenile),<br>*Oncorhynchus kisutch* | R,M,T,I | - | 33 | 96 hr | LC50 | 286 | | Buckley 1983 |
| Coho salmon (6.3 cm),<br>*Oncorhynchus kisutch* | F,U | Copper sulfate | - | 30 days | LC50 | 360 | - | Holland et al. 1960 |
| Coho salmon (6.3 cm),<br>*Oncorhynchus kisutch* | F,U | Copper sulfate | - | 72 hr | LC50 | 370 | - | Holland et al. 1960 |
| Coho salmon (smolts),<br>*Oncorhynchus kisutch* | F,M,T | Copper chloride | 91 | 144 hr | Decrease in survival upon transfer to 30 ppt seawater | 20 | - | Lorz and McPherson 1976 |
| Coho salmon (smolts >10 cm),<br>*Oncorhynchus kisutch* | F,M,T | Copper chloride | 91 | 165 days | Decrease in downstream migration after release | 5 | - | Lorz and McPherson 1976 |
| Coho salmon (7.8 cm),<br>*Oncorhynchus kisutch* | F,M,T | Copper acetate | 276 | 14 wk | 15% reduction in growth | 70 | - | Buckley et al. 1982 |
| Coho salmon (7.8 cm),<br>*Oncorhynchus kisutch* | - | - | 276 | 7 days | LC50 | 220 | - | Buckley et al. 1982 |
| Coho salmon (3-8 g),<br>*Oncorhynchus kisutch* | F,M,T | Copper acetate | 280 | 7 days | LC50 | 275 | - | McCarter and Roch 1983 |
| Coho salmon (3-8 g),<br>*Oncorhynchus kisutch* | F,M,T | Copper acetate | 280 | 7 days | LC50 (acclimated to copper for 2 wk) | 383 | - | McCarter and Roch 1983 |
| Coho salmon (parr),<br>*Oncorhynchus kisutch* | F,M,T,D,I | - | 24.4 | 61 days | NOEC<br>(growth and survival) | 22 | - | Mudge et al. 1993 |
| Coho salmon,<br>*Oncorhynchus kisutch* | F,M,T,D,I | - | 31.1 | 60 days | NOEC<br>(growth and survival) | 18 | - | Mudge et al. 1993 |
| Coho salmon (parr),<br>*Oncorhynchus kisutch* | F,M,T,D,I | - | 31 | 61 days | NOEC<br>(growth and survival) | 33 | - | Mudge et al. 1993 |
| Rainbow trout (15-40g)<br>*Oncorhynchus mykiss* | F,M, | Copper chloride | -- | 120 hr | LA50 (50% mortality) | ~1.4 ug Cu/g gill | - | MacRae et al. 1999 |
| Sockeye salmon (yeasrling),<br>*Oncorhynchus nerka* | S,U | Copper sulfate | 12 | 1-24 hr | Drastic increase in plasma corticosteroids | 64 | - | Donaldson and Dye 1975 |
| Sockeye salmon (fry, 0.132 g, 2.95 cm),<br>*Oncorhynchus nerka* | R,M,T | Copper chloride | 36-46 | 96 hr | LC50 | 220 | - | Davis and Shand 1978 |

## Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Sockeye salmon (fry, 0.132 g, 2.95 cm), *Oncorhynchus nerka* | R,M,T | Copper chloride | 36-46 | 96 hr | LC50 | 210 | - | Davis and Shand 1978 |
| Sockeye salmon (fry, 0.132 g, 2.95 cm), *Oncorhynchus nerka* | R,M,T | Copper chloride | 36-46 | 96 hr | LC50 | 240 | - | Davis and Shand 1978 |
| Sockeye salmon (fry, 0.132 g, 2.95 cm), *Oncorhynchus nerka* | R,M,T | Copper chloride | 36-46 | 96 hr | LC50 | 103 | - | Davis and Shand 1978 |
| Sockeye salmon (fry, 0.132 g, 2.95 cm), *Oncorhynchus nerka* | R,M,T | Copper chloride | 36-46 | 96 hr | LC50 | 240 | - | Davis and Shand 1978 |
| Chinook salmon (18-21 weeks), *Oncorhynchus tshawytscha* | S,U | Copper sulfate | 211 | 96 hr | LC50 | 58 | | Hamilton and Buhl 1990 |
| Chinook salmon (18-21 weeks), *Oncorhynchus tshawytscha* | S,U | Copper sulfate | 211 | 96 hr | LC50 | 54 | | Hamilton and Buhl 1990 |
| Chinook salmon (18-21 weeks), *Oncorhynchus tshawytscha* | S,U | Copper sulfate | 343 | 96 hr | LC50 | 60 | | Hamilton and Buhl 1990 |
| Chinook salmon (5.2 cm), *Oncorhynchus tshawytscha* | S,U | Copper nitrate | - | 5 days | LC50 | 178 | - | Holland et al. 1960 |
| Chinook salmon (eyed embryos), *Oncorhynchus tshawytscha* | F,M,D | Copper sulfate | 44 | 26 days | 93% mortality | 41.67 | - | Hazel and Meith 1970 |
| Chinook salmon (alevin), *Oncorhynchus tshawytscha* | F,M,T | Copper chloride | 23 | 200 hr | LC50 | 20 | - | Chapman 1978 |
| Chinook salmon (alevin), *Oncorhynchus tshawytscha* | F,M,T | Copper chloride | 23 | 200 hr | LC10 | 15 | - | Chapman 1978 |
| Chinook salmon (swimup), *Oncorhynchus tshawytscha* | F,M,T | Copper chloride | 23 | 200 hr | LC50 | 19 | - | Chapman 1978 |
| Chinook salmon (swimup), *Oncorhynchus tshawytscha* | F,M,T | Copper chloride | 23 | 200 hr | LC10 | 14 | - | Chapman 1978 |
| Chinook salmon (parr), *Oncorhynchus tshawytscha* | F,M,T | Copper chloride | 23 | 200 hr | LC50 | 30 | - | Chapman 1978 |
| Chinook salmon (parr), *Oncorhynchus tshawytscha* | F,M,T | Copper chloride | 23 | 200 hr | LC10 | 17 | - | Chapman 1978 |
| Chinook salmon (smolt), *Oncorhynchus tshawytscha* | F,M,T | Copper chloride | 23 | 200 hr | LC50 | 26 | - | Chapman 1978 |
| Chinook salmon (smolt), *Oncorhynchus tshawytscha* | F,M,T | Copper chloride | 23 | 200 hr | LC10 | 18 | - | Chapman 1978 |
| Chinook salmon (3.9-6.8 cm), *Oncorhynchus tshawytscha* | F,M,T | Copper sulfate | 20-22 | 96 hr | LC50 | 32 | - | Finlayson and Verrue 1982 |
| Cutthroat trout (3-5 mo), *Oncorhynchus clarki* | F,M | Copper chloride | 50 | 20 min | avoidance of copper | 7.708 | - | Woodward et al. 1997 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Rainbow trout,<br>*Oncorhynchus mykiss* | - | - | 320 | 48 hr | LC50 | 500 | - | Brown 1968 |
| Rainbow trout (9-16 cm),<br>*Oncorhynchus mykiss* | In situ | - | 21-26 | 48 hr | LC50 | 70 | - | Calamari and Marchetti 1975 |
| Rainbow trout (0.4 g),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | - | 96 hr | LC50 | 185 | - | Bills et al. 1981 |
| Rainbow trout (larva),<br>*Oncorhynchus mykiss* | S, U | Copper sulfate | 41.3 | 96 hr | LC50 | 36 | | Buhl and Hamilton 1990 |
| Rainbow trout (0.60 g juvenile),<br>*Oncorhynchus mykiss* | S, U | Copper sulfate | 41.3 | 96 hr | LC50 | 13.8 | | Buhl and Hamilton 1990 |
| Rainbow trout (13-15 cm),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | 250 | 72 hr | LC50 | 580 | - | Brown et al. 1974 |
| Rainbow trout (13-15 cm),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | 250 | 72 hr | LC50 | 960 | - | Brown et al. 1974 |
| Rainbow trout (3.2 cm),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | - | 24 hr | LC50 | 140 | - | Shaw and Brown 1974 |
| Rainbow trout (3.2 cm),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | - | 24 hr | LC50 | 130 | - | Shaw and Brown 1974 |
| Rainbow trout (4.0-10.6 cm),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | 45 | 24 hr | LC50<br>($5^0$ C) | 950 | - | Cairns et al. 1978 |
| Rainbow trout (4.0-10.6 cm),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | 45 | 24 hr | LC50<br>($15^0$ C) | 430 | - | Cairns et al. 1978 |
| Rainbow trout (4.0-10.6 cm),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | 45 | 24 hr | LC50<br>($30^0$ C) | 150 | - | Cairns et al. 1978 |
| Rainbow trout (0.52-1.55 g),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | - | 96 hr | LC50<br>(Silver Cup diet) | 23.9 | - | Marking et al. 1984 |
| Rainbow trout (0.41-2.03 g),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | - | 96 hr | LC50<br>(purified H440) | 11.3 | - | Marking et al. 1984 |
| Rainbow trout (0.0.40-1.68 g),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | - | 96 hr | LC50<br>(SD-9 diet) | 15.9 | - | Marking et al. 1984 |
| Rainbow trout (0.0.34-1.52 g),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | - | 96 hr | LC50<br>(liver diet) | 14.3 | - | Marking et al. 1984 |
| Rainbow trout (0.0.38-1.30 g),<br>*Oncorhynchus mykiss* | S,U | Copper sulfate | - | 96 hr | LC50<br>(brine shrimp diet) | 11.3 | - | Marking et al. 1984 |
| Rainbow trout (embryo),<br>*Oncorhynchus mykiss* | S,U | Copper chloride | 30 | 56 hr | LC50 | 100 | - | Rombough 1985 |
| Rainbow trout (6.6 cm),<br>*Oncorhynchus mykiss* | R,U | Copper sulfate | 320 | 72 hr | LC50 | 1,100 | - | Lloyd 1961 |
| Rainbow trout (6.6 cm),<br>*Oncorhynchus mykiss* | R,U | Copper sulfate | 17.5 | 7 days | LC50 | 44 | - | Lloyd 1961 |
| Rainbow trout,<br>*Oncorhynchus mykiss* | R,U | Copper sulfate | 320 | 48 hr | LC50 | 270 | - | Herbert and Vandyke 1964 |
| Rainbow trout (yearling),<br>*Oncorhynchus mykiss* | R,U | Copper sulfate | 240 | 48 hr | LC50 | 750 | - | Brown and Dalton 1970 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Rainbow trout (13-15 cm),<br>*Oncorhynchus mykiss* | R,U | Copper sulfate | 250 | 8 days | LC50 | 500 | - | Brown et al. 1974 |
| Rainbow trout (embryo),<br>*Oncorhynchus mykiss* | R,U | Copper sulfate | 104 | 28 days | LC50 | 90 | - | Birge 1978;<br>Birge et al. 1978 |
| Rainbow trout (embryo),<br>*Oncorhynchus mykiss* | R,U | Copper sulfate | 101 | 28 days | EC50 (death or deformity) | 110 | - | Birge et al. 1980;<br>Birge and Black 1979 |
| Rainbow trout (embryo),<br>*Oncorhynchus mykiss* | R,U | Copper sulfate | 101 | 28 days | EC10 (death or deformity) | 16.5 | - | Birge et al. 1980 |
| Rainbow trout (eyed embryos),<br>*Oncorhynchus mykiss* | R,U | Copper sulfate | - | 96 hr | LC50 | 1,150 | - | Kazlauskiene et al. 1994 |
| Rainbow trout (larva),<br>*Oncorhynchus mykiss* | R,U | Copper sulfate | - | 96 hr | LC50 | 430 | - | Kazlauskiene et al. 1994 |
| Rainbow trout (16-18 cm),<br>*Oncorhynchus mykiss* | R,U | Copper sulfate | - | 96 hr | LC50 | 930 | - | Kazlauskiene et al. 1994 |
| Rainbow trout (embryo),<br>*Oncorhynchus mykiss* | R,M,T | Copper sulfate | 62.9 | 7-9 mo | Lesions in olfactory rosettes | 22 | - | Saucier et al. 1991b |
| Rainbow trout (embryo),<br>*Oncorhynchus mykiss* | R,M,T | Copper sulfate | 62.9 | 7-9 mo | 31% mortality | 22 | - | Saucier et al. 1991b |
| Rainbow trout (eyed embryos),<br>*Oncorhynchus mykiss* | R,M,T | Copper sulfate | 40-48 | 96 hr | LC50 | 400 | - | Giles and Klaverkamp 1982 |
| Rainbow trout (yearling),<br>*Oncorhynchus mykiss* | R,M,T | Copper sulfate | 36.5 | 21 days | Elevated plasma cortisol returned to normal | 45 | - | Munoz et al. 1991 |
| Rainbow trout (embryo),<br>*Oncorhynchus mykiss* | R,M,T | Copper sulfate | 44 | 96 hr | 15-20% post-hatch mortality | 80 | - | Giles and Klaverkamp 1982 |
| Rainbow trout (embryo),<br>*Oncorhynchus mykiss* | R,M,T | Copper sulfate | 62.9 | 7-9 mo | Inhibited olfactory discrimination | 22 | - | Saucier et al. 1991a |
| Rainbow trout (5.1-7.6 cm),<br>*Oncorhynchus mykiss* | F,U | Copper nitrate | - | 96 hr | LC50 | 253 | - | Hale 1977 |
| Rainbow trout (11 cm),<br>*Oncorhynchus mykiss* | F,U | - | 100 | 96 hr | LC50 | 250 | - | Goettl et al. 1972 |
| Rainbow trout (5 wk post swimup)<br>*Oncorhynchus mykiss* | F,U | Copper sulfate | 89.5 | 1 hr | Avoidance | 10 | - | Folmar 1976 |
| Rainbow trout (18.5-26.5 cm),<br>*Oncorhynchus mykiss* | F,U | Copper sulfate | 90 | 2 hr | 55% depressed olfactory response | 50 | - | Hara et al. 1976 |
| Rainbow trout (3.2 cm),<br>*Oncorhynchus mykiss* | F,M,I | Copper sulfate | - | 8 days | LC50 | 500 | - | Shaw and Brown 1974 |
| Rainbow trout (12-16 cm),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 300 | 14 days | LC50 | 870 | - | Calamari and Marchetti 1973 |
| Rainbow trout (adult),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 42 | - | LC50 | 57 | - | Chapman 1975, Chapman and Stevens 1978 |
| Rainbow trout (53.5 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 365 | 96 hr | LC50 | 465 | - | Lett et al. 1976 |

## Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Rainbow trout (53.5 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 365 | 15 days | Transient decrease in food consumption | 100 | - | Lett et al. 1976 |
| Rainbow trout (alevin),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 24 | 200 hr | LC50 | 20 | - | Chapman 1978 |
| Rainbow trout (alevin),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 24 | 200 hr | LC10 | 19 | - | Chapman 1978 |
| Rainbow trout (swimup),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 24 | 200 hr | LC50 | 17 | - | Chapman 1978 |
| Rainbow trout (swimup),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 24 | 200 hr | LC10 | 9 | - | Chapman 1978 |
| Rainbow trout (parr),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 25 | 200 hr | LC50 | 15 | - | Chapman 1978 |
| Rainbow trout (parr),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 25 | 200 hr | LC10 | 8 | - | Chapman 1978 |
| Rainbow trout (smolt),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 25 | 200 hr | LC50 | 21 | - | Chapman 1978 |
| Rainbow trout (smolt),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 25 | 200 hr | LC10 | 7 | - | Chapman 1978 |
| Rainbow trout,<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 112.4 | 80 min | Avoidance threshold | 74 | - | Black and Birge 1980 |
| Rainbow trout (>8 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 49 | 15-18 days | LC50 | 48 | - | Miller and MacKay 1980 |
| Rainbow trout (>8 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 51 | 15-18 days | LC50 | 46 | - | Miller and MacKay 1980 |
| Rainbow trout (>8 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 57 | 15-18 days | LC50 | 63 | - | Miller and MacKay 1980 |
| Rainbow trout (>8 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 12 | 15-18 days | LC50 | 19 | - | Miller and MacKay 1980 |
| Rainbow trout (>8 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 99 | 15-18 days | LC50 | 54 | - | Miller and MacKay 1980 |
| Rainbow trout (>8 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 98 | 15-18 days | LC50 | 78 | - | Miller and MacKay 1980 |
| Rainbow trout (>8 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 12 | 15-18 days | LC50 | 18 | - | Miller and MacKay 1980 |
| Rainbow trout (>8 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 97 | 15-18 days | LC50 | 96 | - | Miller and MacKay 1980 |
| Rainbow trout (200-250 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 320 | 4 mo | Altered liver and blood enzymes and mitochondrial function | 30 | - | Arillo et al. 1984 |
| Rainbow trout (7 cm),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 28.4 | 20 min | Avoidance | 6.4 | - | Giattina et al. 1982 |
| Rainbow trout (2.70 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 9.2 | 96 hr | LC50 | 4.2 | - | Cusimano et al. 1986 |
| Rainbow trout (2.88 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 9.2 | 96 hr | LC50 | 66 | - | Cusimano et al. 1986 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Rainbow trout (2.88 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 9.2 | 168 hr | LC50 | 36.7 | - | Cusimano et al. 1986 |
| Rainbow trout (2.70 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 9.2 | 168 hr | LC50 | 3.1 | - | Cusimano et al. 1986 |
| Rainbow trout (2.65 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 9.2 | 168 hr | LC50 | 2.3 | - | Cusimano et al. 1986 |
| Rainbow trout (5 day embryo),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 87.7 | 48 hr | LC50 | 8,000 | - | Shazili and Pascoe 1986 |
| Rainbow trout (10 day embryo),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 87.7 | 48 hr | LC50 | 2,000 | - | Shazili and Pascoe 1986 |
| Rainbow trout (15 day embryo),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 87.7 | 48 hr | LC50 | 400 | - | Shazili and Pascoe 1986 |
| Rainbow trout (22 day embryo),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 87.7 | 48 hr | LC50 | 600 | - | Shazili and Pascoe 1986 |
| Rainbow trout (29 day embryo),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 87.7 | 48 hr | LC50 | 400 | - | Shazili and Pascoe 1986 |
| Rainbow trout (36 day embryo),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 87.7 | 48 hr | LC50 | 100 | - | Shazili and Pascoe 1986 |
| Rainbow trout (2 day larva),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 87.7 | 48 hr | LC50 | 100 | - | Shazili and Pascoe 1986 |
| Rainbow trout (7 day larva),<br>*Oncorhynchus mykiss* | F,M,T | Copper nitrate | 87.7 | 48 hr | LC50 | 100 | - | Shazili and Pascoe 1986 |
| Rainbow trout (yearling),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 63 | 15 days | Olfactory receptor degeneration | 20 | - | Julliard et al. 1993 |
| Rainbow trout (swimup),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 60.9 | 13-40 wk | Inhibited olfactory discrimination | 20 | - | Saucier and Astic 1995 |
| Rainbow trout (swimup),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 60.9 | 40 wk | 43% mortality | 40 | - | Saucier and Astic 1995 |
| Rainbow trout (9.0-11.5 cm, 10.6 g),<br>*Oncorhynchus mykiss* | F,M,T | Copper sulfate | 284 | 96 hr | LC50 | 650 | - | Svecevicius and Vosyliene 1996 |
| Rainbow trout (3.5 cm),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 24.2 | 96 hr | LC50 | 12.7 | - | Marr et al. Manuscript |
| Rainbow trout (3.5 cm),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 24.2 | 96 hr | LC50 | 16.6 | - | Marr et al. Manuscript |
| Rainbow trout (3.5 cm),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 24.2 | 96 hr | LC50 | 21.4 | - | Marr et al. Manuscript |
| Rainbow trout (3.5 cm),<br>*Oncorhynchus mykiss* | F,M,T | Copper chloride | 24.2 | 96 hr | LC50 | 34.2 | - | Marr et al. Manuscript |
| Rainbow trout (10.0 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 362 | 144 hr | LC50<br>(extruded diet) | 276 | - | Dixon and Hilton 1981 |
| Rainbow trout (10.9 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 362 | 144 hr | LC50<br>(steam pelleted diet) | 350 | - | Dixon and Hilton 1981 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Rainbow trout (12.3 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 362 | 144 hr | LC50<br>(Low carbohydrate diet) | 408 | - | Dixon and Hilton 1981 |
| Rainbow trout (11.6 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 362 | 144 hr | LC50<br>(high carbohydrate diet) | 246 | - | Dixon and Hilton 1981 |
| Rainbow trout (1.7-3.3 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 374 | 21 days | Incipient lethal level | 329 | - | Dixon and Sprague 1981a |
| Rainbow trout (1.7-3.3 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 374 | 21 days | Incipient lethal level | 333 | - | Dixon and Sprague 1981a |
| Rainbow trout (1.7-3.3 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 374 | 21 days | Incipient lethal level | 311 | - | Dixon and Sprague 1981a |
| Rainbow trout (1.7-3.3 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 374 | 21 days | Incipient lethal level | 274 | - | Dixon and Sprague 1981a |
| Rainbow trout (1.7-3.3 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 374 | 21 days | Incipient lethal level | 371 | - | Dixon and Sprague 1981a |
| Rainbow trout (1.7-3.3 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 374 | 21 days | Incipient lethal level (acclimated to 30 ug/L) | 266 | - | Dixon and Sprague 1981a |
| Rainbow trout (1.7-3.3 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 374 | 21 days | Incipient lethal level (acclimated to 58 ug/L) | 349 | - | Dixon and Sprague 1981a |
| Rainbow trout (1.7-3.3 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 374 | 21 days | Incipient lethal level (acclimated to 94 ug/L) | 515 | - | Dixon and Sprague 1981a |
| Rainbow trout (1.7-3.3 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 374 | 21 days | Incipient lethal level (acclimated to 131 ug/L) | 564 | - | Dixon and Sprague 1981a |
| Rainbow trout (1.7-3.3 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper sulfate | 374 | 21 days | Incipient lethal level (acclimated to 194 ug/L) | 708 | - | Dixon and Sprague 1981a |
| Rainbow trout (2.9 g),<br>*Oncorhynchus mykiss* | F,M,D | Copper chloride | 30.5 | ca. 2 hr | Inhibited avoidance of serine | 6.667 | - | Rehnberg and Schreck 1986 |
| Rainbow trout (3.2 g),<br>*Oncorhynchus mykiss* | F,M,T,D | Copper sulfate | 30 | 96 hr | LC50 | - | 19.9 | Howarth and Sprague 1978 |
| Rainbow trout (1.4 g),<br>*Oncorhynchus mykiss* | F,M,T,D | Copper sulfate | 101 | 96 hr | LC50 | - | 176 | Howarth and Sprague 1978 |
| Rainbow trout (2.2 g),<br>*Oncorhynchus mykiss* | F,M,T,D | Copper sulfate | 370 | 96 hr | LC50 | - | 232 | Howarth and Sprague 1978 |
| Rainbow trout (smolt),<br>*Oncorhynchus mykiss* | F,M,T,D | Copper sulfate | 363 | >10 days | LC50 | 97.92 | - | Fogels and Sprague 1977 |
| Rainbow trout (parr),<br>*Oncorhynchus mykiss* | F,M,T,D,I | - | 31.0 | 62 days | NOEC<br>(growth and survival) | 90 | - | Mudge et al. 1993 |
| Atlantic salmon (2-3 yr parr),<br>*Salmo salar* | S,M,T | - | 8-10 | 96 hr | LC50 | 125 | - | Wilson 1972 |
| Atlantic salmon (6.4-11.7 cm),<br>*Salmo salar* | F,M,T | Copper sulfate | 20 | 7 days | LC50 | 48 | - | Sprague 1964 |
| Atlantic salmon (7.2-10.9 cm),<br>*Salmo salar* | F,M,T | - | 14 | 7 days | LC50 | 32 | - | Sprague and Ramsay 1965 |
| Brown trout (3-6 day larva),<br>*Salmo trutta* | S,M,T | Copper chloride | 4 | 30 days | >90% mortality | 80 | - | Reader et al. 1989 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Brown trout (larva),<br>*Salmo trutta* | S,M,T | Copper chloride | 4 | 30 days | >90% mortality | 20 | - | Sayer et al. 1989 |
| Brown trout (larva),<br>*Salmo trutta* | S,M,T | Copper chloride | 22 | 30 days | <10% mortality | 80 | - | Sayer et al. 1989 |
| Brown trout (larva),<br>*Salmo trutta* | F,M,T | Copper chloride | 25 | 60 days | Inhibited growth | 4.6 | - | Marr et al. 1996 |
| Brook trout,<br>*Salvelinus fontinalis* | - | - | - | 24 hr | Significant change in cough rate | 9 | - | Drummond et al. 1973 |
| Brook trout (1 g),<br>*Salvelinus fontinalis* | S,M,T | Copper chloride | 4 | 80 hr | 75% mortality | 25.4 | - | Sayer et al. 1991 b, c |
| Brook trout (8 mo),<br>*Salvelinus fontinalis* | R,M,T | - | 20 | 10 days | IC50<br>(growth) | 187 | - | Jop et al. 1995 |
| Brook trout (15-20 cm),<br>*Salvelinus fontinalis* | F,M,T | Copper sulfate | 47 | 21 days | Altered Blood Hct, RBC, Hb, Cl, PGOT, Osmolarity, protein | 38.2 | - | McKim et al. 1970 |
| Brook trout (13-20 cm),<br>*Salvelinus fontinalis* | F,M,T | Copper sulfate | 47 | 337 days | Altered blood PGOT | 17.4 | - | McKim et al. 1970 |
| Goldfish (3.8-6.3 cm),<br>*Carassius auratus* | S,U | Copper sulfate | 20 | 96 hr | LC50 | 36 | | Pickering and Henderson 1966 |
| Goldfish (10.5 g),<br>*Carassius auratus* | S,M,T | Copper sulfate | 34.2 | - | LC50 | 150 | - | Hossain et al. 1995 |
| Goldfish (embryo),<br>*Carrassius auratus* | R,U | Copper sulfate | 195 | 7 days | EC50<br>(death or deformity) | 5,200 | - | Birge 1978;<br>Birge and Black 1979 |
| Goldfish,<br>*Carassius auratus* | R,U | Copper sulfate | 45 | 24 hr | LC50<br>($5^0$ C) | 2,700 | - | Cairns et al. 1978 |
| Goldfish,<br>*Carassius auratus* | R,U | Copper sulfate | 45 | 24 hr | LC50<br>($15^0$ C) | 2,900 | - | Cairns et al. 1978 |
| Goldfish,<br>*Carassius auratus* | R,U | Copper sulfate | 45 | 24 hr | LC50<br>($30^0$ C) | 1,510 | - | Cairns et al. 1978 |
| Common carp (1.8-2.1 cm),<br>*Cyprinus carpio* | S,U | Copper sulfate | 144-188 | 96 hr | LC50 | 117.5 | | Deshmukh and Marathe 1980 |
| Common carp (5.0-6.0 cm),<br>*Cyprinus carpio* | S,U | Copper sulfate | 144-188 | 96 hr | LC50 | 530 | | Deshmukh and Marathe 1980 |
| Common carp (embryo),<br>*Cyprinus carpio* | S,U | Copper sulfate | 360 | - | EC50<br>(hatch and deformity) | 4,775 | - | Kapur and Yadav 1982 |
| Common carp (embryo),<br>*Cyprinus carpio* | S,U | Copper acetate | 274 | 96 hr | LC50 | 140 | - | Kaur and Dhawan 1994 |
| Common carp (larva),<br>*Cyprinus carpio* | S,U | Copper acetate | 274 | 96 hr | LC50 | 4 | - | Kaur and Dhawan 1994 |
| Common carp (fry),<br>*Cyprinus carpio* | S,U | Copper acetate | 274 | 96 hr | LC50 | 63 | - | Kaur and Dhawan 1994 |
| Common carp,<br>*Cyprinus carpio* | S,M,T | Copper nitrate | 53 | - | LC50 | 110 | - | Rehwoldt et al. 1971 |
| Common carp,<br>*Cyprinus carpio* | S,M,T | Copper nitrate | 55 | - | LC50 | 800 | - | Rehwoldt et al. 1972 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Common carp (4.7-6.2 cm),<br>*Cyprinus carpio* | R,U | Copper sulfate | 19 | 96 hr | LC50 | 63 | | Khangarot et al. 1983 |
| Common carp (embryo and larva),<br>*Cyprinus carpio* | R,U | Copper sulfate | 50 | 108 hr | 77% deformed | 10 | - | Wani 1986 |
| Common carp (3.5 cm),<br>*Cyprinus carpio* | R,U | Copper sulfate | - | 96 hr | LC50 | 300 | - | Alam and Maughan 1992 |
| Common carp (6.5 cm),<br>*Cyprinus carpio* | R,U | Copper sulfate | - | 96 hr | LC50 | 1,000 | - | Alam and Maughan 1992 |
| Common carp (embryo),<br>*Cyprinus carpio* | R,M,T | Copper sulfate | 50 | 72 hr | Prevented hatching | 700 | - | Hildebrand and Cushman 1978 |
| Common carp (1 mo),<br>*Cyprinus carpio* | R,M,T | Copper nitrate | 84.8 | 1 wk | Raised critical D.O. and altered ammonia excretion | 14.0 | - | De Boeck et al. 1995a |
| Common carp (22.9 cm),<br>*Cyprinus carpio* | F,M,T | Copper chloride | 17 | 48 hr | LC50 | 170 | - | Harrison and Rice 1981 |
| Common carp (embryo and larva),<br>*Cyprinus carpio* | F,M,T | Copper chloride | 100 | 168 hr | 55% mortality | 19 | - | Stouthart et al. 1996 |
| Common carp (embryo and larva),<br>*Cyprinus carpio* | F,M,T | Copper chloride | 100 | 168 hr | 18% mortality; | 50.8 | - | Stouthart et al. 1996 |
| Bonytail (larva),<br>*Gila elegans* | S, U | Copper sulfate | 199 | 96 hr | LC50 | 364 | | Buhl and Hamilton 1996 |
| Bonytail (100-110 days),<br>*Gila elegans* | S, U | Copper sulfate | 199 | 96 hr | LC50 | 231 | | Buhl and Hamilton 1996 |
| Golden shiner (11-13 cm),<br>*Notemigonus crysoleucas* | S,U | Copper sulfate | 221 | 94 hr | Decreased serum osmolality | 2,500 | - | Lewis and Lewis 1971 |
| Golden shiner,<br>*Notemigonus crysoleucas* | S,U | Copper sulfate | 45 | 24 hr | LC50<br>(5$^{0}$ C) | 330 | - | Cairns et al. 1978 |
| Golden shiner,<br>*Notemigonus crysoleucas* | S,U | Copper sulfate | 45 | 24 hr | LC50<br>(15$^{0}$ C) | 230 | - | Cairns et al. 1978 |
| Golden shiner,<br>*Notemigonus crysoleucas* | S,U | Copper sulfate | 45 | 24 hr | LC50<br>(30$^{0}$ C) | 270 | - | Cairns et al. 1978 |
| Golden shiner,<br>*Notemigonus crysoleucas* | F,M,T | Copper chloride | 72.2 | 15 min | EC50<br>(avoidance) | 26 | - | Hartwell et al. 1989 |
| Striped shiner,<br>*Notropis chrysocephalus* | F,M,T,D | Copper sulfate | 318 | 96 hr | LC50 | 3,400 | - | Geckler et al. 1976 |
| Striped shiner (4.7 cm)<br>*Notropis chrysocephalus* | F,M,T,D | Copper sulfate | 316 | 96 hr | LC50 | 4,000 | - | Geckler et al. 1976 |
| Striped shiner (5.0 cm)<br>*Notropis chrysocephalus* | F,M,T,D | Copper sulfate | 274 | 96 hr | LC50 | 5,000 | - | Geckler et al. 1976 |
| Striped shiner,<br>*Notropis chrysocephalus* | F,M,T,D | Copper sulfate | 314 | 96 hr | LC50 | 8,400 | - | Geckler et al. 1976 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Striped shiner,<br>*Notropis chrysocephalus* | F,M,T,D | Copper sulfate | 303 | 96 hr | LC50 | 16,000 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 208 | 48 hr | LC50 | 290 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 132 | 48 hr | LC50 | 150 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 182 | 48 hr | LC50 | 200 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 233 | 48 hr | LC50 | 180 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 282 | 48 hr | LC50 | 260 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 337 | 48 hr | LC50 | 260 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 322 | 48 hr | LC50 | 6,300 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 322 | 48 hr | LC50 | 11,000 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 322 | 48 hr | LC50 | 25,000 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 203 | 48 hr | LC50 | 160 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 203 | 48 hr | LC50 | 1,100 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,U | Copper sulfate | 203 | 48 hr | LC50 | 2,900 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,M,D | Copper sulfate | 320 | 48 hr | LC50 | 6,300 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,M,D | Copper sulfate | 324 | 48 hr | LC50 | 9,000 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,M,D | Copper sulfate | 324 | 48 hr | LC50 | 4,700 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,M,D | Copper sulfate | 320 | 48 hr | LC50 | 11,000 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,M,D | Copper sulfate | 318 | 48 hr | LC50 | 5,700 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,M,D | Copper sulfate | 318 | 48 hr | LC50 | 10,000 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,M,D | Copper sulfate | 314 | 48 hr | LC50 | 8,000 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,M,D | Copper sulfate | 318 | 48 hr | LC50 | 11,000 | - | Geckler et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | S,M,D | Copper sulfate | 324 | 48 hr | LC50 | 9,700 | - | Geckler et al. 1976 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 339 | 48 hr | LC50 | 7,000 | - | Geckler et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 310 | 48 hr | LC50 | 12,000 | - | Geckler et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 310 | 48 hr | LC50 | 21,000 | - | Geckler et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 302 | 48 hr | LC50 | 19,000 | - | Geckler et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 296 | 48 hr | LC50 | 8,000 | - | Geckler et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 332 | 48 hr | LC50 | 11,000 | - | Geckler et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 340 | 48 hr | LC50 | 6,300 | - | Geckler et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 296 | 48 hr | LC50 | 1,500 | - | Geckler et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 306 | 48 hr | LC50 | 750 | - | Geckler et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 308 | 48 hr | LC50 | 2,500 | - | Geckler et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 304 | 48 hr | LC50 | 1,600 | - | Geckler et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | S,M,D | Copper sulfate | 315 | 48 hr | LC50 | 4,000 | - | Geckler et al. 1976 |
| Bluntnose minnow (3.9 cm), *Pimephales notatus* | F,M,T,D | Copper sulfate | 314 | 96 hr | LC50 | 6,800 | - | Geckler et al. 1976 |
| Bluntnose minnow (5.3 cm), *Pimephales notatus* | F,M,T,D | Copper sulfate | 303 | 96 hr | LC50 | 13,000 | - | Geckler et al. 1976 |
| Fathead minnow (adult), *Pimephales promelas* | S,U | Copper sulfate | 103-104 | 96 hr | LC50 | 210 | | Birge et al. 1983 |
| Fathead minnow (adult), *Pimephales promelas* | S,U | Copper sulfate | 103-104 | 96 hr | LC50 | 310 | | Birge et al. 1983 |
| Fathead minnow (adult), *Pimephales promelas* | S,U | Copper sulfate | 103-104 | 96 hr | LC50 | 120 | | Birge et al. 1983 |
| Fathead minnow (adult), *Pimephales promelas* | S,U | Copper sulfate | 103-104 | 96 hr | LC50 | 210 | | Birge et al. 1983;<br>Benson and Birge 1985 |
| Fathead minnow (adult), *Pimephales promelas* | S,U | Copper sulfate | 254-271 | 96 hr | LC50 | 390 | | Birge et al. 1983;<br>Benson and Birge 1985 |
| Fathead minnow, *Pimephales promelas* | S,U | Copper sulfate | 200 | 96 hr | LC50 | 430 | | Mount 1968 |
| Fathead minnow, *Pimephales promelas* | S,U | Copper sulfate | 31 | 96 hr | LC50 | 84 | | Mount and Stephan 1969 |
| Fathead minnow (3.8-6.3 cm), *Pimephales promelas* | S,U | Copper sulfate | 20 | 96 hr | LC50 | 25 | | Pickering and Henderson 1966 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Fathead minnow (3.8-6.3 cm), *Pimephales promelas* | S,U | Copper sulfate | 20 | 96 hr | LC50 | 23 | | Pickering and Henderson 1966 |
| Fathead minnow (3.8-6.3 cm), *Pimephales promelas* | S,U | Copper sulfate | 20 | 96 hr | LC50 | 23 | | Pickering and Henderson 1966 |
| Fathead minnow (3.8-6.3 cm), *Pimephales promelas* | S,U | Copper sulfate | 20 | 96 hr | LC50 | 22 | | Pickering and Henderson 1966 |
| Fathead minnow (3.8-6.3 cm), *Pimephales promelas* | S,U | Copper sulfate | 360 | 96 hr | LC50 | 1760 | | Pickering and Henderson 1966 |
| Fathead minnow (3.8-6.3 cm), *Pimephales promelas* | S,U | Copper sulfate | 360 | 96 hr | LC50 | 1140 | | Pickering and Henderson 1966 |
| Fathead minnow, *Pimephales promelas* | S,U | Copper sulfate | 20 | 96 hr | LC50 | 50 | | Tarzwell and Henderson 1960 |
| Fathead minnow, *Pimephales promelas* | S,U | Copper sulfate | 400 | 96 hr | LC50 | 1,400 | | Tarzwell and Henderson 1960 |
| Fathead minnow (3.2-4.2 cm), *Pimephales promelas* | S,M | Copper acetate | 44 | 96 hr | LC50 | 117 | - | Curtis et al. 1979;<br>Curtis and Ward 1981 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 294 | 96 hr | LC50 | 16,000 | - | Brungs et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 120 | 96 hr | LC50 | 2,200 | - | Brungs et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 298 | 96 hr | LC50 | 16,000 | - | Brungs et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 280 | 96 hr | LC50 | 3,300 | - | Brungs et al. 1976;<br>Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), Pimephales promelas | S,M,D | Copper sulfate | 244 | 96 hr | LC50 | 1,600 | - | Brungs et al. 1976;<br>Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 212 | 96 hr | LC50 | 2,000 | - | Brungs et al. 1976;<br>Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 260 | 96 hr | LC50 | 3,500 | - | Brungs et al. 1976;<br>Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 224 | 96 hr | LC50 | 9,700 | - | Brungs et al. 1976;<br>Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 228 | 96 hr | LC50 | 5,000 | - | Brungs et al. 1976;<br>Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 150 | 96 hr | LC50 | 2,800 | - | Brungs et al. 1976;<br>Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 310 | 96 hr | LC50 | 11,000 | - | Brungs et al. 1976;<br>Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 280 | 96 hr | LC50 | 12,000 | - | Brungs et al. 1976;<br>Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 280 | 96 hr | LC50 | 11,000 | - | Brungs et al. 1976;<br>Geckler et al. 1976 |

## Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 260 | 96 hr | LC50 | 22,200 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 308 | 96 hr | LC50 | 4,670 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 206 | 96 hr | LC50 | 920 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 262 | 96 hr | LC50 | 1,190 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 322 | 96 hr | LC50 | 2,830 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 210 | 96 hr | LC50 | 1,450 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 260 | 96 hr | LC50 | 1,580 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 252 | 96 hr | LC50 | 1,000 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 312 | 96 hr | LC50 | 5,330 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 276 | 96 hr | LC50 | 4,160 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 252 | 96 hr | LC50 | 10,550 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 298 | 96 hr | LC50 | 22,200 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 282 | 96 hr | LC50 | 21,800 | - | Geckler et al. 1976 |
| Fathead minnow (2.0-6.9 cm), *Pimephales promelas* | S,M,D | Copper sulfate | 284 | 96 hr | LC50 | 23,600 | - | Geckler et al. 1976 |
| Fathead minnow (<24 h), *Pimephales promelas* | S,M,T | Copper nitrate | 290 | 96 hr | LC50 | >200 | - | Schubauer-Berigan et al. 1993 |
| Fathead minnow (<24 h), *Pimephales promelas* | S,M,T | Copper sulfate | 16.8 | 96 hr | LC50 | 36.0 | - | Welsh et al. 1993 |
| Fathead minnow (<24 h), *Pimephales promelas* | S,M,T | Copper sulfate | 19.0 | 96 hr | LC50 | 70.3 | - | Welsh et al. 1993 |
| Fathead minnow (<24 h), *Pimephales promelas* | S,M,T | Copper sulfate | 19.0 | 96 hr | LC50 | 85.6 | - | Welsh et al. 1993 |
| Fathead minnow (<24 h), *Pimephales promelas* | S,M,T | Copper sulfate | 19.0 | 96 hr | LC50 | 182.0 | - | Welsh et al. 1993 |
| Fathead minnow (<24 h; 0.68 mg), *Pimephales promelas* | S,M,T | Copper sulfate | 17 | 96 hr | LC50 | 1.99 | - | Welsh et al. 1993 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Fathead minnow (<24 h; 0.68 mg),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 20.5 | 96 hr | LC50 | 4.86 | - | Welsh et al. 1993 |
| Fathead minnow (<24 h; 0.68 mg),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 16.5 | 96 hr | LC50 | 11.1 | - | Welsh et al. 1993 |
| Fathead minnow (<24 h; 0.68 mg),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 17.5 | 96 hr | LC50 | 9.87 | - | Welsh et al. 1993 |
| Fathead minnow (<24 h; 0.68 mg),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 17 | 96 hr | LC50 | 15.7 | - | Welsh et al. 1993 |
| Fathead minnow (60-90 days),<br>*Pimephales promelas* | S,M,T | - | 110 | 48 hr | LC50 | 284 | - | Dobbs et al. 1994 |
| Fathead minnow (3 wk),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 101 | 48 hr | Short-term intolerance of hypoxia (2 mg D.O./L) | 186 | - | Bennett et al. 1995 |
| Fathead minnow (2-4 day),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 6-10 | - | LC50 | 12.5 | - | Suedel et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 9.9 | 96 hr | LC50 | 10.7 | - | Welsh et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 7.1 | 96 hr | LC50 | 6.3 | - | Welsh et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 8.3 | 96 hr | LC50 | 12.2 | - | Welsh et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 8.9 | 96 hr | LC50 | 9.5 | - | Welsh et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 16.8 | 96 hr | LC50 | 26.8 | - | Welsh et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 12.2 | 96 hr | LC50 | 21.2 | - | Welsh et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 9.4 | 96 hr | LC50 | 19.8 | - | Welsh et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 11.4 | 96 hr | LC50 | 31.9 | - | Welsh et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 10.9 | 96 hr | LC50 | 26.1 | - | Welsh et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 12.4 | 96 hr | LC50 | 26.0 | - | Welsh et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T | Copper sulfate | 17.4 | 96 hr | LC50 | 169.5 | - | Welsh et al. 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T,D | Copper sulfate | 46 | 96 hr | LC50 | 17.15 | 14.87 | Erickson et al. 1996a,b |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | S,M,T,D | Copper sulfate | 46 | 96 hr | LC50 | 21.59 | 18.72 | Erickson et al. 1996a,b |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Fathead minnow (<24 hrs), *Pimephales promelas* | S,M,T,D | Copper sulfate | 47 | 96 hr | LC50 | 123.19 | 106.8 | Erickson et al. 1996a,b |
| Fathead minnow (<24 hrs), *Pimephales promelas* | S,M,T,D | Copper sulfate | 45 | 96 hr | LC50 | 42.56 | 36.89 | Erickson et al. 1996a,b |
| Fathead minnow (<24 hrs), *Pimephales promelas* | S,M,T,D | Copper sulfate | 46 | 96 hr | LC50 | 83.19 | 72.13 | Erickson et al. 1996a,b |
| Fathead minnow, *Pimephales promelas* | S,M,T,D | Copper sulfate | 100 | 96 hr | LC50 (fish from metal-contaminated pond) | 360 | - | Birge et al. 1983 |
| Fathead minnow, *Pimephales promelas* | S,M,T,D | Copper sulfate | 250 | 96 hr | LC50 (fish from metal-contaminated pond) | 410 | - | Birge et al. 1983 |
| Fathead minnow (<24 hr), *Pimephales promelas* | R,U | - | 45 | 7 days | LC50 | 70 | - | Norberg and Mount 1985 |
| Fathead minnow (<24 hr), *Pimephales promelas* | R,U | - | 45 | 7 days | LOEC (growth) | 26 | - | Norberg and Mount 1985 |
| Fathead minnow (<24 hr), *Pimephales promelas* | R,U | Copper sulfate | 345 | 4 days | RNA threshhold effect | 130 | - | Parrott and Sprague 1993 |
| Fathead minnow (embryo), *Pimephales promelas* | R,U | Copper sulfate | 106 | 5 days | LC50 | 480 | - | Fort et al. 1996 |
| Fathead minnow (embryo), *Pimephales promelas* | R,U | Copper sulfate | 106 | 5 days | LC50 | 440 | - | Fort et al. 1996 |
| Fathead minnow (embryo), *Pimephales promelas* | R,U | Copper sulfate | 106 | 5 days | EC50 (malformation) | 270 | - | Fort et al. 1996 |
| Fathead minnow (embryo), *Pimephales promelas* | R,U | Copper sulfate | 106 | 5 days | EC50 (malformation) | 260 | - | Fort et al. 1996 |
| Fathead minnow (embryo), *Pimephales promelas* | R,U | Copper sulfate | 106 | 7 days | LC50 | 310 | - | Fort et al. 1996 |
| Fathead minnow (embryo), *Pimephales promelas* | R,U | Copper sulfate | 106 | 7 days | LC50 | 330 | - | Fort et al. 1996 |
| Fathead minnow (embryo), *Pimephales promelas* | R,U | Copper sulfate | 106 | 7 days | EC50 (malformation) | 190 | - | Fort et al. 1996 |
| Fathead minnow (embryo), *Pimephales promelas* | R,U | Copper sulfate | 106 | 7 days | EC50 (malformation) | 170 | - | Fort et al. 1996 |
| Fathead minnow (embryo), *Pimephales promelas* | R,U | Copper sulfate | 106 | 7 days | LOEC (length) | 160 | - | Fort et al. 1996 |
| Fathead minnow (embryo), *Pimephales promelas* | R,U | Copper sulfate | 106 | 7 days | LOEC (length) | 180 | - | Fort et al. 1996 |
| Fathead minnow (larva), *Pimephales promelas* | R,M,T | Copper sulfate | 180 | 7 days | LOEC (growth) | 25 | - | Pickering and Lazorchak 1995 |
| Fathead minnow (larva), *Pimephales promelas* | R,M,T | Copper sulfate | 218 | 7 days | LOEC (growth) | 38 | - | Pickering and Lazorchak 1995 |
| Fathead minnow (larva), *Pimephales promelas* | R,M,T | Copper sulfate | 218 | 7 days | LOEC (growth) | 38 | - | Pickering and Lazorchak 1995 |
| Fathead minnow (3-7 days), *Pimephales promelas* | R,M,T | Copper sulfate | 74 | 48 hr | LC50 | 225 | - | Diamond et al. 1997b |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Fathead minnow (larva),<br>*Pimephales promelas* | R,M,T,D | Copper sulfate | 80 | 48 hr | LC50 | 35.9 | - | Diamond et al. 1997a |
| Fathead minnow (larva),<br>*Pimephales promelas* | R,M,T,D | Copper sulfate | 80 | 48 hr | LC50 | 28.9 | - | Diamond et al. 1997a |
| Fathead minnow (larva),<br>*Pimephales promelas* | R,M,T,D | Copper sulfate | 80 | 48 hr | LC50 | 20.7 | - | Diamond et al. 1997a |
| Fathead minnow (larva),<br>*Pimephales promelas* | R,M,T,D | Copper sulfate | 80 | 48 hr | LC50 | 80.8 | - | Diamond et al. 1997a |
| Fathead minnow (3-7 days),<br>*Pimephales promelas* | R,M,T,D | Copper sulfate | 80 | 48 hr | LC50 | 297.1 | - | Diamond et al. 1997b |
| Fathead minnow (3-7 days),<br>*Pimephales promelas* | R,M,T,D | Copper sulfate | 72 | 48 hr | LC50 | 145.8 | - | Diamond et al. 1997b |
| Fathead minnow (32-38 mm),<br>*Pimephales promelas* | F,M,T | Copper sulfate | 244 | 9 mo | LOEC<br>(93% lower fecundity) | 120 | - | Brungs et al. 1976 |
| Fathead minnow (larva),<br>*Pimephales promelas* | F,M,T | Copper sulfate | 202 | - | LC50 | 250 | - | Scudder et al. 1988 |
| Fathead minnow (embryo),<br>*Pimephales promelas* | F,M,T | Copper sulfate | 202 | 34 days | Reduced growth; increased abnormality | 61 | - | Scudder et al. 1988 |
| Fathead minnow (embryo),<br>*Pimephales promelas* | F,M,T | Copper sulfate | 202 | 34 days | LC50 | 123 | - | Scudder et al. 1988 |
| Fathead minnow (24-96 hr),<br>*Pimephales promelas* | F,M,T | Copper sulfate | 10.7 | 21 days | Incipient lethal level | 6.2 | - | Welsh 1996 |
| Fathead minnow (24-96 hr),<br>*Pimephales promelas* | F,M,T | Copper sulfate | 10.7 | 21 days | Growth (length) reduced by 8% | 5.3 | - | Welsh 1996 |
| Fathead minnow (24-96 hr),<br>*Pimephales promelas* | F,M,T | Copper sulfate | 9.3 | 21 days | Incipient lethal level | 17.2 | - | Welsh 1996 |
| Fathead minnow (24-96 hr),<br>*Pimephales promelas* | F,M,T | Copper sulfate | 9.3 | 21 days | Growth (length) reduced by 17% | 16.2 | - | Welsh 1996 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | F,M,T | Copper sulfate | 46 | 96 hr | LC50 | 305 | - | Erickson et al. 1996 a,b |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | F,M,T | Copper sulfate | 46 | 96 hr | LC50 | 298.6 | - | Erickson et al. 1996 a, b |
| Fathead minnow,<br>*Pimephales promelas* | F,M,T | - | 30 | 96 hr | LC50<br>(TOC=12 mg/L) | 436 | - | Lind et al. manuscript |
| Fathead minnow,<br>*Pimephales promelas* | F,M,T | - | 37 | 96 hr | LC50<br>(TOC=13 mg/L) | 516 | - | Lind et al. manuscript |
| Fathead minnow,<br>*Pimephales promelas* | F,M,T | - | 87 | 96 hr | LC50<br>(TOC=36 mg/L) | 1,586 | - | Lind et al. manuscript |
| Fathead minnow,<br>*Pimephales promelas* | F,M,T | - | 73 | 96 hr | LC50<br>(TOC=28 mg/L) | 1,129 | - | Lind et al. manuscript |
| Fathead minnow,<br>*Pimephales promelas* | F,M,T | - | 84 | 96 hr | LC50<br>(TOC=15 mg/L) | 550 | - | Lind et al. manuscript |
| Fathead minnow,<br>*Pimephales promelas* | F,M,T | - | 66 | 96 hr | LC50<br>(TOC=34 mg/L) | 1,001 | - | Lind et al. manuscript |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Fathead minnow,<br>*Pimephales promelas* | F,M,T | - | 117 | 96 hr | LC50<br>(TOC=30 mg/L) | 2,050 | - | Lind et al. manuscript |
| Fathead minnow,<br>*Pimephales promelas* | F,M,T | - | 121 | 96 hr | LC50<br>(TOC=30 mg/L) | 2,336 | - | Lind et al. manuscript |
| Fathead minnow,<br>*Pimephales promelas* | F,M,T | Copper sulfate | 117 | 96 hr | LC50 | 2,050 | - | Lind et al. manuscript |
| Fathead minnow,<br>*Pimephales promelas* | F,M,T | Copper sulfate | 121 | 96 hr | LC50 | 2,336 | - | Lind et al. manuscript |
| Fathead minnow (4.4 cm),<br>*Pimephales promelas* | F,M,T,D | Copper sulfate | 314 | 96 hr | LC50 | 11,000 | - | Geckler et al. 1976 |
| Fathead minnow (4.2 cm),<br>*Pimephales promelas* | F,M,T,D | Copper sulfate | 303 | 96 hr | LC50 | 15,000 | - | Geckler et al. 1976 |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | F,M,T,D | Copper sulfate | 45 | 96 hr | LC50 | 158.8 | 138.1 | Erickson et al. 1996a,b |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | F,M,T,D | Copper sulfate | 45 | 96 hr | LC50 | 80.01 | 72.01 | Erickson et al. 1996a,b |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | F,M,T,D | Copper sulfate | 46 | 96 hr | LC50 | 20.96 | 18.23 | Erickson et al. 1996a,b |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | F,M,T,D | Copper sulfate | 44 | 96 hr | LC50 | 50.8 | 39.12 | Erickson et al. 1996a,b |
| Fathead minnow (<24 hrs),<br>*Pimephales promelas* | F,M,T,D | Copper sulfate | 45 | 96 hr | LC50 | 65.41 | 45.78 | Erickson et al. 1996a,b |
| Colorado squawfish (larva),<br>*Ptychocheilus lucius* | S,U | Copper sulfate | 199 | 96 hr | LC50 | 363 | | Buhl and Hamilton 1996 |
| Colorado squawfish (155-186 days),<br>*Ptychocheilus lucius* | S,U | Copper sulfate | 199 | 96 hr | LC50 | 663 | | Buhl and Hamilton 1996 |
| Colorado squawfish (32-40 days posthatch),<br>*Ptychocheilus lucius* | S,U | Copper sulfate | 144 | 96 hr | LC50 | 293 | | Hamilton and Buhl 1997 |
| Colorado squawfish (32-40 days posthatch),<br>*Ptychocheilus lucius* | S,U | Copper sulfate | 144 | 96 hr | LC50 | 320 | | Hamilton and Buhl 1997 |
| Creek chub,<br>*Semotilus atromaculatus* | F,M,T | Copper sulfate | 316 | 96 hr | LC50 | 11,500 | - | Geckler et al. 1976 |
| Creek chub,<br>*Semotilus atromaculatus* | F,M,T | Copper sulfate | 274 | 96 hr | LC50 | 1,100 | - | Geckler et al. 1976 |
| Razorback sucker (larva),<br>*Xyrauchen texanus* | S,U | Copper sulfate | 199 | 96 hr | LC50 | 404 | | Buhl and Hamilton 1996 |
| Razorback sucker (102-116 days),<br>*Xyrauchen texanus* | S,U | Copper sulfate | 199 | 96 hr | LC50 | 331 | | Buhl and Hamilton 1996 |
| Razorback sucker (13-23 days posthatch),<br>*Xyrauchen texanus* | S,U | Copper sulfate | 144 | 96 hr | LC50 | 231 | | Hamilton and Buhl 1997 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Razorback sucker (13-23 days posthatch), *Xyrauchen texanus* | S,U | Copper sulfate | 144 | 96 hr | LC50 | 314 |  | Hamilton and Buhl 1997 |
| Brown bullhead, *Ictallurus nebulosus* | F,M,T | Copper sulfate | 303 | 96 hr | LC50 | 12,000 | - | Geckler et al. 1976 |
| Brown bullhead (5.2 cm), *Ictalurus nebulosus* | F,M,T | Copper sulfate | 314 | 96 hr | LC50 | 5,200 | - | Geckler et al. 1976 |
| Channel catfish (13-14 cm), *Ictalurus punctatus* | S,U | Copper sulfate | 221 | 94 hr | Decreased serum osmolality | 2,500 | - | Lewis and Lewis 1971 |
| Channel catfish, *Ictalurus punctatus* | S,U | Copper sulfate | 45 | 24 hr | LC50 ($5^0$ C) | 3,700 | - | Cairns et al. 1978 |
| Channel catfish, *Ictalurus punctatus* | S,U | Copper sulfate | 45 | 24 hr | LC50 ($15^0$ C) | 2,600 | - | Cairns et al. 1978 |
| Channel catfish, *Ictalurus punctatus* | S,U | Copper sulfate | 45 | 24 hr | LC50 ($30^0$ C) | 3,100 | - | Cairns et al. 1978 |
| Channel catfish, *Ictalurus punctatus* | S,U | Copper sulfate | 100 | 10 days | EC50 (death and deformity) | 6,620 | - | Birge and Black 1979 |
| Channel catfish (fingerlings), *Ictalurus punctatus* | S,U | Copper sulfate | 16 | 96 hr | LC50 | 54 |  | Straus and Tucker 1993 |
| Channel catfish (fingerlings), *Ictalurus punctatus* | S,U | Copper sulfate | 16 | 96 hr | LC50 | 55 |  | Straus and Tucker 1993 |
| Channel catfish (fingerlings), *Ictalurus punctatus* | S,U | Copper sulfate | 83 | 96 hr | LC50 | 762 |  | Straus and Tucker 1993 |
| Channel catfish (fingerlings), *Ictalurus punctatus* | S,U | Copper sulfate | 83 | 96 hr | LC50 | 700 |  | Straus and Tucker 1993 |
| Channel catfish (fingerlings), *Ictalurus punctatus* | S,U | Copper sulfate | 161 | 96 hr | LC50 | 768 |  | Straus and Tucker 1993 |
| Channel catfish (fingerlings), *Ictalurus punctatus* | S,U | Copper sulfate | 161 | 96 hr | LC50 | 1139 |  | Straus and Tucker 1993 |
| Channel catfish (fingerlings), *Ictalurus punctatus* | S,U | Copper sulfate | 287 | 96 hr | LC50 | 1041 |  | Straus and Tucker 1993 |
| Channel catfish (fingerlings), *Ictalurus punctatus* | S,U | Copper sulfate | 287 | 96 hr | LC50 | 925 |  | Straus and Tucker 1993 |
| Channel catfish (400-600 g), *Ictalurus punctatus* | F,M,T | Copper sulfate | - | 10 wk | Significant mortality | 354 | - | Perkins et al. 1997 |
| Channel catfish (4.1 gm), *Ictalurus punctatus* | F,M,T,D | Copper sulfate | 319 | 14 days | LC50 | 1,229 | - | Richey and Roseboom 1978 |
| Channel catfish (5.7 gm), *Ictalurus punctatus* | F,M,T,D | Copper sulfate | 315 | 14 days | LC50 | 1,073 | - | Richey and Roseboom 1978 |
| Banded killifish, *Fundulus diaphanus* | S,M,T | Copper nitrate | 53 | - |  | 860 | - | Rehwoldt et al. 1971 |
| Banded killifish, *Fundulus diaphanus* | S,M,T | Copper nitrate | 55 | - |  | 840 | - | Rehwoldt et al. 1972 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Flagfish (0.1-0.3 g), *Jordanella floridae* | F,M,T,D | Copper sulfate | 363 | 10 days | LC50 | - | 680 | Fogels and Sprague 1977 |
| Flagfish (0.1-0.3 g), *Jordanella floridae* | F,M,T,D | Copper sulfate | 363 | 96 hr | LC50 | - | 1,270 | Fogels and Sprague 1977 |
| Mosquitofish (3.8-5.1 cm female), *Gambusia affinis* | S,U | Copper nitrate | 27-41 | 96 hr | LC50 | 93 | | Joshi and Rege 1980 |
| Mosquitofish (3.8-5.1 cm female), *Gambusia affinis* | S,U | Copper sulfate | 27-41 | 96 hr | LC50 | 200 | | Joshi and Rege 1980 |
| Mosquitofish (2.5 cm male), *Gambusia affinis* | S,U | - | 50 | 96 hr | LC50 | 3,500 | | Kallanagoudar and Patil 1997 |
| Mosquitofish (2.5 cm male), *Gambusia affinis* | S,U | - | 150 | 96 hr | LC50 | 5,000 | | Kallanagoudar and Patil 1997 |
| Mosquitofish (2.5 cm male), *Gambusia affinis* | S,U | - | 300 | 96 hr | LC50 | 6,000 | | Kallanagoudar and Patil 1997 |
| Mosquitofish (3.5 cm female), *Gambusia affinis* | S,U | - | 50 | 96 hr | LC50 | 2,500 | | Kallanagoudar and Patil 1997 |
| Mosquitofish (3.5 cm female), *Gambusia affinis* | S,U | - | 150 | 96 hr | LC50 | 2,900 | | Kallanagoudar and Patil 1997 |
| Mosquitofish (3.5 cm female), *Gambusia affinis* | S,U | - | 300 | 96 hr | LC50 | 5,000 | | Kallanagoudar and Patil 1997 |
| Mosquitofish (0.8 cm fry), *Gambusia affinis* | S,U | - | 50 | 96 hr | LC50 | 900 | | Kallanagoudar and Patil 1997 |
| Mosquitofish (0.8 cm fry), *Gambusia affinis* | S,U | - | 150 | 96 hr | LC50 | 1,400 | | Kallanagoudar and Patil 1997 |
| Mosquitofish (0.8 cm fry), *Gambusia affinis* | S,U | - | 300 | 96 hr | LC50 | 2,000 | | Kallanagoudar and Patil 1997 |
| Mosquito fish, *Gambusia affinis* | S,U | Copper sulfate | - | 96 hr | LC50 (high turbidity) | 75,000 | - | Wallen et al. 1957 |
| Mosquito fish, *Gambusia affinis* | R,M | Copper sulfate | 45 | 48 hr | LC50 | 180 | - | Chagnon and Guttman 1989 |
| Guppy (1.5 cm), *Poecilia reticulata* | S,U | Copper sulfate | 230 | 96 hr | LC50 | 1,230 | | Khangarot 1981 |
| Guppy (1.62 cm), *Poecilia reticulata* | S,U | Copper sulfate | 240 | 96 hr | LC50 | 764 | | Khangarot et al. 1981b |
| Guppy (1.9-2.5 cm), *Poecilia reticulata* | S,U | Copper sulfate | 20 | 96 hr | LC50 | 36 | | Pickering and Henderson 1966 |
| Guppy (1.5 cm), *Poecilia reticulata* | R,U | Copper sulfate | 260 | 96 hr | LC50 | 2,500 | | Khangarot et al. 1981a |
| Guppy (0.8-1.0 cm), *Poecilia reticulata* | R,U | Copper sulfate | 144-188 | 96 hr | LC50 | 160 | | Deshmukh and Marathe 1980 |
| Guppy (1.2-2.3 cm; female), *Poecilia reticulata* | R,U | Copper sulfate | 144-188 | 96 hr | LC50 | 275 | | Deshmukh and Marathe 1980 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Guppy (2.3-2.8 cm; male), *Poecilia reticulata* | R,U | Copper sulfate | 144-188 | 96 hr | LC50 | 210 | | Deshmukh and Marathe 1980 |
| Guppy (340 mg; female), *Poecilia reticulata* | R,U | Copper sulfate | 144-188 | 96 hr | LC50 | 480 | | Deshmukh and Marathe 1980 |
| Guppy (1.5 cm), *Poecilia reticulata* | R,U | Copper sulfate | 260 | 48 hr | LC50 | 2,500 | - | Khangarot et al. 1981a |
| Guppy (1.5 cm), *Poecilia reticulata* | R, U | Copper sulfate | 181 | 96 hr | LC50 | 986 | - | Khangarot and Ray 1987b |
| Guppy (1 mo), *Poecilia reticulata* | F,U | Copper sulfate | 76 | 24 hr | LC50 | 1,370 | - | Minicucci 1971 |
| Guppy (1 mo), *Poecilia reticulata* | F,U | Copper sulfate | 76 | 24 hr | LC50 | 930 | - | Minicucci 1971 |
| Guppy (1 mo), *Poecilia reticulata* | F,U | Copper sulfate | 76 | 24 hr | LC50 | 1,130 | - | Minicucci 1971 |
| White perch, *Morone americana* | S,M,T | Copper nitrate | 53 | - | LC50 | 6,200 | - | Rehwoldt et al. 1971 |
| White perch, *Morone americana* | S,M,T | Copper nitrate | 55 | - | LC50 | 6,400 | - | Rehwoldt et al. 1972 |
| Striped bass (larva), *Morone saxitilis* | S,U | Copper chloride | 34.6 | 96 hr | LC50 | 50 | | Hughes 1973 |
| Striped bass (larva), *Morone saxitilis* | S,U | Copper sulfate | 34.6 | 96 hr | LC50 | 100 | | Hughes 1973 |
| Striped bass (3.5-5.1 cm), *Morone saxitilis* | S,U | Copper chloride | 34.6 | 96 hr | LC50 | 50 | | Hughes 1973 |
| Striped bass (3.1-5.1 cm), *Morone saxitilis* | S,U | Copper sulfate | 34.6 | 96 hr | LC50 | 150 | | Hughes 1973 |
| Striped bass (35-80 day), *Morone saxitilis* | S,U | Copper sulfate | 285 | 96 hr | LC50 | 270 | | Palawski et al. 1985 |
| Striped bass (6 cm), *Morone saxitilis* | S,U | Copper sulfate | 35 | 96 hr | LC50 | 620 | | Wellborn 1969 |
| Striped bass, *Morone saxitilis* | S,M,T | Copper nitrate | 53 | 96 hr | LC50 | 4,300 | - | Rehwoldt et al. 1971 |
| Striped bass, *Morone saxitilis* | S,M,T | Copper nitrate | 55 | 96 hr | LC50 | 2,700 | - | Rehwoldt et al. 1972 |
| Rock bass, *Ambloplites rupestris* | F,M,T | - | 24 | 96 hr | LC50 (high TOC) | 1,432 | - | Lind et al. manuscript |
| Pumpkinseed (1.2 g), *Lepomis gibbosus* | S,M,T | Copper nitrate | 53 | - | LC50 | 2,400 | - | Rehwoldt et al. 1971 |
| Pumpkinseed (1.2 g), *Lepomis gibbosus* | S,M,T | Copper nitrate | 55 | - | LC50 | 2,700 | - | Rehwoldt et al. 1972 |
| Pumpkinseed, *Lepomis gibbosus* | S,M,T | Copper nitrate | 53 | 96 hr | LC50 | 2,400 | - | Rehwoldt et al. 1971 |
| Pumpkinseed, *Lepomis gibbosus* | S,M,T | Copper nitrate | 55 | 96 hr | LC50 | 2,700 | - | Rehwoldt et al. 1972 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method$^a$ | Chemical | Hardness (mg/L as CaCO$_3$) | Duration | Effect | Total Concentration (µg/L)$^b$ | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Bluegill,<br>*Lepomis macrochirus* | S,U | Copper chloride | 43 | 96 hr | LC50 | 770 | | Academy of Natural Sciences 1960 |
| Bluegill,<br>*Lepomis macrochirus* | S,U | Copper sulfate | 43 | 96 hr | LC50 | 1,250 | | Academy of Natural Sciences 1960<br>Cairns and Scheier 1968; Patrick et |
| Bluegill,<br>*Lepomis macrochirus* | S,U | Copper sulfate | 45 | 24 hr | LC50<br>(5$^0$ C) | 2,590 | - | Cairns et al. 1978 |
| Bluegill,<br>*Lepomis macrochirus* | S,U | Copper sulfate | 45 | 24 hr | LC50<br>(15$^0$ C) | 2,500 | - | Cairns et al. 1978 |
| Bluegill,<br>*Lepomis macrochirus* | S,U | Copper sulfate | 45 | 24 hr | LC50<br>(30$^0$ C) | 3,820 | - | Cairns et al. 1978 |
| Bluegill (3-4 cm),<br>*Lepomis macrochirus* | S,U | - | 119 | 8 days | 33% reduction in locomotor activity | 40 | - | Ellgaard and Guillot 1988 |
| Bluegill (4.2 cm),<br>*Lepomis macrochirus* | S,U | Copper sulfate | 52 | 96 hr | LC50 | 254 | | Inglis and Davis 1972 |
| Bluegill (4.2 cm),<br>*Lepomis macrochirus* | S,U | Copper sulfate | 209 | 96 hr | LC50 | 437 | | Inglis and Davis 1972 |
| Bluegill (4.2 cm),<br>*Lepomis macrochirus* | S,U | Copper sulfate | 365 | 96 hr | LC50 | 648 | | Inglis and Davis 1972 |
| Bluegill (5-15 g),<br>*Lepomis macrochirus* | S,U | Copper sulfate | 35 | 2-6 days | 8% increase in oxygen consumption rates | 300 | - | O'Hara 1971 |
| Bluegill (3.8-6.3 cm),<br>*Lepomis macrochirus* | S,U | Copper sulfate | 20 | 96 hr | LC50 | 660 | | Pickering and Henderson 1966 |
| Bluegill (3.8-6.3 cm),<br>*Lepomis macrochirus* | S,U | Copper sulfate | 360 | 96 hr | LC50 | 10,200 | | Pickering and Henderson 1966 |
| Bluegill,<br>*Lepomis macrochirus* | S,U | Copper sulfate | 20 | 96 hr | LC50 | 200 | | Tarzwell and Henderson 1960 |
| Bluegill,<br>*Lepomis macrochirus* | S,U | Copper sulfate | 400 | 96 hr | LC50 | 10,000 | | Tarzwell and Henderson 1960 |
| Bluegill (5-11 cm),<br>*Lepomis macrochirus* | S,U | Copper sulfate | 46 | 48 hr | LC50 | 3,000 | - | Turnbull et al. 1954 |
| Bluegill (5-11 cm),<br>*Lepomis macrochirus* | S,U | Copper sulfate | 101.2 | 48 hr | LC50 | 7,000 | - | Turnbull et al. 1954 |
| Bluegill (0.51g),<br>*Lepomis macrochirus* | S,M,T | - | 110 | 48 hr | LC50 | 4,300 | - | Dobbs et al. 1994 |

# Appendix B. Other Data on Effects of Copper on Freshwater Organisms

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Total Concentration (µg/L)[b] | Dissolved Concentration (µg/L) | Reference |
|---|---|---|---|---|---|---|---|---|
| Bluegill (5-9 cm),<br>*Lepomis macrochirus* | S,M,T | Copper chloride | 45-47 | - | LC50 | 710 | - | Trama 1954 |
| Bluegill (5-9 cm),<br>*Lepomis macrochirus* | S,M,T | Copper sulfate | 45-47 | - | LC50 | 770 | - | Trama 1954 |
| Bluegill (5-15 g),<br>*Lepomis macrochirus* | F,M | Copper sulfate | 35 | - | LC50 | 2400 | - | O'Hara 1971 |
| Bluegill (3.5-6.0 cm),<br>*Lepomis macrochirus* | F,M,T | Copper sulfate | 112.4 | 80 min | Avoidance threshold | 8,480 | - | Black and Birge 1980 |
| Bluegill (3.2-6.7 cm),<br>*Lepomis macrochirus* | F,M,T | Copper chloride | 21.2-59.2 | 96 hr | LC50 | 1,100 | - | Thompson et al. 1980 |
| Bluegill (3.2-6.7 cm),<br>*Lepomis macrochirus* | F,M,T | Copper chloride | 21.2-59.2 | 96 hr | LC50 | 900 | - | Thompson et al. 1980 |
| Bluegill (35.6-62.3 g),<br>*Lepomis macrochirus* | F,M,T | Copper sulfate | 273.3 | 24-96 hr | Various behavioral changes | 34 | - | Henry and Atchison 1986 |
| Bluegill,<br>*Lepomis macrochirus* | F,M,T | Copper chloride | 157 | 24-96 hr | 27% reduction in food consumption | 31 | - | Sandheinrich and Atchison 1989 |
| Bluegill,<br>*Lepomis macrochirus* | F,M,T,D | Copper sulfate | 316 | 96 hr | LC50 (high BOD) | 16,000 | - | Geckler et al. 1976 |
| Bluegill,<br>*Lepomis macrochirus* | F,M,T,D | Copper sulfate | 318 | 96 hr | LC50 (high BOD) | 17,000 | - | Geckler et al. 1976 |
| Bluegill (0.14-0.93 g),<br>*Lepomis macrochirus* | F,M,T,D | Copper sulfate | 246 | 14 days | LC50 | - | 2,500 | Richey and Roseboom 1978 |
| Bluegill (1.15-2.42 g),<br>*Lepomis macrochirus* | F,M,T,D | Copper sulfate | 237 | 14 days | LC50 | - | 3,700 | Richey and Roseboom 1978 |
| Bluegill (48.3 g),<br>*Lepomis macrochirus* | F,M,T,D | Copper sulfate | 40 | 96 hr | Biochemical changes | 2,000 | - | Heath 1984 |
| Largemouth bass (embryo),<br>*Micropterus salmoides* | R,U | Copper sulfate | 100 | 8 days | EC50 (death and deformity) | 6,560 | - | Birge et al. 1978; Birge and Black 1979 |
| Largemouth bass,<br>*Micropterus salmoides* | F,U | - | - | 24 hr | Affected opercular rhythm | 48 | - | Morgan 1979 |
| Rainbow darter,<br>*Etheostoma caeruleum* | F,M,T,D | Copper sulfate | 318 | 96 hr | LC50 (high BOD) | 4,500 | - | Geckler et al. 1976 |
| Rainbow darter,<br>*Etheostoma caeruleum* | F,M,T,D | Copper sulfate | 316 | 96 hr | LC50 (high BOD) | 8,000 | - | Geckler et al. 1976 |
| Rainbow darter,<br>Etheostoma caeruleum | F,M,T,D | Copper sulfate | 274 | 96 hr | LC50 (high BOD) | 2,800 | - | Geckler et al. 1976 |
| Rainbow darter (4.6 cm),<br>*Etheostoma caeruleum* | F,M,T,D | Copper sulfate | 314 | 96 hr | LC50 (high BOD) | 4,800 | - | Geckler et al. 1976 |
| Rainbow darter (4.6 cm),<br>*Etheostoma caeruleum* | F,M,T,D | Copper sulfate | 303 | 96 hr | LC50 (high BOD) | 5,300 | - | Geckler et al. 1976 |
| Fantail,<br>*Etheostoma flabellare* | S,M,T | Copper sulfate | 170 | 96 hr | Lowered critical thermal maximum | 43 | - | Lydy and Wissing 1988 |

# Appendix C. Estimation of Water Chemistry Parameters for Acute Copper Toxicity Tests

# FINAL REPORT

# ESTIMATION OF WATER CHEMISTRY PARAMETERS FOR ACUTE COPPER TOXICITY TESTS

For:

U.S. Environmental Protection Agency
Health and Ecological Criteria Division
Office of Science and Technology, Office of Water
1200 Pennsylvania Avenue, NW
Washington, DC 20460

Great Lakes Environmental Center Program Manager
G.M. DeGraeve
Great Lakes Environmental Center, Inc.
739 Hastings Street, Traverse City, Michigan 49686
Phone: (231) 941-2230

# CONTENTS

## TABLES

## FIGURES

# FOREWORD

This report was developed by the Great Lakes Environmental Center. Some minor revisions were made by the U.S. Environmental Protection Agency (EPA). These revisions were primarily editorial. Additional editorial and formatting revisions were made by the CDM Group, Inc.

The purpose of this report is to provide input water chemistry information for a Biotic Ligand Model (BLM) analysis of the acute copper toxicity data in Table 1a of the U.S. Environmental Protection Agency's (EPA) draft 2003 Update of Ambient Water Quality Criteria for Copper. EPA will use these BLM data to derive adjusted aquatic life criteria for copper. Many of the reported Table 1a acute copper toxicity data lack sufficient information on the chemistry of the dilution water to generate BLM-derived critical accumulation values. This compendium contains data from the primary authors of these articles. It also contains recommendations for the use of these data, additional supporting documentation and/or computations, and recommendations for estimating missing parameters.

# Estimation of Water Chemistry Parameters for Acute Copper Toxicity Tests

To prepare for the possibility of incorporating the Biotic Ligand Model (BLM) (Di Toro et al. 2001) into an updated copper aquatic life criteria document, the U.S. Environmental Protection Agency (EPA) sought to generate a data table summarizing the acute toxicity of copper to freshwater organisms that included the following parameters: alkalinity, dissolved organic carbon (DOC), pH, and the major anions (Cl and $SO_4$) and cations (Ca, Mg, Na, K) of the test water. Published literature was reviewed and appropriate information tabulated, but measurements for many of the aforementioned parameters were not reported. To resolve the overwhelming number of missing test water chemistry values in the database, certain authors were contacted for additional information and to obtain additional measurements in waters where critical information was either not measured or not reported. EPA also attempted to determine appropriate methods for estimating test water chemistry in the absence of reported values. The information received from the authors and recommended procedures for estimating missing parameters are the subject of this report.

## 1.0 Data Acquisition

The authors of several studies were contacted for additional information on the chemistry of the water or methods used in their studies. If the primary or corresponding authors could not be contacted, an attempt was made to contact secondary authors or personnel from the laboratories where the studies had been conducted. In a few instances, this initial effort failed to produce the desired information, and censored databases (U.S. Geological Survey's [USGS] National Stream Quality Accounting Network [NASQAN] and EPA's STOrage and RETrieval [STORET] data warehouse) were consulted to obtain the missing data. As a last resort, other available sources of water compositional data (e.g., city drinking water treatment officials) were contacted.

The acquired data were scrutinized for representativeness and usefulness in estimating surrogate values to complete the water quality information in the original studies. Summary tables and figures generated from these data are included in the following pages, which serve as the basis for the addition of values in the spreadsheets. Information used for the tabular and graphical summaries of these data is included in separate appendices.

## 2.0 Technical Issues and Corresponding Recommendations

### 2.1 *Estimating Ion Concentrations*

Develop a methodology for estimating Ca, Mg, Na, K, Cl, and $SO_4$ concentrations in laboratory-reconstituted waters.

**Recommendation:** The best approach for estimating ion concentrations in standard laboratory-reconstituted water involves scaling default ion concentrations based on measured hardness. The default ion concentrations can be computed from the concentrations of the salts added. The use of calculated ion concentrations as input for the BLM applies only to reconstituted water prepared following the standard recipes reported in guidance documents for conducting acute bioassays with aquatic organisms (ASTM 2000; U.S. EPA 1993) (see Table 1). If similar salts are added in different amounts, then the ion concentrations must be calculated using the recipe reported in the article. Otherwise, specific ion ratios, and more importantly ion concentrations, cannot be calculated.

**Table 1. Standard Reconstituted Water Composition and Target Water Quality Characteristics**

| | Reagent Added (mg/L) | | | | Final Water Quality | | |
|---|---|---|---|---|---|---|---|
| Water Type | $NaHCO_3$ | $CaSO_4 \bullet 2H_2O$ | $MgSO_4$ | KCl | pH[a] | Hardness[a] | Alkalinity[b] |
| Very Soft | 12.0 | 7.5 | 7.5 | 0.5 | 6.4-6.8 | 10-13 | 10-13 |
| Soft | 48.0 | 30.0 | 30.0 | 2.0 | 7.2-7.6 | 40-48 | 30-35 |
| Mod. Hard | 96.0 | 60.0 | 60.0 | 4.0 | 7.4-7.8 | 80-100 | 60-70 |
| Hard | 192.0 | 120.0 | 120.0 | 8.0 | 7.6-8.0 | 160-180 | 110-120 |
| Very Hard | 384.0 | 240.0 | 240.0 | 16.0 | 8.0-8.4 | 280-320 | 225-245 |

[a] Approximate equilibrium pH after 24-hour aeration
[b] Expressed as mg/L $CaCO_3$

When standard laboratory-reconstituted water is cited as the dilution water, and no additional measurements are reported, the recommended approach for estimating ion concentrations is to use the ion concentrations calculated from the amount of salts added for the type of reconstituted water reported in the article. For example, if the range of hardness of the reconstituted water is reported as 80-100 mg/L $CaCO_3$, then the specific ion concentrations calculated from the standard recipe for moderately hard reconstituted water should be used for BLM input (see Table 2 and example calculation in Appendix D-2). The use of ion concentrations calculated from the standard recipes assumes that salts were stored in a manner to prevent hydration and that technician errors in weighing of salts, measurements of dilution water, and measurement of solution volumes were minimal.

Alternatively, if the authors state that moderately hard water was prepared following one of the standard recipes, and they measured the hardness of the water, then the calculated ion concentrations should be adjusted to account for any difference from the mean of the expected range. For example, if the mean measured hardness in a test water prepared using the recipe for moderately hard reconstituted water was 78 mg/L $CaCO_3$, the Ca:Mg ratio would be 0.700 for all reconstituted water types, and the respective Ca and Mg concentrations could be calculated using the following equations:

$$\text{Ca} = (0.4008 \times \text{measured hardness}) \div [1+(1 \div \text{Ca:Mg ratio})] \qquad \textbf{Equation 1}$$

$$\text{Mg} = (0.2431 \times \text{measured hardness}) \div (1+\text{Ca:Mg ratio}) \qquad \textbf{Equation 2}$$

The remaining ion concentrations are each multiplied by 0.92 (quotient of 78 and 85 mg/L $CaCO_3$, the latter of which is the expected hardness for moderately hard reconstituted water), as in Table 1.

Table 3 provides ion concentrations predicted for a standard reconstituted water mix using the hardness adjustment in accordance with the example above.

Note that this same rationale for scaling the default major anions and cations in reconstituted water also applies to a variety of natural surface and well waters. Analysis of St. Louis River, MN, water and Western Fish Toxicology Station (WFTS) well water indicated that a strong linear relationship also exists between water hardness and the major anion (Cl, $SO_4$) and cation (Ca, Mg, Na) concentrations in these water types (see Sections 2.6, 2.7, and 2.19). The strong relationships are consistent with findings

**Table 2. Calculated Ion Concentrations Based on the Standard Salts Added**

| Water Type (Nominal Hardness Range) | Specific Ions[a] (mg/L) | | | | | | Ca:Mg[b] | Expected Hardness (mg/L $CaCO_3$)[c] |
|---|---|---|---|---|---|---|---|---|
| | Ca | Mg | Na | K | Cl | $SO_4$ | | |
| Very Soft<br>(10-13 mg/L $CaCO_3$) | 1.75 | 1.51 | 3.28 | 0.262 | 0.238 | 10.2 | 0.700 | 11 |
| Soft<br>(40-48 mg/L $CaCO_3$) | 6.99 | 6.06 | 13.1 | 1.05 | 0.951 | 40.7 | 0.700 | 42 |
| Moderately Hard<br>(80-100 mg/L $CaCO_3$) | 14.0 | 12.1 | 26.3 | 2.10 | 1.90 | 81.4 | 0.700 | 85 |
| Hard<br>(160-180 mg/L $CaCO_3$) | 27.9 | 24.2 | 52.5 | 4.20 | 3.80 | 163 | 0.700 | 170 |
| Very Hard<br>(280-320 mg/L $CaCO_3$) | 55.9 | 48.5 | 105 | 8.39 | 7.61 | 325 | 0.700 | 339 |

[a] Ion concentrations were calculated from standard salt recipes (refer to Table 1 and example calculation for very soft water in Appendix D-1).

[b] Ratio equals quotient of (Ca÷40.08) and (Mg÷24.31), where 40.08 and 24.31 are the molecular weights of Ca and Mg, respectively, in units of mg/mmol.

[c] Hardness calculated according to the concentrations of Ca and Mg given here and the equation given in Appendix D-1.

**Table 3. Adjusted Ion Concentrations for a Standard Reconstituted Water Mix Based on Reported Hardness**

| Moderately Hard Reconstituted Water | Hardness (mg/L $CaCO_3$) | Specific Ions (mg/L) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Ca | Mg | Na | K | Cl | $SO_4$ |
| Nominal | 85[a] | 14.0 | 12.1 | 26.3 | 2.10 | 1.90 | 81.4 |
| Adjusted | 78 | 12.9 | 11.2 | ***24.2*** | ***2.10*** | ***1.75*** | ***74.9*** |

[a] Expected hardness based on the amount of salts added (from Table 1). Calcium and magnesium are calculated using Equations 1 and 2. Other adjusted values (italic and bold) are a result of the product of the ratio of measured hardness (78 mg/L) to expected hardness (85 mg/L) and nominal ion concentrations, e.g., the adjusted sodium ion concentration for a standard laboratory reconstituted water mix based on a reported total hardness of 78 mg/L $CaCO_3$ is: 78÷85=0.92; 0.92*26.3=24.2.

presented in an earlier comprehensive report by Erickson (1985). Note, however, that because there is generally poor correlation between K and water hardness in the various ambient surface and ground water types (see Section 2.6), the value calculated for K should not be scaled according to hardness.

## 2.2 *pH Adjustment with HCl*

Schubauer-Berigan et al. (1993) adjusted pH using HCl but reported only nominal hardness and alkalinity. The tests were conducted at the EPA Office of Research and Development, Mid-Continent Ecology Division, Duluth, MN, using a standard very hard reconstituted water mix. The authors need to be contacted to obtain any additional water chemistry data they might have.

**Recommendation:** Alkalinity and hardness were not measured in the tests reported in Schubauer-Berigan et al. (1993), and no additional water chemistry data are available from the study (Phil Monson, U.S. EPA-Duluth, personal communication). The HCl required to adjust the pH was assumed to be added in amounts too small to significantly affect any of the other water quality parameters (Gerald Ankley, U.S. EPA-Duluth, personal communication). Based on these remarks, we believe ion concentrations for this particular study should be estimated using methods outlined in Section 2.1.

## 2.3 *Estimation of DOC*

How should DOC be estimated if only total organic carbon (TOC) was measured in the study? Can DOC be estimated if no measurements of organic carbon were reported in the study?

**Recommendation:** As a general rule, TOC values can be used directly in place of DOC for dechlorinated and de-ionized city tap water, well water, and oligotrophic lake water (e.g., Lake Superior water). TOC values are not recommended in place of DOC for water from estuaries, wetlands, or higher order streams unless data are included that indicate otherwise. Rather, the proportion of organic carbon expected to be dissolved in surface waters should be estimated and used to scale the measured TOC value. When possible, the DOC:TOC ratio for a surface water should be obtained using the USGS NASQAN dataset. The NASQAN dataset can be reached through the USGS Web site (water.usgs.gov/nasqan/data/finaldata.html). If a representative ratio for a particular body of water cannot be determined, the ratio for the particular water type (lake or stream) should be obtained from the final draft of the Ambient Water Quality Criteria Derivation Methodology Human Health Technical Support Document (U.S. EPA 1998a, Table 2.4.11). A summary of these data, by State, is provided in Appendix D-2. In this appendix, TOC is operationally defined as the sum of DOC and particulate organic carbon (POC). The national mean fraction of organic carbon is 86 percent for streams and 88 percent for lakes. The DOC:TOC ratio can be applied to lakes or streams within a State to obtain an estimate of DOC from values reported for TOC.

<u>Example</u>:

| Reference | Water Body | TOC (mg/L) | DOC:TOC | Estimated DOC (mg/L) |
|---|---|---|---|---|
| Lind et al. manuscript | St. Louis R, MN | 32 | 0.87 | 28 |

For tests with reconstituted, city tap, or well water, default DOC values can be applied if the author does not report a measured value. The recommended default TOC (DOC) value for laboratory prepared reconstituted water is 0.5 mg carbon/L (note: some newer laboratory water systems can achieve a TOC of less than 0.5 mg/L). For regular city tap and well water, a value of 1.6 mg carbon/L can be assumed. The recommended default value for laboratory-prepared reconstituted water is based on the arithmetic mean of recent measurements of DOC in reconstituted water prepared at two Federal (U.S. EPA Cincinnati, OH, and USGS Yankton, SD) and two consulting (Commonwealth Biomonitoring and GLEC) laboratories (range 0.1 to 1 mg/L). The recommended default value for dechlorinated city tap and well water is based on the arithmetic mean of measurements of DOC in source water from Lake Ontario (Environment Canada, Burlington, ON) and the New River, VA (City of Blacksburg, VA), and well water from Oak Ridge National Laboratory (Oak Ridge, TN) and EPA's WFTS (Corvallis, OR). The DOC values in these waters ranged from 1.1 to 2.5 mg/L.

For tests conducted in surface waters, we do not recommend the use of a default DOC value because of the large variability of DOC observed. Rather, a reliable database such as USGS NASQAN (as described above) should be searched for DOC measurements. If a database such as NASQAN is consulted, only those DOC measurements closest to the time of the study should be considered as surrogate values. In general, these DOC concentrations should not differ by more than a factor of 1.25. If DOC measurements for the surface water cannot be obtained from a reliable source, then the toxicity test should not be included in Table 1 for BLM normalization.

### 2.4 *DOC in Lake Superior Water*

Lake Superior water has been used in a number of acute and chronic toxicity studies included in the Aquatic Life Criteria for Copper (U.S. EPA 1998b). Dissolved organic matter (DOM) in Lake Superior is assumed to be anywhere from 1 to 3 mg/L (Russ Erickson, U.S. EPA-Duluth, personal communication; McGeer et al. 2000). This value is expected to be at least 90 percent of TOC (or 2 mg/L) (see Spehar and Fiandt 1986). A default value based on recent measurements is needed for DOC in Lake Superior water.

**Recommendation:** Recent measurements of TOC in Lake Superior dilution water are in Appendix D-3 (Greg Lien, U.S. EPA-Duluth, personal communication). The geometric mean concentration of TOC in Lake Superior dilution water from multiple measurements is 1.27 mg/L. Given the recommendation in Section 2.3, the recommended DOC for Lake Superior dilution water is 1.1 mg/L (1.27 mg/L × 0.88).

### 2.5 *Applying Water Chemistry Data to Lake Superior Water*

The ionic composition included in the Table 1 spreadsheet for Lake Superior water is based on concentrations converted from values reported in Erickson et al. (1996b): Ca at 0.68 meq/L = 13.6 mg/L; Mg at 0.24 meq/L = 2.9 mg/L; Na at 0.065 meq/L = 1.5 mg/L; K at 0.015 meq/L = 0.59 mg/L; $SO_4$ at 0.070 meq/L = 3.4 mg/L; Cl at 0.035 meq/L = 1.2 mg/L; and alkalinity at 0.85 meq/L = 43 mg/L. The concentrations for most of these parameters were also reported in Biesinger and Christensen (1972) and approximate those listed above. Should the Erickson et al. (1996b) data be applied to all Lake Superior studies, or is there a stronger rationale for applying the Biesinger and Christensen (1972) data to the older studies?

**Recommendation:** We recommend applying the mean of the Erickson et al. (1996b) citation and Biesinger and Christensen (1972) water chemistry data to all Lake Superior studies prior to 1987, when the results were initially reported. After 1987, we recommend use of the Erickson et al. (1996b) water chemistry data alone (Table 4). For each test, Ca and Mg concentrations should be estimated using Equations 1 and 2, the Ca:Mg ratios given below, and the measured hardness of the test water (Section 2.1). Ions other than K should be scaled according to the measured test hardness, also discussed in Section 2.1.

**Table 4. Recommended Spreadsheet Addition for Lake Superior Dilution Water**

| | | | Specific Ions (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Applied to: | Hardness (mg/L $CaCO_3$) | Alkalinity (mg/L $CaCO_3$) | Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |
| Pre-1987[a] | 46 | 42 | 13.6 | 3.0 | 2.75 | 1.3 | 0.57 | 1.2 | 3.4 |
| Post-1987[b] | 46 | 43 | 13.6 | 2.9 | 2.84 | 1.5 | 0.59 | 1.2 | 3.4 |

[a] Mean of the Erickson et al. (1996b) and Biesinger and Christensen (1972) water chemistry data

[b] Erickson et al. (1996b) water chemistry data alone

## 2.6 *Predicting Ionic Composition of WFTS Well Water*

The following studies seem were conducted at EPA's WFTS using well water: Andros and Garton (1980), Chapman (1975, 1978), Chapman and Stevens (1978), Lorz and McPherson (1976), Nebeker et al. (1984a, 1986a, b), and Seim et al. (1984). Among these studies, however, there is a wide range of hardness values (20-100 mg/L), and the ionic composition of the water was not always reported.

The large variation in WFTS well water hardness, and consequently, ionic composition, is due to seasonal variability (Samuelson 1976). The TOC content of this water has been reported to be 1.1 mg/L (McCrady and Chapman 1979), of which 100 percent is expected to be dissolved. A general strategy is needed to predict the ionic composition of WFTS well water based on measured water hardness.

**Recommendation:** The well feeding the WFTS is susceptible to influx from ground water during rain events in late fall and winter (November through March or April). During this period the water hardness can reach measured levels as high as 100 mg/L $CaCO_3$. Over the remaining months (particularly from July to November), hardness stabilizes at around 25 to 40 mg/L $CaCO_3$, as do other water quality parameters (Al Nebeker, U.S. EPA Corvallis, personal communication; Samuelson 1976). It is important to note that the high hardness reported for WFTS well water is sporadic, even in the winter.

The recommended strategy for filling the existing gaps in data reported from studies using this well water is to estimate the ion concentrations on the basis of their relationship to the total hardness measured during a particular test. The acceptability of tests conducted using WFTS water depends on the range of hardness values reported, i.e., if the hardness varies widely over the course of a particular test, then perhaps the test should not be used. Regression analyses were performed using measured hardness and ion data for the WFTS well water reported in Samuelson (1976), April 1972 to April 1974, and supplemented with additional data from Gary Chapman, personal communication (only those data from May 1974 to April 1978; see Appendix D-4). These relationships and the corresponding regression equations are presented in Figures 1 through 6 (found at the end of this report). Major ion concentrations for WFTS well water were predicted using the regression equations over a wide range of water hardness (10 to 80 mg/L $CaCO_3$) to determine the accuracy of the procedure (Table 5). The error between predicted and measured ion concentrations is generally within 10 percent for all ions except K, where a default value of 0.7 mg/L was chosen for all hardness levels (actual range is 0.1 to 1.1 mg/L, with the majority of data falling between 0.5 and 0.9 mg/L). The correlation coefficient ($R^2$) for the relationship between K and water hardness in WFTS well water was only 0.124. Note: BLM predictions of copper gill accumulation and toxicity are relatively insensitive to the concentration of K, so errors in its estimation should not appreciably affect model predictions. The following regression equations were used to generate the example data provided in Table 5:

$$[Ca] = 0.3085 + (\text{measured hardness} * 0.2738)$$
$$[Mg] = 0.5429 + (\text{measured hardness} * 0.0573)$$
$$[Na] = 3.3029 + (\text{measured hardness} * 0.0713)$$
$$[Cl] = 2.7842 + (\text{measured hardness} * 0.1278)$$
$$[SO_4] = -3.043 + (\text{measured hardness} * 0.2816)$$

Lorz and McPherson (1976) and the Seim et al. (1984) tests were not run in WFTS well water, but in water from different wells along the Willamette River. Water chemistry appears to be less variable for these wells (Harold Lorz and Wayne Seim, personal communication). The following additional water chemistry information for the two well water types used in these studies was provided by the respective authors in January 2001.

Many of the studies conducted by Chapman used reverse osmosis treatment to maintain a blended water supply that was of essentially constant ion content throughout the tests. All the test data from Chapman appear to be acceptable; the only test complicated by fluctuating hardness was the 22-month chronic zinc test with sockeye salmon, and that test produced only a NOEC.

**Table 5. Predicted Ion Concentrations in WFTS Well Water Based on Measured Hardness**

| Total Hardness (Mean Measured value) mg/L $CaCO_3$ | Predicted Ion Concentrations (mg/L) | | | | | |
|---|---|---|---|---|---|---|
| | Ca | Mg | Na | Cl | $SO_4$ | Default[a] K |
| 15.00 | 4.42 | 1.40 | 4.10 | 4.70 | 1.18 | 0.70 |
| 20.00 | 5.78 | 1.69 | 4.46 | 5.34 | 2.59 | 0.70 |
| 25.00 | 7.15 | 1.98 | 4.82 | 5.98 | 4.00 | 0.70 |
| 30.00 | 8.52 | 2.26 | 5.17 | 6.62 | 5.41 | 0.70 |
| 35.00 | 9.89 | 2.55 | 5.53 | 7.26 | 6.81 | 0.70 |
| 40.00 | 11.26 | 2.83 | 5.88 | 7.90 | 8.22 | 0.70 |
| 45.00 | 12.63 | 3.12 | 6.24 | 8.54 | 9.63 | 0.70 |
| 50.00 | 14.00 | 3.41 | 6.60 | 9.17 | 11.04 | 0.70 |
| 55.00 | 15.37 | 3.69 | 6.95 | 9.81 | 12.45 | 0.70 |
| 60.00 | 16.74 | 3.98 | 7.31 | 10.45 | 13.85 | 0.70 |
| 65.00 | 18.11 | 4.27 | 7.67 | 11.09 | 15.26 | 0.70 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 70.00 | 19.47 | 4.55 | 8.02 | 11.73 | 16.67 | 0.70 |
| 75.00 | 20.84 | 4.84 | 8.38 | 12.37 | 18.08 | 0.70 |
| 80.00 | 22.21 | 5.13 | 8.74 | 13.01 | 19.49 | 0.70 |

[a] Value not corrected. Assume default value of 0.70 mg/L.

**Recommended Spreadsheet Addition for Oregon Well Water.**

| | | | | | Specific Ions[a] (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Applied to: | Hardness (mg/L $CaCO_3$) | Alkalinity (mg/L $CaCO_3$) | pH | DOC | Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |
| Lorz and McPherson 1976 | 95 | 66 | 6.8-7.9 | 1.6[B] | 19 | 12 | 1.0 | 7.6 | 1.0 | 7.0 | 12 |
| Seim et al. 1984 | 120 | 126 | 7.7 | 1.6[B] | 34 | 8.6 | 2.4 | 15 | 0.7 | 5.0 | 2.3 |

[a] Specific ion values were obtained through personal communication with the primary authors; hardness, alkalinity, and pH values are as reported in the article. The Ca:Mg ratios were calculated on the basis of data provided by authors, then Ca and Mg values used were back-calculated on the basis of these ratios and the measured test hardness (see Equations 1 and 2).

[b] Suggested default value for untreated well water (see Section 2.3).

### 2.7 *Data for Measurement of Blacksburg/New River Water*

A substantial amount of acute copper toxicity data to various freshwater organisms is reported using dechlorinated City of Blacksburg, VA, tap water. These include studies by Belanger et al. (1989), Cairns et al. (1981), Hartwell et al. (1989), and Thompson et al. (1980). Hardness, alkalinity, and pH values are reported for City of Blacksburg water in all of these studies, but the ionic compositional data are not. This information is required to obtain BLM-normalized LC50s for these data.

**Recommendation:** According to Don Cherry (personal communication), tests conducted at Virginia Polytechnic Institute and State University used City of Blacksburg, VA, tap water, which is drawn from the nearby New River. Don Cherry collected a sample of New River water for analysis under Work Assignment 1-20. The results of the analysis are provided in Appendix D-5. The sample was of untreated natural water prior to any treatment by the City of Blacksburg. Values for treated New River water (city) were provided by Jerry Higgins, Water Superintendent, City of Blacksburg. Table 6 summarizes the measured values for New River and City of Blacksburg dechlorinated tap water.

Historically, hardness and alkalinity vary substantially in dechlorinated City of Blacksburg tap water and in raw New River water (Table 6). Some of this difference may be attributed to seasonal effects. For example, strong seasonal influence was observed in both well water (influenced by surface water, i.e., WFTS well water; see Section 2.6) and a natural surface water (St. Louis River, MN; refer ahead to Section 2.19). Previously, we plotted ion concentrations against hardness for each of these two water types (Figures 1 through 6 and Appendix D-6). The relationships were good in almost all cases (positive, $R^2 = 0.5$ to 0.9), and the resultant regression equations were used to scale ion concentrations according to reported water hardness. Incomplete datasets, however, preclude the use of the same approach for City of Blacksburg tap and raw New River water. Instead, we recommend using the ion and hardness values from the City of Blacksburg water sample and USGS NASQAN ion data, respectively (Table 6), to generate surrogate ion values for the respective waters that were not reported in the previous studies (indicated by the shaded area in Table 6). The operation is simply to multiply ion concentrations for the "acquired data" by the ratio of hardness values in City of Blacksburg and NASQAN water and the corresponding test waters as was done in Section 2.1. We used the NASQAN ion data as the basis for scaling the raw New River water ion estimates because NASQAN represents data collected over several representative years, including the years in the timeframe in which the studies of interest were initiated and completed. The exception was with DOC. We felt that the DOC value obtained from the sample of New River water collected in August 2000 would be more representative than the few values generated from NASQAN (all pre-1980).

### 2.8 *Cu Concentrations and Alkalinity*

The methods sections of both Belanger and Cherry (1990) and Belanger et al. (1989) state that total and dissolved Cu were measured, but it is not clear whether the reported LC50s are based on total or dissolved copper concentration. Also, in Belanger and Cherry (1990), pH was adjusted with sodium hydroxide (NaOH) or nitric acid ($HNO_3$), but only nominal pHs were reported. Alkalinity and hardness after pH adjustment were not reported. Can alkalinity be adjusted for these tests?

**Recommendation:** The concentration Cu in algae is reported on a total metal basis in Belanger et al. (1989) and Belanger and Cherry (1990). The Cu in water is reported on an acid-soluble basis. The acid-soluble concentration of Cu in water was used to derive the LC50. For all intents and purposes, acid-soluble Cu can be considered as dissolved Cu because the acidification of the filtrate after filtration is probably sufficient to obtain most of the Cu associated with colloidal material. Normally a digestion procedure is required to convert all Cu to the dissolved form. If the sample had not been filtered, it would not have been acceptable because it could have been elevated by dissolution of particulate copper.

The pH levels achieved in the batch culture pH tests in Belanger and Cherry (1990) were reported as 6.15, 8.02, and 8.95. Given the proximity of these values to the desired target pH values of 6, 8, and 9, respectively, it would appear that the researchers were able to closely approximate the nominal pH levels, including those selected for the acute heavy metal tests (also pH 6, 8, and 9, respectively). Assuming that the target pH values of 6, 8, and 9 were achieved in the acute tests, adjustment with NaOH and $HNO_3$ would have affected alkalinity, but probably not hardness or the major anion and cation concentrations, except possibly Na. The contribution to Na by the addition of NaOH was probably small, so no further adjustment would be necessary.

**Table 6. Comparison of Values for Untreated (Natural) and Treated (Dechlorinated City of Blacksburg, VA) New River Water**

| | | | | | Specific Ions (mg/L) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | Water Type | pH | Total Hardness (mg/L $CaCO_3$) | Total Alkalinity (mg/L $CaCO_3$) | Ca | Mg | Na | K | Cl | $SO_4$ | $NO_3$ | Ca:Mg ratio | DOC (mg/L) |
| | | | | Acquired Data | | | | | | | | | |
| City of Blacksburg, VA[a] | City | 8.5 | 44 | 39 | - | - | 9.3 | - | 33 | 45 | - | - | 1.5 |
| Cherry 2000 (08/00)[b] | New R. | 8.0 | - | 52 | 15 | 0.6 | 6.6 | 2.0 | 6.1 | 9.8 | 0.7 | | 2 |
| NASQAN[c] | New R. | - | 61 | - | 15 | 5.8 | 3.4 | 1.6 | 4.0 | 13 | 0.8 | 1.6 | 5.4 |
| | | | | Values To Be Applied to Table 1 Toxicity Tests[d] | | | | | | | | | |
| Belanger et al. 1989 | City | 7.7 | 45 | 40 | 11 | 4.2 | 9.5 | 1.6 | 34 | 46 | - | 1.6 | 1.5 |
| Hartwell et al. 1989 | City | 7.5 | 72 | 43 | 18 | 6.8 | 15 | 1.6 | 54 | 74 | - | 1.6 | 1.5 |
| Cairns et al. 1981 | City | 7.0 | 26 | 27 | 6.4 | 2.4 | 5.5 | 1.6 | 19 | 26 | - | 1.6 | 1.5 |
| Thompson et al. 1980 | City | 7.2 | 40 | 28 | 9.9 | 3.8 | 8.5 | 1.6 | 30 | 41 | - | 1.6 | 1.5 |
| Belanger et al. 1989 | New R. | 8.2 | 94 | 70 | 23 | 8.8 | 5.2 | 1.6 | 6.2 | 20 | - | 1.6 | 2 |
| Belanger and Cherry 1990 | New R. | 6, 8, 9 | 98 | 74 | 24 | 9.1 | 5.4 | 1.6 | 6.4 | 21 | - | 1.6 | 2 |

[a] Data provided by Gerard (Jerry) Higgins of Blacksburg-Christianburg VPI Water Authority, Blacksburg, VA. Values presented are from a grab sample collected January 31, 2000. Organic carbon (originally measured and reported as TOC) is assumed to be 100 percent dissolved.

[b] Sample provided by Don Cherry, Virginia Polytechnic Institute and State University, Blacksburg, VA, and analyzed by Environmental Health Laboratories, South Bend, IN. Values presented are from a grab sample collected August 2000. The value for Mg of 0.6 mg/L appears to be a reporting error, and was not used for subsequent calculations of total hardness or scaling of ion values.

[c] Data obtained from USGS NASQAN database. Values presented are means of 213 samples, except for DOC, which is a mean of seven samples, collected and analyzed from January 1973 to August 1995.

[d] Shaded area indicates mean values estimated from previously (NASQAN) or recently measured (Cherry 2000 or City of Blacksburg; nonadjusted) ion values. All values have been rounded to two significant figures. Shaded values were derived according to text above using the approach outlined in Section 2.1.

Using a nomograph found in Faust and Aly (1981), alkalinity at pH 6 should be approximately 33 percent of the alkalinity at pH 8, and alkalinity at pH 9 should be 5 percent higher than the alkalinity at pH 8 (Table 7). Therefore, the values for alkalinity in Table 7 should be used for the acute toxicity tests presented in Belanger and Cherry (1990) in this case. For other analyses, different adjustment factors may be appropriate, based on other interpretations from the Faust and Aly nomograph or other methods as well. Appropriate consideration should also be given to the test system equilibration with the atmosphere.

**Table 7. Estimated Alkalinity in Natural Surface Water Based on pH**

| Source Water | Nominal pH | Alkalinity (mg/L $CaCO_3$) |
|---|---|---|
| New River | 6 | 24.5 |
| | 8.1 | 74.2[a] |
| | 9 | 77.9 |
| Clinch River | 6 | 47.6 |
| | 8.3 | 144[a] |
| | 9 | 152 |
| Amy Bayou | 6 | 40.2 |
| | 8.3 | 122[a] |
| | 9 | 128 |

[a] Indicates values reported in text.

## 2.9 *Calculation of DOC and Humic Acid*

What was the technical approach used to calculate DOC and percent humic acid (HA) for the Winner (1985) toxicity tests?

**Recommendation:** At a nominal HA concentration of 0.0 mg/L in soft and medium hardness test waters, the DOC is assumed to be that of the ultrapure laboratory water, which is estimated to be 0.3 mg/L (approximately one-half of the recommended default value for DOC in laboratory water; see Section 2.3). At nominal HA concentrations of 0.15, 0.75, and 1.50 mg/L, the DOC is calculated by dividing by a value of 2, based on the assumption in the BLM User's Guide (Di Toro et al. 2000) that the percent carbon in HA is 0.50 (see example below and Table 8). Because the water used to obtain these HA concentrations was ultrapure laboratory water, 0.3 mg carbon/L was added; final rounded values of 0.38, 0.68, and 1.1 are recommended.

**Table 8. Estimates of Dissolved Organic Carbon and Percent Humic Acid for the Winner (1985) Toxicity Tests**

| Humic Acid Added (mg/L)[a] | Calculated DOC (mg/L) | Calculated Percent Humic Acid |
|---|---|---|
| 0 | 0.3 | 10 |
| 0.15 | 0.38 | 28 |
| 0.75 | 0.68 | 60 |
| 1.5 | 1.1 | 74 |

[a] As indicated in Table 3 of Winner (1985).

### 2.10 *Alkalinity of Lake Superior Water*

For the Lind et al. (manuscript) tests conducted in Lake Superior water (adjusted with $CaSO_4$ or $MgSO_4$), is there any way to estimate alkalinity values?

**Recommendation:** For tests conducted in Lake Superior water, assume an alkalinity of 42 mg/L $CaCO_3$ (see Section 2.5).

### 2.11 *Availability of LC50s*

The LC50s reported by Collyard et al. (1994) are shown graphically in publication. The LC50s provided in Table 1 are interpolated from the figure. Are the actual measured LC50s available from the authors?

**Recommendation:** The actual LC50s generated and presented graphically in Collyard et al. (1994) have been archived at U.S. EPA-Duluth, as reported by Gerald Ankley (personal communication, 3 November 2000). These values are not readily available in any other form. The data are acceptable as is on the basis of recommendations in the Guidelines (Stephan et al. 1985). Precedence for the use of values gleaned from graphical data is provided in the 2001 Update of Ambient Water Quality Criteria for Cadmium (U.S. EPA 2001).

### 2.12 *Cl and Na Concentrations*

Cl and Na ion concentrations of the tap water used for testing in Rice and Harrison (1983) were derived from the addition of 20 mg/L sodium chloride (NaCl). What are the specific concentrations of the individual ions from the addition of the salt? What concentrations do you suggest using for K and $SO_4$ in this water?

**Recommendation:** The Cl content of the tap dilution water used in Rice and Harrison (1983) was reported as having been derived from the addition of 20 mg/L of NaCl. Assuming that the initial Na and Cl concentrations in tap water were essentially zero, the concentrations of these ions can be calculated in the following way:

The molecular weight of NaCl is 58.44 g/mol. The atomic weight of Na is 22.98 mg/L and the atomic weight of Cl is 35.453 mg/L.

The concentration of Na is:

20 mg NaCl/L * 1 mmol NaCl/58.44 mg NaCl = 0.342 mmol NaCl/L.

0.342 mmol NaCl * 1 mmol Na/1 mmol NaCl * 22.98 mg Na/1 mmol Na
= 7.86 mg Na/L.

The concentration of Cl is:

20 mg NaCl/L × 1 mmol NaCl/58.44 mg NaCl = 0.342 mmol NaCl/L.

0.342 mmol NaCl × 1 mmol Na/1 mmol NaCl × 35.453 mg Cl/1 mmol Cl
= 12.12 mg Cl/L.

Given the potentially large dichotomy between the default ion concentrations and measured hardness of the water used in this study, we recommend adjusting the default $SO_4$ concentration according to measured hardness as in Section 2.1. We do not, however, recommend adjusting the current default value of 1.0 mg/L for K.

### 2.13 *Calculating DOC in Dilution Water*

The dilution water used in the acute copper toxicity tests with cutthroat trout in Chakoumakos et al. (1979) was a different mix of spring water and de-ionized water for each test. Ca and Mg concentrations were measured and reported for each of the test waters used, but measurements of the other ions were reported only for the undiluted spring water. Based on a percentage dilution, ions other than Ca and Mg were estimated in the following way: hardness was measured in the spring water and in each of the test waters; the proportion of spring water was calculated for each test using these measured hardness values; this proportion was then multiplied by the concentration of, for example, Na in the spring water to get an estimated Na value for each test. TOC in the spring water was 3.3 mg/L. Should the same approach as that used to estimate the other ions be used to calculate DOC, which was only measured in undiluted spring water?

**Recommendation:** The concentrations of the major cations and anions in the dilution water used by Chakoumakos et al. (1979) were calculated based on the percent dilution of natural spring water with de-ionized water. The same correction can be used to estimate DOC, with the following assumptions. First, the TOC in spring water was 100 percent dissolved. Second, the DOC of de-ionized water was 0.5 mg/L. If these assumptions are acceptable, the DOCs for H/H, M/H, L/H, H/M, M/M, L/M, H/L, M/L, and L/L would be 3.3, 1.5, 0.75, 3.3, 1.7, 0.94, 2.8, 1.5, and 0.87 mg/L, respectively.

### 2.14 *Ionic Composition of Chehalis River Water*

The ionic composition of Chehalis River, WA, water is needed to fill in existing data gaps used for BLM analysis of acute toxicity reported in Mudge et al. (1993). The publication states, “Water quality data collected during this bioassay program is similar to historical data for Chehalis River (WPPSS 1982) and other Pacific NW streams (Samuelson 1976).” Are data from Samuelson (1976) acceptable for use in approximating these ion concentrations? Furthermore, are there any dissolved or ionic LC50s available other than those reported in the publication?

**Recommendation:** The following additional water chemistry information for the Chehalis River dilution water used in the studies reported by Mudge et al. (1993) was provided by the author on 20 November 2000. These measurements were made on Chehalis River water at the time of testing. A corresponding value for DOC was obtained from the NASQAN dataset.

**Recommended spreadsheet addition for Chehalis River dilution water**

| | | Specific Ions (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Applied to: | DOC (mg/L) | Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mudge et al. 1993 | 3.2[a] | 7.1 | 2.4 | 1.8 | 5.1 | 0.65 | 4.5 (May)<br>4.2 (Jun)<br>3.1 (Sep) | 4.0 (May)<br>3.5 (May-Jul)<br>2.3 (Sep) |

[a] Value from the USGS NASQAN dataset, 1980-1982, when the tests were conducted.

### 2.15 *Chemistry of Water in Howarth and Sprague (1978)*

What is the ionic composition and organic carbon content of test waters used in Howarth and Sprague (1978)? The waters used for testing were various mixes of University of Guelph (Guelph, ON, Canada) well water and de-ionized well water. The de-ionized well water was reported as "having retained its original chloride content (22 mg/l)," but the values for the other major anion and cation concentrations were not reported. Furthermore, the equation provided for calculating alkalinity from pH and hardness (supposedly accounting for 96.7 percent of the variability) appears unreliable. For example, using the equation and a total water hardness of 364 mg/L $CaCO_3$ at pH 9, one obtains an estimated alkalinity value of 341 mg/L $CaCO_3$. In contrast, the measured alkalinity reported in the text for this level of hardness and pH was 263 mg/L $CaCO_3$.

**Recommendation:** The equation provided in the text of Howarth and Sprague (1978) for calculating alkalinity appears unreliable. The calculated alkalinity does not approximate measured alkalinity within a reasonable degree of accuracy. Values of hardness, pH, and alkalinity in Dixon and Sprague (1981a), which used the same water source in their toxicity tests, give greater evidence of this; i.e., using the measured value of hardness of 374 mg/L $CaCO_3$ and a pH of 7.75, the alkalinity calculated with the equation is 98 mg/L $CaCO_3$. This compares rather poorly with the measured alkalinity of 223 mg/L $CaCO_3$. Instead, alkalinity can be estimated using the nomograph from Faust and Aly (1981) as in Section 2.8.

It is possible to apply the procedure used with the Chakoumakos et al. (1979) data here, i.e., using the ratio of hardness in full-strength well water and de-ionized well water to calculate the dilution of the other major ion concentrations. However, no values are given for Na or K in University of Guelph well water. This study is also complicated by the reverse-osmosis unit used to create the de-ionized well water. In particular, the statement concerning the retention of the original Cl concentration in the de-ionized well water implies an ionic exchange that would also require a cation (to maintain charge balance). The cation involved is unknown. As discussed in a phone conversation with John Sprague on 17 November 2000, and later that day with Scott Howarth (Environment Canada), NaCl may have leached through the RO unit. Assuming that Na and Cl leached through the unit in equivalent proportions, a value of 14 mg/L for Na can be back-calculated from the reported Cl concentration of 22 mg/L.

Default DOC concentrations of 1.6 and 0.5 mg/L were assumed for the well water and de-ionized water used in the tests, respectively (see Section 2.3). The DOC concentrations were adjusted for each particular test water hardness level based on the proportion of well water and de-ionized water used to achieve the desired test hardness level. In the example provided in Table 9, the dilution factor of 0.27, based on the ratio of the average hardness of well water (366 mg/L $CaCO_3$) versus the average hardness of well plus de-ionized well water (100 mg/L $CaCO_3$), was applied to the starting DOC concentrations to achieve an estimate of the DOC concentrations at 100 mg/L $CaCO_3$). Table

9 shows the results of similar adjustments made for the major anions and cations based on the data reported in Howarth and Sprague (1978).

## 2.16 *Default Values for Analyte Concentrations*

What value should be used when a specific analyte is not detected at its designated detection limit?

**Recommendation:** The use of half the detection limit (DL) is most appropriate when the concentration of an analyte is not detected. One-half the DL will closely approximate a replacement value for censored data in a log-normally distributed population that includes several measured values (Berthouex and Brown 1994; Dolan and El-Shaarawi 1991). This way some of the "nondetect" samples will actually be counted as detected.

**Table 9. Example Calculations to Estimate Water Chemistry of Tests Conducted at 100 mg/L $CaCO_3$ by Howarth and Sprague (1978) Using a Mixture of University of Guelph Well Water and De-ionized Water**

| Parameter (units in mg/L) | De-ionized water | Well Water | Example Calculations for Mixture |
|---|---|---|---|
| Hardness | 0 | 366 | 100<br>(i.e., 0.27 dilution factor) |
| Ca | 0 | 77 (from Dixon & Sprague 1981) | 21 |
| Mg | 0 | 43 (from Dixon & Sprague 1981) | 12 |
| Na | 14 (assuming NaCl used for the softening process) | 14 (estimated from [Cl]) | 14 |
| K | 0 | 2.4 (based on personal communication from Dr. Patricia Wright, Univ. of Guelph, Guelph, ON) | 0.66 |
| Cl | 22 (stated as not having changed from the water softening process) | 22 | 22 |
| $SO_4$ | 0 | 129 | 35 |
| DOC | 0.5 (default value for de-ionized waters) | 1.6 (default value for well waters) | 0.8 |
| Alkalinity (calculated using ratios as in Section 2.8): | | | |
| at pH 6 | 0[a] | 81.5 | 22 |
| at pH 7 | 0[a] | 205 | 55 |
| at pH 8 | 0[a] | 250 | N/A |
| at pH 9 | 0[a] | 263 | 70 |

[a] Alkalinity in de-ionized well water is assumed to be 0.0 mg/L.

### 2.17 *Organic Carbon Content of Samples*

Can any information be obtained on the organic carbon content of the spring water / City of Cincinnati, OH, tap water mixes used in Brungs et al. (1973), Geckler et al. (1976), Horning and Neiheisel (1979), Mount (1968), Mount and Stephan (1969), and Pickering et al. (1977)?

**Recommendation:** The water used for all tests was a mixture of spring-fed pond water (originating at the Newtown Fish Farm) and carbon-filtered, demineralized Cincinnati tap water. The water was mixed to achieve the desired test hardness level and discharged to a large (several thousand gallon) concrete reservoir that fed the test system. The detention time varied anywhere from 30 to 90 days, depending on the study, which was sufficient to allow the growth of phytoplankton and zooplankton in moderate abundance. No additional information regarding the TOC (DOC) concentration or treatment of this water is available at this time. The recommended organic carbon content of spring/city water mix is currently a conservative 1.6 mg/L, but could be as high as 2.5 mg/L, the highest DOC concentration recorded for a natural surface or well water used for studies included in this report (see Section 2.3). Considering the long retention time, and the fact that the natural water was spring-fed pond water, the more conservative DOC value of 2.5 mg/L is recommended for this water.

### 2.18 *Additional Water Chemistry Data Needed*

Additional water chemistry data are needed for Bennett et al. (1995) and Richards and Beitinger (1995). In the case of Richards and Beitinger 1995, only the ranges of measured pH, alkalinity, and hardness across all tests were given.

**Recommendation:** Detailed pH, alkalinity, and hardness values were provided by both Bennett et al. (1995) and Richards and Beitinger (1995) (Appendixes D-7 and D-9, respectively). The studies performed by Bennett et al. were conducted using dechlorinated City of Denton, TX, tap water (from Lake Roy Roberts). The author was not able to provide any additional data regarding the ionic composition of this water; however, based on supplementary data, mean values of pH, alkalinity, and temperature were 8.07 and 89.7 mg/L $CaCO_3$ and 21.4 C, respectively. Richards and Beitinger's studies were conducted using standard reconstituted (hard) water. To estimate the ionic composition of this water, refer to recommendations provided in Section 2.1.

### 2.19 *Estimating Data for Waters*

Values for DOC, TSS, Ca, Mg, Na, K, $SO_4$, and Cl are needed for the following natural waters:

| Water Body | Reference |
|---|---|
| American River, California – sand filtered | Finlayson and Verrue 1982 |
| Clinch River – 11µm filtered | Belanger et al. 1989<br>Belanger and Cherry 1990 |
| Amy Bayou | Belanger and Cherry 1990 |
| Blaine Creek, Kentucky – 1.6 µm filtered | Dobbs et al. 1994 |
| S. Kawishiwi | Lind et al. manuscript |
| St. Louis River | Lind et al. manuscript |
| Lake One | Lind et al. manuscript |

| | |
|---|---|
| Colby Lake | Lind et al. manuscript |
| Cloquet Lake | Lind et al. manuscript |
| Greenwood Lake | Lind et al. manuscript |
| Embarrass River | Lind et al. manuscript |
| Green Duwamish River | Buckley 1983 |
| Chehalis River | Mudge et al. 1993 |
| Pinto Creek, AZ | Lewis 1978 |
| Naugatuck River | Carlson et al. 1986 |

**Recommendation:** On the following pages are data (current and/or historical, presented as arithmetic means) from selected natural waters that were retrieved from NASQAN, STORET, or a secondary source (as indicated). As mentioned earlier (see Sections 2.6 and 2.7), given the reasonably good correlation between most of the major anion and cations (except K) and water hardness in natural surface and well waters, we recommend using the ion and hardness values retrieved from these various sources to estimate the ion concentrations in the test water used in the previous studies. The operation, again, is simply to multiply the ion concentrations listed below by the ratio of hardness values presented below and the earlier test waters.

Note that additional data were not available for Blaine Creek, KY, or Pinto Creek, AZ, and although additional data were obtained from the City of Sacramento, CA, regarding the American River, the default DOC value (8.2 mg/L) for California streams may be artificially high on the basis of reported values of DOC in the Sacramento River (1.2 mg C/L), of which the American River is a tributary. Therefore, the data from Finlayson and Verrue (1982) have been relegated to "other data." Likewise, Amy Bayou is a highly contaminated and dynamic system (Don Cherry, personal communication), and BLM normalization is not recommended for these data. A large annual variability in water quality also excludes the use of surrogate STORET data for the Embarrass River, MN, for BLM analysis (Lind et al. manuscript).

American River, CA (Appendix C-9). Source: Ron Myers, City of Sacramento, CA, Water Quality Laboratory

| | | | | | Specific Ions (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Applied to: | Hardness (mg/L $CaCO_3$) | Alkalinity (mg/L $CaCO_3$) | pH | DOC | Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |
| Finlayson and Verrue 1982 | 21 | 22 | 7.5 | -[a] | 5.6 | 1.8 | 2.0 | 3.0 | - | 2.6 | 3.8 |

[a] DOC and K data for the American River were not available.

Clinch River, VA (Appendix D-5): Source: Don Cherry, VA Poly. Inst. & State Univ., Blacksburg,VA

| | | | | | Specific Ions (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Applied to: | Hardness (mg/L $CaCO_3$) | Alkalinity (mg/L $CaCO_3$) | pH | DOC | Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |
| Belanger et al. 1989, and Belanger and Cherry 1990 | 150 | 150 | 8.3 | 2.3 | 42 | 11 | 2.3 | 12 | 2.4 | 9.2 | 19 |

S. Kawishiwi River, MN (Appendix C-10). Source: STORET

| | | | | | Specific Ions (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Applied to: | Hardness (mg/L $CaCO_3$) | Alkalinity (mg/L $CaCO_3$) | pH | DOC | Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |
| Lind et al. manuscript | 24 | 18 | 6.6 | -[a] | 5.6 | 2.4 | 1.5 | 1.3 | 0.5 | 1.0 | 4.9 |

[a] DOC data for this river were not available. TOC measurements reported by Lind et al. (manuscript) should be adjusted based on a mean DOC:TOC ratio (0.8721) in Minnesota streams (see Section 2.3 and Appendix D-2).

Lake One, MN (Appendix C-10). Source: STORET

| | | | | | Specific Ions (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Applied to: | Hardness (mg/L $CaCO_3$) | Alkalinity (mg/L $CaCO_3$) | pH | DOC | Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |
| Lind et al. manuscript | 10 | 15 | 6.7 | -[a] | 2.8 | 0.7 | 1.8 | 0.1 | 0.3 | 0.2 | 4.2 |

[a] DOC data for this lake were not available. TOC measurements reported by Lind et al. (manuscript) should be adjusted based on a mean DOC:TOC ratio (0.9677) in Minnesota lakes (see Section 2.3 and Appendix D-2).

Colby Lake, MN (Appendix C-10). Source: STORET

| | | | | | Specific Ions (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Applied to: | Hardness (mg/L $CaCO_3$) | Alkalinity (mg/L $CaCO_3$) | pH | DOC | Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |
| Lind et al. manuscript | 56 | 33 | 7.1 | -[a] | 13.3 | 5.4 | 1.6 | 4.0 | 1.4 | 7.3 | 23 |

[a] DOC data for this lake were not available. TOC measurements reported by Lind et al. (manuscript) should be adjusted based on a mean DOC:TOC ratio (0.9677) in Minnesota lakes (see Section 2.3 and Appendix D-2).

Cloquet Lake, MN (Appendix C-10). Source: STORET

| | | | | | Specific Ions (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Applied to: | Hardness (mg/L $CaCO_3$) | Alkalinity (mg/L $CaCO_3$) | pH | DOC | Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |
| Lind et al. manuscript | 27 | 21 | 7.2 | -[a] | 6.9 | 2.3 | 1.4 | 1.9[b] | 1.4[c] | 1.2 | 5.6 |

[a] DOC data for this lake were not available. TOC measurements reported by Lind et al. (manuscript) should be adjusted based on a mean DOC:TOC ratio (0.9677) in Minnesota lakes (see Section 2.3 and Appendix D-2).

[b] Na data for this lake were not available. The Na value given here is based on data for Colby Lake, MN, and was scaled on the basis of hardness (see Section 2.1): Na = 4.0 mg Na/L * (27 mg/L $CaCO_3$ / 56 mg/L $CaCO_3$).

[c] K data for this lake were not available. The K value given here is from data for Colby Lake, MN. This value was not scaled on the basis of hardness (see discussion of K-hardness relationship in Sections 2.1 and 2.7).

Greenwood Lake (Appendix C-10), MN.  Source: STORET

| Applied to: | Hardness (mg/L $CaCO_3$) | Alkalinity (mg/L $CaCO_3$) | pH | DOC | Specific Ions (mg/L) Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lind et al. manuscript | 17 | 11 | 6.4 | -[a] | 4 | 1.8 | 2.4 | 0.2[b] | 0.3[c] | 1.7 | 7.6 |

[a] DOC data for this lake were not available. TOC measurements reported by Lind et al. (manuscript) should be adjusted based on a mean DOC:TOC ratio (0.9677) in Minnesota lakes (see Section 2.3 and Appendix D-2).

[b] Na data for this lake were not available. The Na value given here is based on data for Lake One, MN, and was scaled based on hardness: Na = 0.1 mg Na/L * (17 mg/L $CaCO_3$ / 10 mg/L $CaCO_3$).

[c] K data for this lake were not available. The K value given here is from data for Lake One, MN. This value was not scaled on the basis of hardness (see discussion of K-hardness relationship in Sections 2.1 and 2.7).

St. Louis River, MN (Appendix C-6). Source: NASQAN

Note: for the St. Louis River dataset (1973 to 1993), a question arose as to which data would be most representative for estimating the ion concentrations in St. Louis River water for BLM analysis. In order to determine this, the relationship between hardness and Na ion for all 20 years was plotted. Linear regression was used to fit the data. Most data showed very high coefficient correlation (0.8-0.94). For each of these 20 regression lines, the slope and intercept coefficients were plotted on separate graphs as functions of time (Figures 7 and 8). The following conclusions were derived:

- A significant event occurred in 1976 and perhaps 1977 that affected the water balance of the St. Louis River. A wastewater treatment plant was built, which substantially improved the water quality (Jesse Anderson, Minn. Pollution Control Bd., personal communication).

- For the 1979-1993 period, hardness and ion concentrations did not change significantly as absolute values. Therefore, general equations (which could be used to extrapolate water chemistry data till year 2000 and before 1979) can be obtained connecting hardness, alkalinity, pH, and the major ion concentrations.

- The exponential growth in the values between 1973 and 1979 shows that averaging values on seasonal and annual basis is not appropriate. The constant values for the slopes and intercepts for 1979-1993 allow mean monthly and annual interpretation of the data.

- The regression equations derived for 1977 alone are recommended to predict ion concentrations based on the water hardness levels measured in the Lind et al. (manuscript). The equations derived for each ion are provided in Appendix D-6 with the corresponding figures.

Green-Duwamish River, WA. Source: James Buckley

| Applied to: | Hardness (mg/L $CaCO_3$) | Alkalinity (mg/L $CaCO_3$) | pH | DOC | Specific Ions (mg/L) Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Buckley 1983 | 33 | 29 | 7.2 | 3.2[a] | 8.9 | 2.8 | 2.0 | 7.5 | 1.2 | 7.0 | 6.3 |

[a] Value given as TOC. DOC data for this river were not available. TOC measurements reported by Buckley et al. (1983) should be adjusted on the basis of a mean DOC:TOC ratio (0.7803) in Washington streams (see Section 2.3 and Appendix C-2).

Naugatuck River, WA. Source: STORET

| Applied to: | Hardness (mg/L $CaCO_3$) | Alkalinity (mg/L $CaCO_3$) | pH | DOC | Specific Ions (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Ca | Mg | Ca:Mg | Na | K | Cl | $SO_4$ |
| Carlson et al. 1986 | 39 | 20 | 6.4 | 3.7[a] | 9.9 | 3.3 | 1.9 | 9.9 | 2.3 | - | 22 |

[a] Value given as TOC. DOC data for this river were not available. TOC measurements reported by Carlson et al. (1986) should be adjusted on the basis of a mean DOC:TOC ratio (0.8711) in Connecticut streams (see Section 2.3 and Appendix C-2).

Figure 1. Relationship between Ca and hardness in WFTS well water

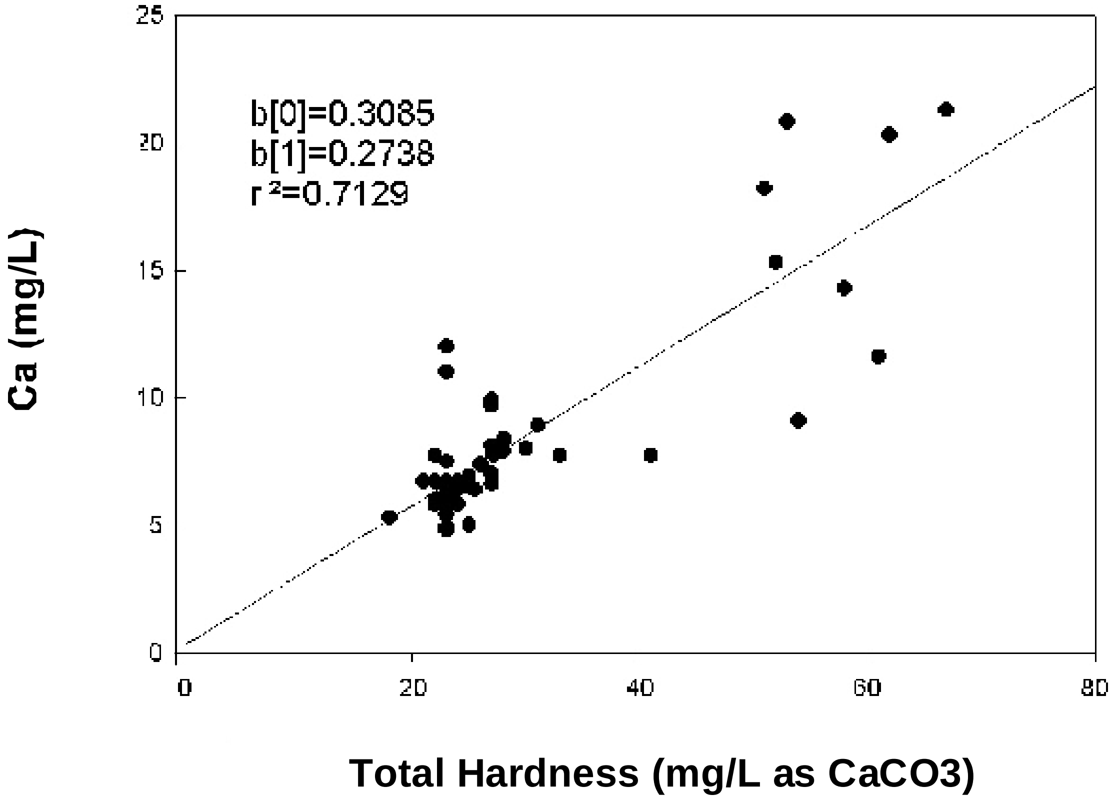


Figure 2. Relationship between Mg and hardness in WFTS well water.

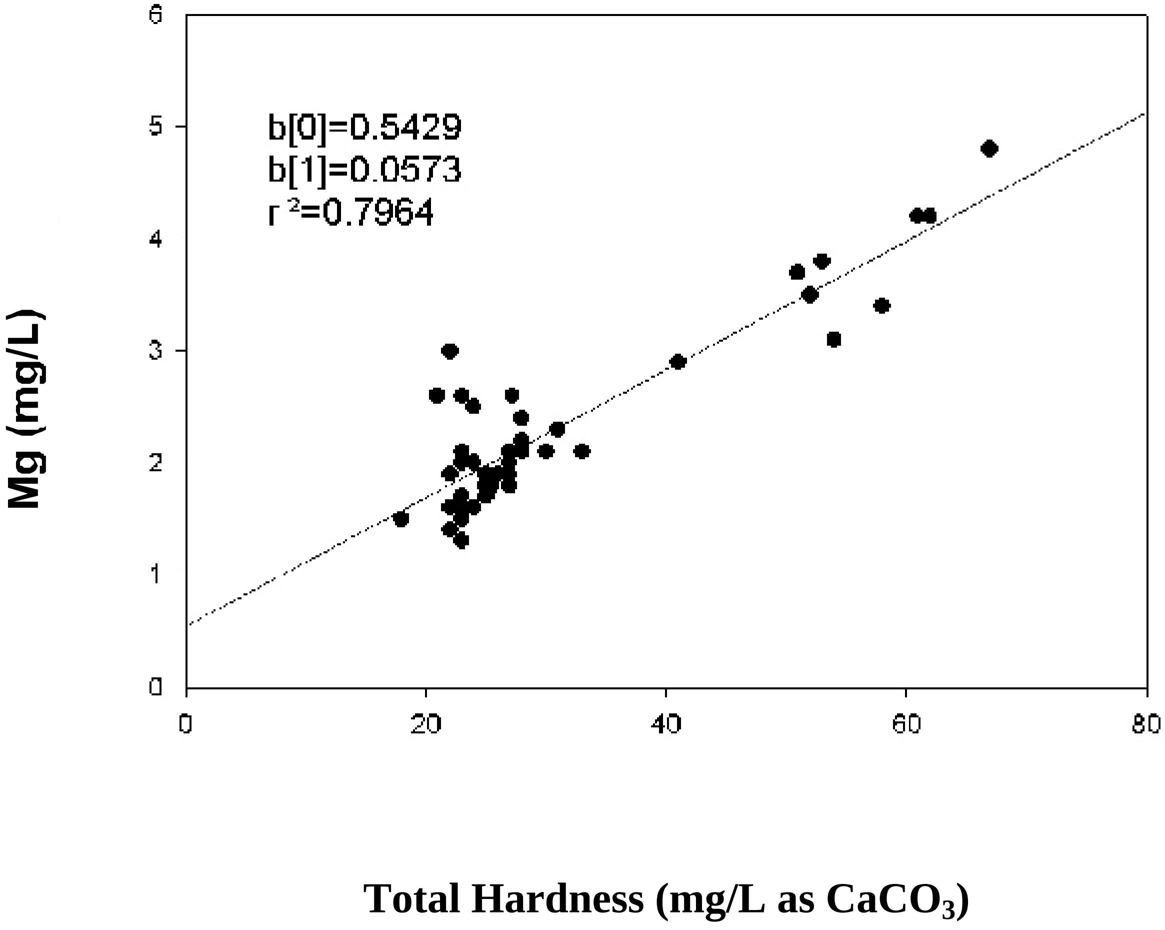
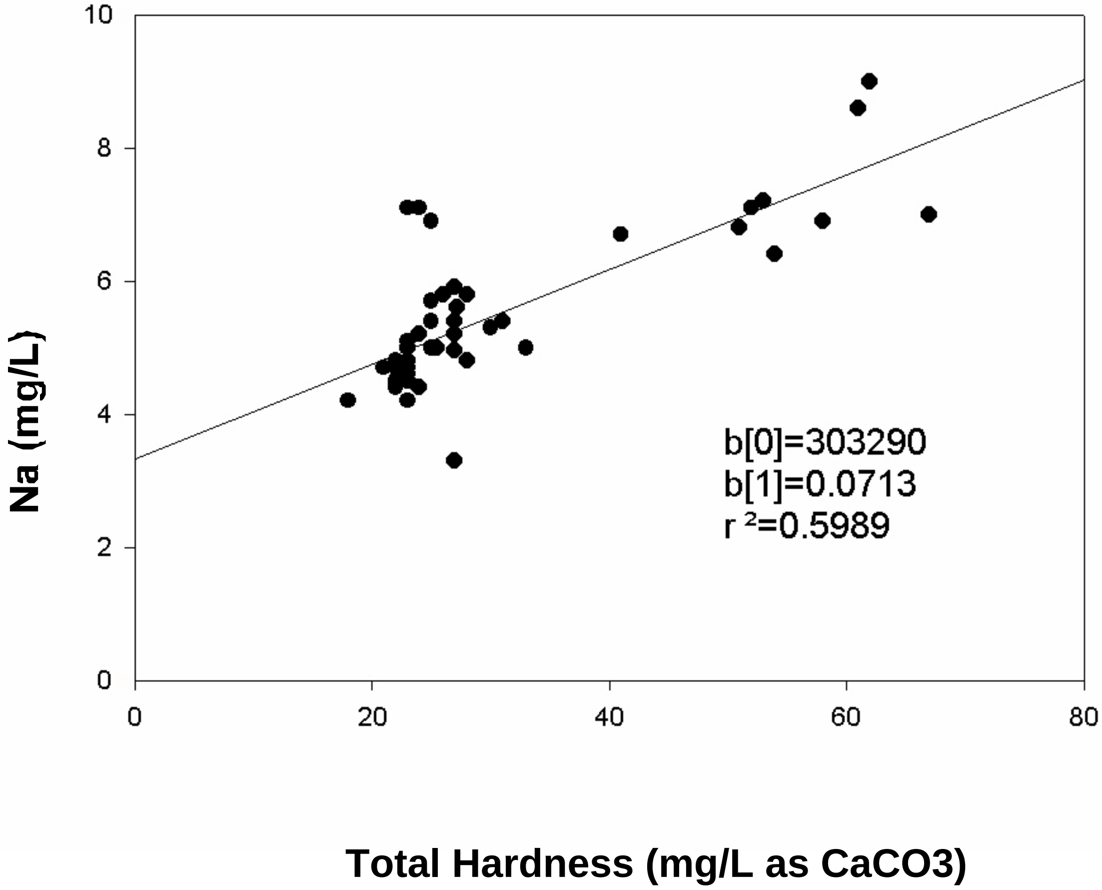


**Figure 3. Relationship between Na and hardness in WFTS well water.**



## Figure 4. Relationship between K and hardness in WFTS well water

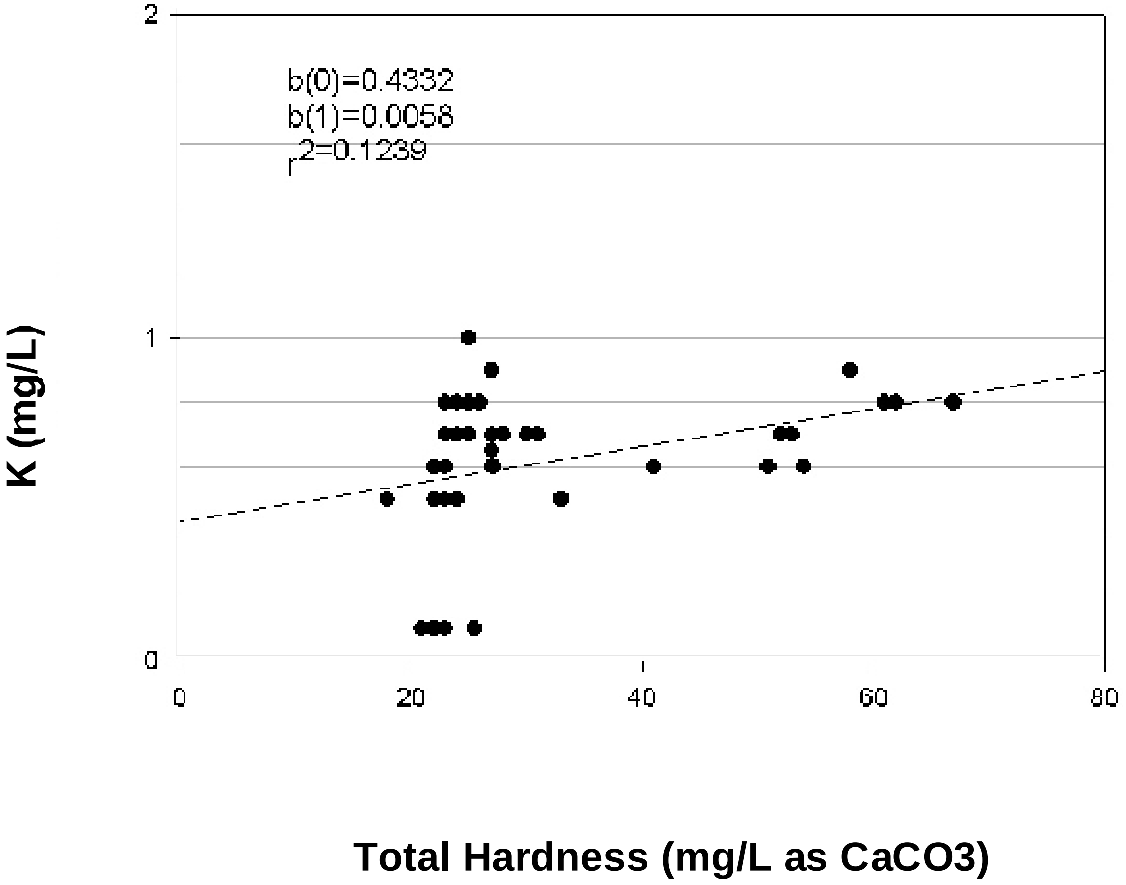


Figure 5. Relationship between Cl and hardness in WFTS well water.

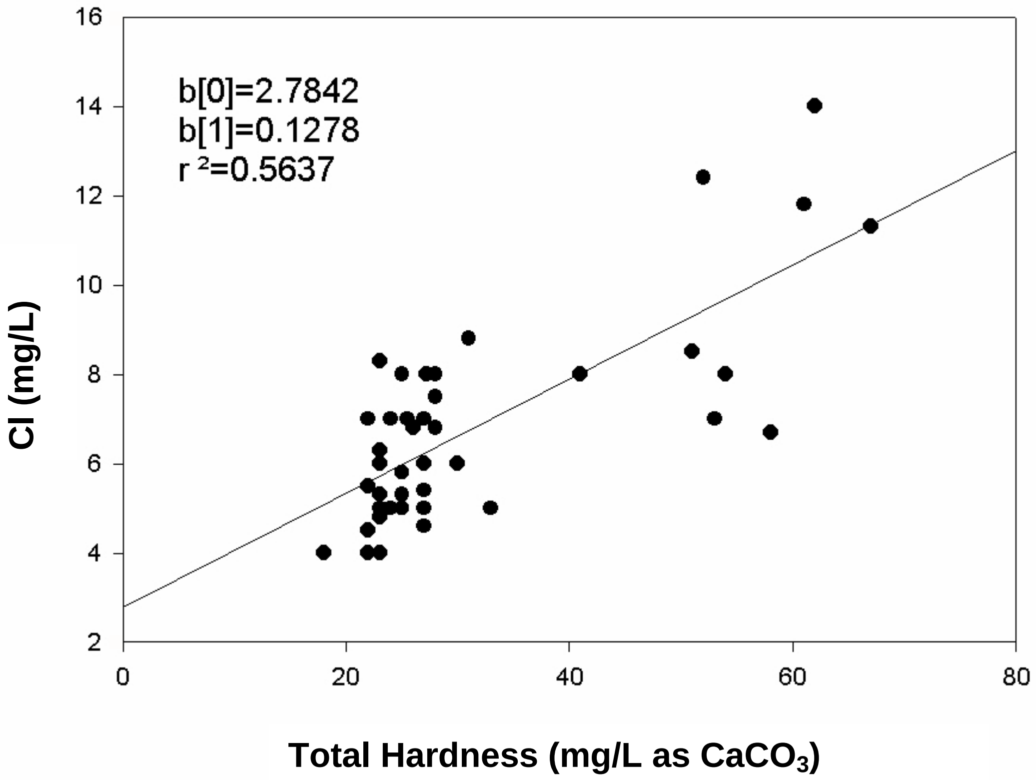


Figure 6. Relationship between $SO_4$ and hardness in WFTS well water.

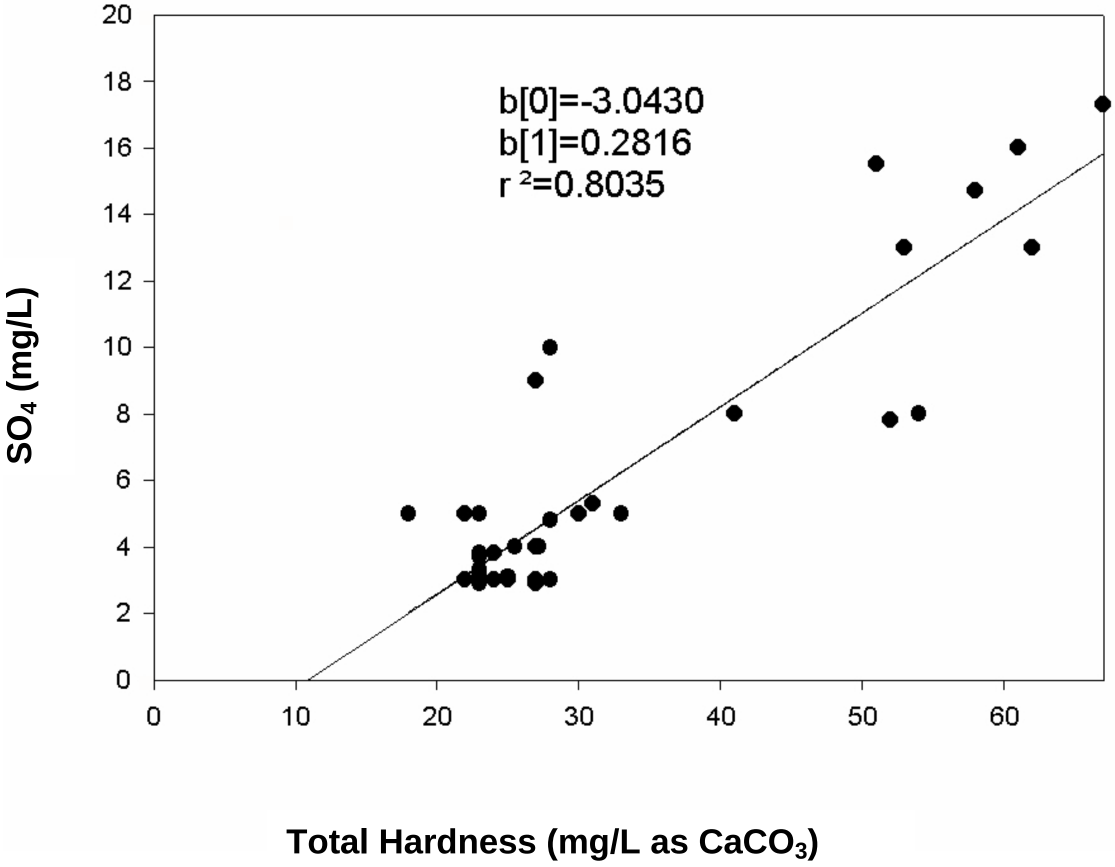


Figure 7. Slopes of the regression equations derived for Na concentration in St. Louis River, MN, water versus water hardness from 1973 to 1993.

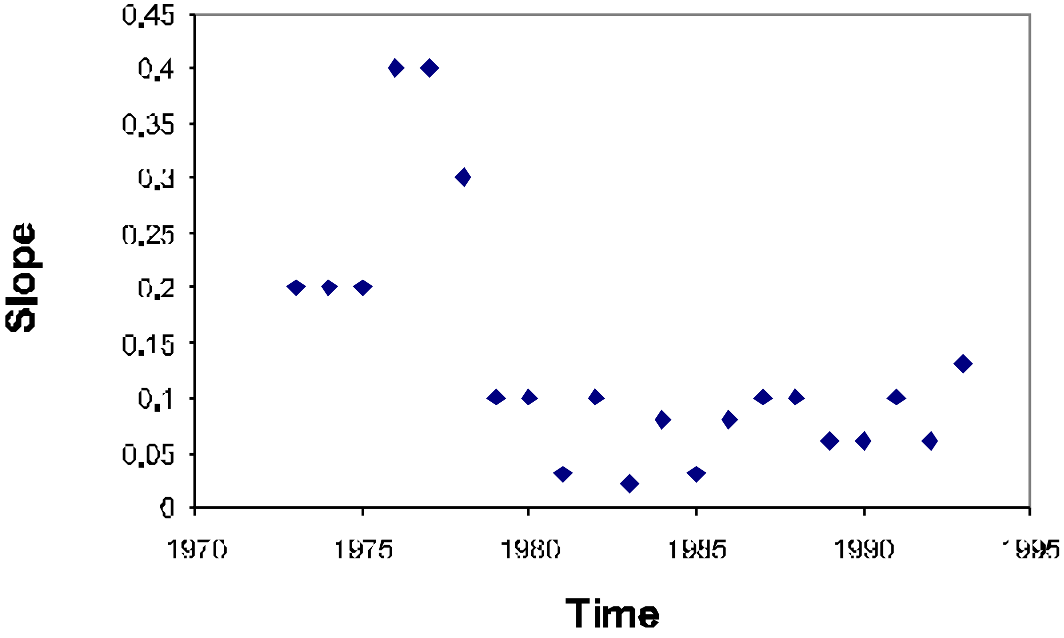
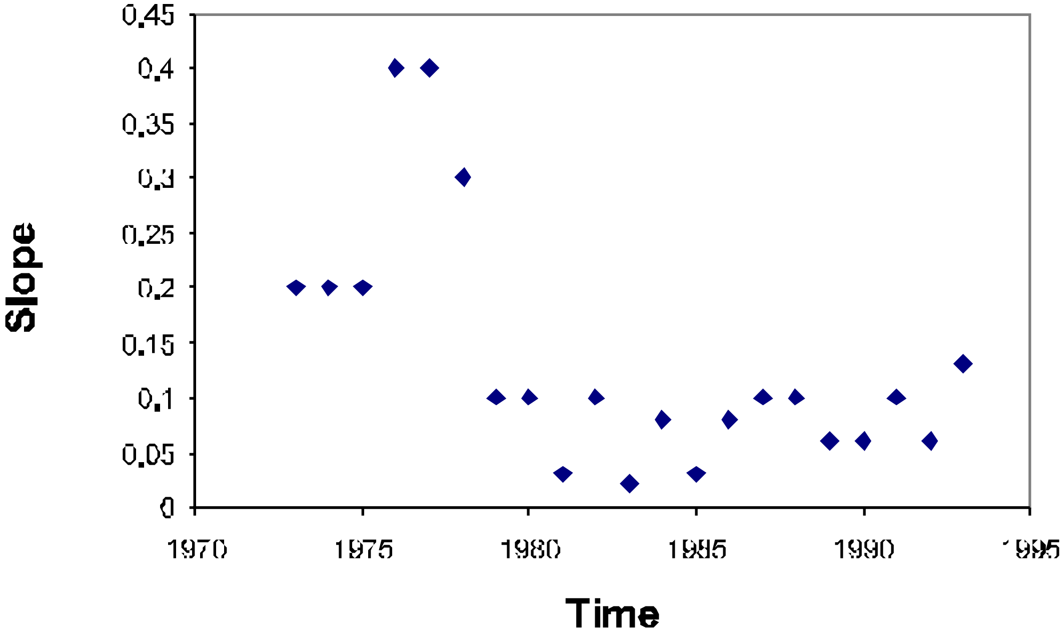


**Figure 8.** Intercepts of the regression equations derived for Na concentration in St. Louis River, MN water versus water hardness from 1973 to 1993.



## References

Andros, J.D. and R.R. Garton. 1980. Acute lethality of copper, cadmium, and zinc to northern squawfish. Trans. Am. Fish. Soc. 109:235.

ASTM. 2000. Standard guide for conducting acute toxicity tests on test materials with fishes, macroinvertebrates, and amphibians. E729-96. In: Annual book of ASTM standards. Section 11, Volume 5. American Society for Testing and Materials, Pennsylvania, PA.

Belanger, S.E. and D.S. Cherry. 1990. Interacting effects of pH acclimation, pH, and heavy metals of acute and chronic toxicity to *Ceriodaphnia dubia* (Cladoceran). J. Crustacean Biol. 10(2):225-235.

Belanger, S.E., J.L. Farris and D.S. Cherry. 1989. Effects of diet, water hardness, and population source on acute and chronic copper toxicity to *Ceriodaphnia dubia*. Arch. Environ. Contam. Toxicol. 18(4):601-611.

Bennett, W.A., A. Sosa and T.L. Beitinger. 1995. Oxygen tolerance of fathead minnows previously exposed to copper. Bull. Environ. Contam. Toxicol. 55(4):517-524.

Berthouex, P.M. and L.C. Brown. 1994. Statistics for environmental engineers. Lewis Publishers/CRC Press, Boca Raton, FL.

Biesinger, K.E. and G.M. Christensen. 1972. Effects of various metals on survival, growth, reproduction, and metabolism of *Daphnia magna*. Jour. Fish Res. Board Can. 29:1691.

Brungs, W.A., E.N. Leonard and J.M. McKim. 1973. Acute and long-term accumulation of copper by the brown bullhead, *Ictalurus nebulosus*. J. Fish. Res. Board Can. 30(4):583-586.

Buckley, J.A. 1983. Complexation of copper in the effluent of a sewage treatment plant and an estimate of its influence on toxicity to coho salmon. Water Res. 17(12):1929-1934.

Cairns, J., Jr., K.W. Thompson and A.C. Hendricks. 1981. Effects of fluctuating, sublethal applications of heavy metal solutions upon the gill ventilation response of bluegills (*Lepomis macrochirus*). EPA-600/3-81-003. National Technical Information Service, Springfield, VA.

Carlson, A.R., H. Nelson and D. Hammermeister. 1986. Development and validation of site-specific water quality criteria for copper. Environ. Toxicol. Chem. 5(11):997-1012.

Chakoumakos, C., R.C. Russo and R.V. Thurston. 1979. The toxicity of copper to cutthroat trout (*Salmo clarki*) under different conditions of alkalinity, pH, and hardness. Environ. Sci. Technol. 13:213-219.

Chapman, G.A. 1975. Toxicity of copper, cadmium and zinc to Pacific Northwest salmonids. U.S. EPA, Corvallis, OR.

Chapman, G.A. 1978. Toxicities of cadmium, copper, and zinc to four juvenile stages of chinook salmon and steelhead. Trans. Am. Fish. Soc. 107:841-847.

Chapman, G.A. and D.G. Stevens. 1978. Acute lethal levels of cadmium, copper, and zinc to adult male coho salmon and steelhead. Trans. Am. Fish. Soc. 107:837-840.

Collyard, S.A., G.T. Ankley, R.A. Hoke and T. Goldstein. 1994. Influence of age on the relative sensitivity of *Hyalella azteca* to diazinon, alkylphenol ethoxylates, copper, cadmium and zinc. Arch. Environ. Contam. Toxicol. 26(1):110-113.

Di Toro, D.M., H.E. Allen, H.L. Bergman, J.S. Meyer, P.R. Paquin and R.C. Santore, 2001. A Biotic Ligand Model of the Acute Toxicity of Metals. I. Technical Basis, *Environmental Toxicology and Chemistry*. 20:2383-2396.

Di Toro, D.M., H. Allen, H. Bergman, J. Meyer, R.C. Santore and P.R. Paquin. 2000. The Biotic Ligand Model: A computational approach for assessing the ecological effects of copper and other metals in aquatic systems. International Copper Association, Ltd.

Dixon, D.G. and J.B. Sprague. 1981a. Acclimation to copper by rainbow trout (*Salmo gairdneri*): A modifying factor in toxicity. Can. J. Fish. Aquat. Sci. 38:880-888.

Dolan, D.M. and A.H. El-Shaarawi. 1991. Application of mass balance approach with censored data. J. Gr. Lakes Res. 17:220-228.

Erickson, R.J. 1985. Analysis of major ionic content of selected U.S. waters and application to experimental design for the evaluation of the effect of water chemistry on the toxicity of copper. Draft report. U.S. EPA, Duluth, MN.

Erickson, R.J., D.A. Benoit, V.R. Mattson, H.P. Nelson, Jr. and E.N. Leonard. 1996b. The effects of water chemistry on the toxicity of copper to fathead minnows. Environ. Toxicol. Chem. 15(2):181-193.

Faust, S.D. and O.M. Aly. 1981. Chemistry of natural waters. Ann Arbor Science Publishers, Inc., Ann Arbor, MI.

Finlayson, B.J. and K.M. Verrue. 1982. Toxicities of copper, zinc, and cadmium mixtures to juvenile chinook salmon. Trans. Am. Fish. Soc. 111:645-650.

Geckler, J.R., W.B. Horning, T.M. Neiheisel, Q.H. Pickering, E.L. Robinson and C.E. Stephan. 1976. Validity of laboratory tests for predicting copper toxicity in streams. EPA-600/3-76-116. National Technical Information Service, Springfield, VA.

Hartwell, S.I., J.H. Jin, D.S. Cherry and J. Cairns, Jr. 1989. Toxicity versus avoidance response of golden shiner, *Notemigonus crysoleucas*, to five metals. J. Fish Biol. 35(3):447-456.

Horning, W.B. and T.W. Neiheisel. 1979. Chronic effect of copper on the bluntnose minnow, *Pimephales notatus* (Rafinesque). Arch. Environ. Contam. Toxicol. 8:545-552.

Howarth, R.S. and J.B. Sprague. 1978. Copper lethality to rainbow trout in waters of various hardness and pH. Water Res. 12:455-462.

Lind, D., Alto and Chatterton. Manuscript. Regional copper-nickel study: Aquatic toxicology study. Preliminary draft report, Minnesota Environmental Quality Board, St. Paul, MN.

Lorz, H.W. and B.P. McPherson. 1976. Effects of copper or zinc in fresh water on the adaptation to sea water and ATPase activity, and the effects of copper on migratory disposition of coho salmon (*Oncorhynchus kisutch*). J. Fish. Res. Board Can. 33:2023.

McCrady, J.K. and G.A. Chapman. 1979. Determination of copper completing capacity of natural river water, well water and artificially reconstituted water. Water Res. 13:143-150.

McGeer, J.C., R.C. Playle, C.M. Wood and F. Galvez. 2000. A physiologically based biotic ligand model for predicting the acute toxicity of waterborne silver to rainbow trout in freshwaters. Environ. Sci. Technol. 34:4199-4207.

Mount, D.I. 1968. Chronic toxicity of copper to fathead minnows (*Pimephales promelas* Rafinesque). Water Res. 2:215-223.

Mount, D.I. and C.E. Stephan. 1969. Chronic toxicity of copper to the fathead minnow (*Pimephales promelas*) in soft water. J. Fish. Res. Board Can. 26:2449-2457.

Mudge, J.E., T.E. Northstrom, G.S. Jeane, W. Davis and J.L. Hickam. 1993. Effect of varying environmental conditions on the toxicity of copper to salmon. In: Environmental toxicology and risk assessment. Gorsuch, J.W., F.J. Dwyer, C.G. Ingersoll and T.W. LaPoint (Eds.). ASTM STP 1216. American Society for Testing and Materials, Philadelphia, PA. pp. 19-33.

Nebeker, A.V., M.A. Cairns and C.M. Wise. 1984a. Relative sensitivity of *Chironomus tentans* life stages to copper. Environ. Toxicol. Chem. 3(1):151-158.

Nebeker, A.V., M.A. Cairns, S.T. Onjukka and R.H. Titus. 1986a. Effect of age on sensitivity of *Daphnia magna* to cadmium, copper and cyanazine. Environ. Toxicol. Chem. 5(6):527-30.

Nebeker, A.V., A. Stinchfield, C. Savonen and G.A. Chapman. 1986b. Effects of copper, nickel and zinc on three species of Oregon freshwater snails. Environ. Toxicol. Chem. 5(9):807-811.

Pickering, Q.H., W. Brungs and M. Gast. 1977. Effect of exposure time and copper concentration on reproduction of the fathead minnow (*Pimephales promelas*). Water Res. 11:1079-1083.

Rice, D.W., Jr. and F.L. Harrison. 1983. The sensitivity of adult, embryonic, and larval crayfish *Procambaris clarkii* to copper. UCRL-53048. National Technical Information Service, Springfield, VA.

Richards, V.L. and T.L. Beitinger. 1995. Reciprocal influences of temperature and copper on survival of fathead minnows, *Pimephales promelas*. Bull. Environ. Contam. Toxicol. 55(2):230-6.

Samuelson, D.F. 1976. Water quality: Western Fish Toxicology Station and Western Oregon rivers. EPA-600/3-76-077. U.S. EPA, Duluth, MN.

Schubauer-Berigan, M.K., J.R. Dierkes, P.D. Monson and G.T. Ankley. 1993. pH-dependent toxicity of cadmium, copper, nickel, lead and zinc to *Ceriodaphnia dubia*, *Pimephales promelas*, *Hyalella azteca* and *Lumbriculus variegatus*. Environ. Toxciol. Chem. 12(7):1261-1266.

Seim, W.K., L.R. Curtis, S.W. Glenn and G.A. Chapman. 1984. Growth and survival of developing steelhead trout (*Salmo gairdneri*) continuously or intermittently exposed to copper. Can. J. Fish. Aquat. Sci. 41(3):433-438.

Spehar, R.L. and J.T. Fiandt. 1986. Acute and chronic effects of water quality criteria-based metal mixtures on three aquatic species. Environ. Toxicol. Chem. 5(10):917-931.

Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman and W.A. Brungs. 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.

Thompson, K.W., A.C. Hendricks and J. Cairns, Jr. 1980. Acute toxicity of zinc and copper singly and in combination to the bluegill (*Lepomis macrochirus*). Bull. Environ. Contam. Toxicol. 25:122.

U.S. EPA. 1993. Methods for measuring the acute toxicity of effluents and receiving water to freshwater and marine organisms. Fourth Edition. EPA/600/4-90/027F. National Technical Information Service, Springfield, VA.

U.S. EPA. 1998a. Ambient water quality criteria derivation methodology human health technical support document. EPA-822-B-98-005. Office of Water. Washington, DC.

U.S. EPA. 1998b. Ambient aquatic life water quality criteria for copper. Draft Report. Office of Water. Washington, DC.

U.S. EPA. 2001. 2001 update of ambient water quality criteria for cadmium. EPA-822-R-01-001. Office of Water. Washington, DC.

Winner, R.W. 1985. Bioaccumulation and toxicity of copper as affected by interactions between humic acid and water hardness. Water Res. 19(4):449-455.

WPPSS (Washington Public Power Supply System). 1982. Supply system nuclear project No. 3. Environmental Report - Operating License Stage Docket No. 50-508. Richland, WA.

# Appendix C-1. Calculations for Ionic Composition of Standard Laboratory-Reconstituted Water

| Molecular Weights | Atomic Weights |
|---|---|
| $NaHCO_3$ = 84.03 | Na = 22.98 |
| $CaSO_4.2H_2$ O = 172.12 | Ca = 40.08 |
| $MgSO_4$= 120.37 | Mg = 24.31 |
| KCl = 74.55 | K = 39.10 |
| $SO_4$ = 96.06 | Cl = 35.45 |

***Example Calculation***

[Na] in very soft water:
12 mg $NaHCO_3$/L x 1 mmol $NaHCO_3$/84.03 mg $NaHCO_3$ = 0.143 mmol $NaHCO_3$/L.
0.143 mmol $NaHCO_3$/L x (1 mmol Na/1 mmol $NaHCO_3$) x 22.98 mg Na/1 mmol Na = 3.3 mg Na/L.

[Ca] in very soft water:
7.5 mg $CaSO_4$.2H2O/L x 1 mmol $CaSO_4.2H_2O$/172.12 mg $CaSO_4.2H_2O$ = 0.044 mmol $CaSO_4.2H_2O$/L.
0.044 mmol $CaSO_4.2H_2O$/L x (1 mmol Ca/1 mmol $CaSO_4.2H_2O$) x 40.08 mg Ca/1 mmol Ca = 1.8 mg Ca/L.

[Mg] in very soft water:
7.5 mg $MgSO_4$/L x 1 mmol $MgSO_4$/120.37 mg $MgSO_4$ = 0.062 mmol $MgSO_4$/L.
0.062 mmol $MgSO_4$/L x (1 mmol Mg/1 mmol $MgSO_4$) x 24.31 mg Mg/1 mmol Mg = 1.5 mg Mg/L.

[K] in very soft water:
0.5 mg KCl/L x 1 mmol KCl/74.55 mg KCl = 0.0067 mmol KCl/L.
0.0067 mmol KCl/L x (1 mmol K/1 mmolKCl) x 39.102 mg K/1 mmol K = 0.26 mg K/L.

[Cl] in very soft water:
0.5 mg KCl/L x 1 mmol KCl/74.55 mg KCl = 0.0067 mmol KCl/L.
0.0067 mmol KCl/L x (1 mmol Cl/1 mmolKCl) x 35.453 mg Cl/1 mmol K = 0.24 mg Cl/L.

[$SO_4$] in very soft water:
7.5 mg $CaSO_4.2H_2O$/L x 1 mmol $CaSO_4.2H_2$ O/172.12 mg $CaSO_4.2H_2O$ = 0.044 mmol $CaSO_4.2H_2O$/L.
0.044 mmol $CaSO_4.2H_2O$/L x (1 mmol $SO_4$/1 mmol $CaSO_4.2H_2O$) x 96.064 mg Ca/1 mmol Ca = 4.2 mg Ca/L.

[$SO_4$] in very soft water:
7.5 mg $MgSO_4$/L x 1 mmol $MgSO_4$/120.37 mg $MgSO_4$ = 0.062 mmol $MgSO_4$/L.
0.062 mmol $MgSO_4$/L x (1 mmol $SO_4$/1 mmol $MgSO_4$) x 96.064 mg Mg/1 mmol Mg = 6.0 mg Mg/L.

**Total $SO_4$ = 10.2 mg/L**

Conversion Factors to calculate water hardness (as $CaCO_3$) from [Ca] and [Mg]:

[Ca] x 2.497
[Mg] x 4.116

## Appendix C-2. Dissolved, Particulate, and Estimated Total Organic Carbon for Streams and Lakes by State (as presented in EPA Document #822-B-98-005)

| | | | Streams | | | | Lakes | |
|---|---|---|---|---|---|---|---|---|
| State | POC | DOC | Est. TOC | Est. DOC:TOC | POC | DOC | Est. TOC | Est. DOC:TOC |
| AK | 0.54 | 4.6 | 5.14 | 89.49 | 0.53 | 6.4 | 6.93 | 92.35 |
| AL | 0.72 | 3.4 | 4.12 | 82.52 | --- | --- | --- | --- |
| AR | 0.8 | 7.2 | 8 | 90.00 | 0.4 | 2.7 | 3.1 | 87.10 |
| AZ | 0.71 | 5.2 | 5.91 | 87.99 | 0.52 | 4.2 | 4.72 | 88.98 |
| CA | 1.13 | 8.2 | 9.33 | 87.89 | 0.32 | 2.3 | 2.62 | 87.79 |
| CO | 1.29 | 8.6 | 9.89 | 86.96 | --- | --- | --- | --- |
| CT | 0.71 | 4.8 | 5.51 | 87.11 | --- | --- | --- | --- |
| DC | --- | --- | --- | --- | --- | --- | --- | --- |
| DE* | 0.7 | 7.1 | 7.8 | 91.03 | --- | --- | --- | --- |
| FL^ | 0.68 | 16.1 | 16.78 | 95.95 | 2.9 | 12.1 | 15 | 80.67 |
| GA | 0.67 | 4.3 | 4.97 | 86.52 | --- | --- | --- | --- |
| HI | 0.59 | 4 | 4.59 | 87.15 | --- | --- | --- | --- |
| IA | 1.79 | 11.6 | 13.39 | 86.63 | --- | --- | --- | --- |
| ID | 0.6 | 3.2 | 3.8 | 84.21 | --- | --- | --- | --- |
| IL | 1.77 | 6.8 | 8.57 | 79.35 | 0.12 | 4.7 | 4.82 | 97.51 |
| IN | 0.71 | 9.2 | 9.91 | 92.84 | --- | --- | --- | --- |
| KS | 1.75 | 5.2 | 6.95 | 74.82 | 1.53 | 4.5 | 6.03 | 74.63 |
| KY | 0.75 | 3.1 | 3.85 | 80.52 | --- | --- | --- | --- |
| LA | 1.52 | 6.9 | 8.42 | 81.95 | 0.65 | 5.6 | 6.25 | 89.60 |
| MA | 0.47 | 5.9 | 6.37 | 92.62 | --- | --- | --- | --- |
| MD | 1.66 | 3.7 | 5.36 | 69.03 | --- | --- | --- | --- |
| ME | 0.46 | 15.3 | 15.76 | 97.08 | --- | --- | --- | --- |
| MI | 0.58 | 6.3 | 6.88 | 91.57 | 0.32 | 2.7 | 3.02 | 89.40 |
| MN | 1.79 | 12.2 | 13.99 | 87.21 | 0.16 | 4.8 | 4.96 | 96.77 |
| MO | 0.56 | 4.2 | 4.76 | 88.24 | --- | --- | --- | --- |
| MT | 0.9 | 9.4 | 10.3 | 91.26 | 0.91 | 8.2 | 9.11 | 90.01 |
| NC | 1.14 | 11.5 | 12.64 | 90.98 | --- | --- | --- | --- |
| ND | 1.14 | 14.5 | 15.64 | 92.71 | 0.8 | 14.9 | 15.7 | 94.90 |
| NE | 1.84 | 6.8 | 8.64 | 78.70 | --- | --- | --- | --- |
| NH | 0.28 | 4.2 | 4.48 | 93.75 | --- | --- | --- | --- |
| NJ | 0.69 | 5.5 | 6.19 | 88.85 | 1.04 | 5 | 6.04 | 82.78 |
| NM | 1.43 | 6.3 | 7.73 | 81.50 | 0.51 | 5.2 | 5.71 | 91.07 |
| NV | 0.82 | 4.2 | 5.02 | 83.67 | --- | --- | --- | --- |
| NY | 1.4 | 4 | 5.4 | 74.07 | 0.46 | 2.4 | 2.86 | 83.92 |
| OH | 0.57 | 5 | 5.57 | 89.77 | 0.49 | 2.6 | 3.09 | 84.14 |
| OK^ | 1.27 | 7.7 | 8.97 | 85.84 | 1.72 | 15 | 16.72 | 89.71 |
| OR*^ | 1.14 | 2.1 | 3.24 | 64.81 | 0.64 | 4.4 | 5.04 | 87.30 |
| PA | 2.19 | 5.4 | 7.59 | 71.15 | 0.63 | 3.2 | 3.83 | 83.55 |
| RI* | 0.42 | 8.3 | 8.72 | 95.18 | --- | --- | --- | --- |
| SC | 0.7 | 5.7 | 6.4 | 89.06 | --- | --- | --- | --- |
| SD | 1.25 | 7.6 | 8.85 | 85.88 | --- | --- | --- | --- |
| TN | 0.67 | 2.3 | 2.97 | 77.44 | --- | --- | --- | --- |
| TX | 1.33 | 6.5 | 7.83 | 83.01 | 1.55 | 10.3 | 11.85 | 86.92 |
| UT^ | 1.38 | 8.9 | 10.28 | 86.58 | 0.5 | 2.4 | 2.9 | 82.76 |
| VA | 0.81 | 4.7 | 5.51 | 85.30 | --- | --- | --- | --- |
| VT | 0.31 | 4.5 | 4.81 | 93.56 | --- | --- | --- | --- |
| WA | 1.52 | 5.4 | 6.92 | 78.03 | 0.61 | 2.8 | 3.41 | 82.11 |
| WI | 1.03 | 9.2 | 10.23 | 89.93 | 0.16 | 4.1 | 4.26 | 96.24 |
| WV | 0.63 | 2.8 | 3.43 | 81.63 | --- | --- | --- | --- |
| WY | 1.07 | 8.2 | 9.27 | 88.46 | --- | --- | --- | --- |

| | | | Streams | | | | Lakes | |
|---|---|---|---|---|---|---|---|---|
| State | POC | DOC | Est. TOC | Est. DOC:TOC | POC | DOC | Est. TOC | Est. DOC:TOC |
| | | | Mean | 85.71 | | | Mean | 87.84 |
| | | | Max | 97.08 | | | Max | 97.51 |
| | | | Min | 64.81 | | | Min | 74.63 |

* States where sample size was low for streams.

^ States where sample size was low for lakes.

## Appendix C-3. Mean TOC and DOC in Lake Superior Dilution Water (data from Greg Lien, U.S. EPA-Duluth, MN)

| | Replicate | Ambient (8/29/2000) | pH 7.0 (8/30/2000) | pH 6.2 (8/31/2000) |
|---|---|---|---|---|
| Filter Blank* | | -0.04 | 0.22 | 0.38 |
| Pre-gill experiment TOC | a | 1.13 | 1.34 | 1.26 |
| | b | 1.37 | 1.30 | 1.36 |
| | Mean | 1.25 | 1.32 | 1.31 |
| Post-gill experiment TOC | a | 1.20 | 1.24 | 1.18 |
| | b | 1.27 | 1.46 | 1.10 |
| | Mean | 1.24 | 1.35 | 1.14 |
| Pre-gill experiment DOC | a | 1.96 | 1.51 | 1.34 |
| | b | 1.52 | 1.28 | 0.99 |
| | Mean | 1.74 | 1.40 | 1.17 |
| Post-gill experiment DOC | a | 1.49 | 1.36 | 1.44 |
| | b | 1.64 | 1.58 | 1.24 |
| | Mean | 1.57 | 1.47 | 1.34 |

* Filter blank is ultra-pure Duluth-EPA laboratory water.

## Appendix C-4. Measured Hardness and Major Ion and Cation Concentrations in WFTS Well Water from April 1972 to April 1978. Concentrations Given as Mg/L (data from Samuelson 1976 and Chapman, personal communication)

| Month | Total Hardness | Ca | Mg | Na | K | $SO_4$ | Cl |
|---|---|---|---|---|---|---|---|
| Mar-72 | | | | | | | |
| Apr-72 | | 7.9 | 2 | 5 | 1.1 | <10.0 | 8 |
| May-72 | 22 | 5.8 | 1.4 | 4.4 | 0.5 | <5.0 | 7 |
| Jun-72 | 24 | 5.8 | 1.6 | 4.4 | 0.5 | 3 | 7 |
| Jul-72 | 23 | 6.7 | 1.6 | 4.6 | 0.5 | <1.0 | 8.3 |
| Aug-72 | 23 | 6.5 | 1.7 | 4.7 | 0.5 | <10.0 | 6.3 |
| Sep-72 | 22 | 6 | 1.6 | 4.5 | 0.6 | <10.0 | 4 |
| Oct-72 | 22 | 6.7 | 1.9 | 4.7 | 0.6 | 5 | 5.5 |
| Nov-72 | 23 | 6.2 | 1.6 | 4.2 | 0.6 | 3.7 | 5.3 |
| Dec-72 | 23 | 6.2 | 1.5 | 4.2 | 0.5 | 3 | 4 |
| Jan-73 | 52 | 15.3 | 3.5 | 7.1 | 0.7 | 7.8 | 12.4 |
| Feb-73 | 33 | 7.7 | 2.1 | 5 | 0.5 | 5 | 5 |
| Mar-73 | 30 | 8 | 2.1 | 5.3 | 0.7 | 5 | 6 |
| Apr-73 | 31 | 8.9 | 2.3 | 5.4 | 0.7 | 5.3 | 8.8 |
| May-73 | 28 | 8.3 | 2.4 | 5.8 | 0.7 | 3 | 8 |
| Jun-73 | 28 | 8.4 | 2.2 | 5.8 | 0.7 | 4.8 | 7.5 |
| Jul-73 | 26 | 7.4 | 1.9 | 5.8 | 0.8 | <5.0 | 6.8 |
| Aug-73 | 25 | 6.5 | 1.7 | 5.7 | 0.7 | 3.1 | 5.8 |
| Sep-73 | 25 | 6.7 | 1.7 | 5.4 | 0.7 | 3.1 | 5.3 |
| Oct-73 | 27 | 7 | 1.8 | 5.4 | 0.7 | 2.9 | 5.4 |
| Nov-73 | 28 | 7.9 | 2.1 | 4.8 | 0.7 | 10 | 6.8 |
| Dec-73 | 62 | 20.3 | 4.2 | 9 | 0.8 | 13 | 14 |
| Jan-74 | 67 | 21.3 | 4.8 | 7 | 0.8 | 17.3 | 11.3 |
| Feb-74 | 58 | 14.3 | 3.4 | 6.9 | 0.9 | 14.7 | 6.7 |
| Mar-74 | 53 | 20.8 | 3.8 | 7.2 | 0.7 | 13 | 7 |
| Apr-74 | 51 | 18.2 | 3.7 | 6.8 | 0.6 | 15.5 | 8.5 |
| May-74 | 23 | 7.5 | 2.1 | 4.6 | 0.6 | 5 | 4.8 |
| Jun-74 | 22 | 6 | 1.9 | 4.8 | 0.5 | 3 | 4.5 |
| Jul-74 | 23 | 5.4 | 1.7 | 5 | 0.6 | 3.3 | 6.3 |
| Aug-74 | 23 | 4.8 | 1.6 | 5 | 0.7 | 3 | 6 |
| Sep-74 | 23 | 5.8 | 1.5 | 5.1 | 0.7 | 2.9 | 4.8 |
| Oct-74 | 23 | 11 | 2 | 7.1 | 0.8 | 3.1 | 5 |
| Nov-74 | 23 | 12 | 2.6 | 4.5 | 0.5 | 3.8 | 5.3 |
| Dec-74 | 24 | 6.4 | 2.5 | 5.2 | 0.7 | 3.8 | 5 |
| Jan-75 | 41 | 7.7 | 2.9 | 6.7 | 0.6 | 8 | 8 |
| Feb-75 | 61 | 11.6 | 4.2 | 8.6 | 0.8 | 16 | 11.8 |
| Mar-75 | 54 | 9.1 | 3.1 | 6.4 | 0.6 | 8 | 8 |
| Apr-75 | | 4.4 | 1.6 | 4.4 | 0.5 | 3 | 5 |
| May-75 | | 7.2 | 2 | 5 | 0.5 | 6 | 7 |
| Jun-75 | | 4.4 | 1.6 | 4.6 | 0.6 | 5 | 6 |
| Jul-75 | | 5.2 | 1.6 | 7 | 0.7 | 5 | 7 |
| Aug-75 | | 5.2 | 1.4 | 7 | 0.6 | 5 | 5 |
| Sep-75 | | 4.5 | 1.5 | 4.5 | 0.7 | 5 | 4 |
| Oct-75 | | 7.1 | 1.9 | 4.3 | 0.5 | 20 | 5 |
| Nov-75 | 18 | 5.3 | 1.5 | 4.2 | 0.5 | 5 | 4 |
| Dec-75 | | | | | | | |
| Jan-76 | | | | | | | |
| Feb-76 | | 9.8 | 5 | 5.4 | 0.4 | 9 | 9 |
| Mar-76 | | | | 4.1 | 0.1 | 3 | 6 |
| Apr-76 | | | | 5.3 | 0.1 | 6 | 9 |

| Month | Total Hardness | Ca | Mg | Na | K | $SO_4$ | ClD |
|---|---|---|---|---|---|---|---|
| May-76 |  | 7.9 | 1.8 | 4.5 | 0.5 | 3 | 6 |
| Jun-76 | 27 | 8.1 | 1.9 | 3.3 | 0.6 | 4 | 7 |
| Jul-76 | 26 |  |  |  |  |  |  |
| Aug-76 | 23 | 4.9 | 1.3 | 4.8 | 0.1 | 3 | 6 |
| Sep-76 | 23 | 6.7 | 2.6 | 4.7 | 0.1 |  |  |
| Oct-76 | 21 | 6.7 | 2.6 | 4.7 | 0.1 |  |  |
| Nov-76 | 22 | 7.7 | 3 | 4.7 | 0.1 | 3 |  |
| Dec-76 | 25.5 | 6.4 | 1.8 | 5 | 0.1 | 4 | 7 |
| Jan-77 | 27.2 | 7.7 | 2.6 | 5.6 | 0.6 | 4 | 8 |
| Feb-77 |  | 10.7 | 4.9 | 5.9 | 0.6 | 3 | 11 |
| Mar-77 |  |  |  |  |  | 3 | 8 |
| Apr-77 |  | 10.7 | 2.2 | 5.5 | 0.8 | 3 | 7 |
| May-77 | 25 | 5 | 1.8 | 5 | 0.8 | 3 | 5 |
| Jun-77 | 27 | 6.6 | 2 | 5.2 | 0.7 | 3 | 5 |
| Jul-77 | 24 | 6.7 | 2 | 7.1 | 0.8 | 3 | 7 |
| Aug-77 | 25 | 6.9 | 1.9 | 6.9 | 1 |  | 8 |
| Sep-77 | 27 | 9.9 | 2.1 | 5.9 | 0.9 | 3 | 6 |
| Oct-77 |  |  |  |  |  | 3 |  |
| Nov-77 |  | 6.6 | 2.1 | 5.6 | 0.9 | 10 | 4.6 |
| Dec-77 | 27 | 9.7 |  | 4.95 | 0.65 | 9 | 4.6 |
| Jan-78 |  | 10.9 | 3.75 |  | 0.85 | 6 | 12 |
| Feb-78 |  | 10.6 | 3.8 | 8.6 | 0.7 | 5 | 11 |
| Mar-78 |  | 10.2 | 2.6 | 4.7 | 0.6 | 6 | 9 |
| Apr-78 |  | 8.3 | 2.4 |  | 0.7 | 5 | 9.55 |

| Date | pH | Hardness | Alkalinity | Ca | Mg | Na | K | Cl | $SO_4$ | $NO_3$ | DOCD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 19790329 | 7.6 | 80 | 63 | 19 | 8 | 8.4 | 2.3 | 7.8 | 13 | | |
| 19790430 | 7.6 | 37 | 29 | 8.7 | 3.7 | 2.2 | 1.3 | 2.8 | 8.9 | | 20 |
| 19790611 | 7.2 | 47 | 34 | 11 | 4.8 | 3.1 | 0.8 | 2.8 | 9.4 | | |
| 19790723 | 7.6 | 73 | 55 | 17 | 7.3 | 3.9 | 0.9 | 3.7 | 8.9 | | 30 |
| 19790827 | 7.2 | | | | | | | | | | |
| 19791015 | 8.1 | 74 | 54 | 16 | 8.2 | 5 | 1.1 | 3.9 | 13 | 0.01 | 12 |
| 19791126 | 7.8 | 61 | 52 | 14 | 6.3 | 3.8 | 0.9 | 3.6 | 11 | 0.37 | |
| 19800121 | 7.6 | 60 | 53 | 14 | 6 | 3.8 | 0.9 | 3.2 | 9.9 | 0.15 | |
| 19800219 | 7.4 | 63 | 51 | 15 | 6.2 | 3.9 | 0.8 | 2.9 | 9.2 | 0.19 | 17 |
| 19800331 | 8.4 | 68 | 64 | 16 | 6.9 | 4.2 | 1.1 | 3.5 | 9.2 | 0.3 | |
| 19800602 | 8.3 | 84 | 72 | 19 | 8.8 | 6.4 | 1.2 | 5 | 15 | 0.01 | 21 |
| 19800630 | 8.3 | 93 | 68 | 21 | 9.9 | 7.9 | 1.4 | 6.7 | 24 | 0.02 | |
| 19800804 | 8.1 | 130 | 110 | 28 | 14 | 10 | 1.9 | 11 | 24 | 0.01 | 13 |
| 19800902 | 7.8 | 110 | 82 | 24 | 11 | 7.2 | 1.7 | 7.6 | 18 | 0.01 | |
| 19800929 | 7.6 | 73 | 54 | 16 | 8.1 | 5.7 | 1.4 | 5.8 | 14 | 0.12 | |
| 19801103 | 7 | 82 | 58 | 18 | 8.9 | 5.6 | 1.3 | 6.9 | 18 | 0.19 | 23 |
| 19801208 | | 67 | 50 | 15 | 7.2 | 4.6 | 1 | 4.1 | 11 | 0.19 | |
| 19810105 | 7.6 | 70 | 55 | 16 | 7.2 | 4.2 | 1.1 | 4.1 | 13 | 0.23 | |
| 19810209 | 7.5 | 68 | 58 | 16 | 6.9 | 4.9 | 1 | 3.5 | 8.1 | 0.27 | 14 |
| 19810309 | 7.7 | 61 | 57 | 14 | 6.2 | 5.2 | 1.8 | 5.1 | 8.6 | 0.36 | |
| 19810504 | 7.3 | 42 | 40 | 9.6 | 4.3 | 3.7 | 1.2 | 3.6 | 9.6 | 0.18 | 21 |
| 19810706 | 7.4 | 51 | 39 | 12 | 5 | 3.5 | 1.2 | 3.2 | 7.5 | 0.14 | 10 |
| 19810908 | 7.9 | 73 | 64 | 16 | 8 | 4.2 | 0.8 | 4.2 | 8.3 | 0.11 | |
| 19811020 | 7.6 | 51 | 37 | 12 | 5.2 | 4.3 | 1.2 | 4.2 | 8.9 | 0.31 | |
| 19820113 | | 62 | 52 | 14 | 6.5 | 4 | 0.9 | 3.7 | 9.3 | 0.24 | |
| 19820309 | 7.4 | 66 | 58 | 15 | 7 | 5.3 | 1 | 3.8 | 11 | 0.36 | |
| 19820420 | 7.2 | 32 | 25 | 7.5 | 3.3 | 2.1 | 1.3 | 2.3 | 6 | 0.19 | |
| 19820621 | 7.9 | 61 | 55 | 14 | 6.4 | 4.3 | 1.1 | 4 | 10 | 0.1 | |
| 19820809 | 7.4 | 66 | 54 | 15 | 6.9 | 3.9 | 0.6 | 3.5 | 9 | 0.25 | |
| 19821004 | 8 | 73 | 63 | 15 | 8.7 | 4.9 | 1 | 4.7 | 13 | 0.11 | |
| 19821207 | 7.3 | 55 | 43 | 12 | 6.1 | 4.2 | 0.8 | 3.3 | 16 | 0.24 | |
| 19830131 | 6.9 | 62 | 50 | 14 | 6.5 | 4.1 | 0.8 | 3.5 | 15 | 0.36 | |
| 19830328 | 7.5 | 68 | 56 | 15 | 7.3 | 4.5 | 1.2 | 4.1 | 15 | 0.35 | |
| 19830523 | 8.2 | 68 | 53 | 15 | 7.5 | 4 | 1.3 | 0.8 | 23 | 0.12 | |
| 19830718 | 7.6 | 67 | 53 | 15 | 7.2 | 3.7 | 1.3 | 3.7 | 22 | 0.15 | |
| 19831031 | 7.7 | 64 | 48 | 14 | 7 | 3.9 | 1.2 | 3.5 | 24 | 0.12 | |
| 19840109 | 7.4 | 57 | 50 | 13 | 6 | 3.6 | 0.9 | 3.4 | 13 | 0.23 | |
| 19840306 | 7.1 | 66 | 57 | 15 | 7 | 4.4 | 0.9 | 5.2 | 8.7 | 0.31 | |
| 19840424 | 7.2 | 51 | 39 | 11 | 5.6 | 3.1 | 1.4 | 3.2 | 14 | 0.12 | |
| 19840619 | 9.5 | 52 | 39 | 12 | 5.3 | 2.9 | 0.8 | 3.6 | 10 | 0.13 | |
| 19840822 | 6.4 | 70 | 58 | 15 | 7.9 | 4.7 | 1 | 3.8 | 17 | 0.1 | |
| 19841009 | 7.6 | 73 | | 16 | 7.9 | 4.6 | 1 | 3.7 | 15 | 0.1 | |
| 19841120 | 7.1 | 64 | | 14 | 7.1 | 3.9 | 0.9 | 3.7 | 14 | 0.24 | |
| 19850211 | 7 | 69 | | 15 | 7.7 | 4.6 | 1.1 | 4 | 11 | 0.27 | |
| 19850325 | 7.3 | 61 | | 13 | 7 | 5.6 | 2.5 | 6.6 | 16 | 0.31 | |
| 19850506 | 7.4 | 55 | | 12 | 6 | 3.6 | 1.7 | 4.2 | 14 | 0.15 | |
| 19850730 | 7.6 | 62 | | 14 | 6.6 | 3.2 | 0.9 | 4 | 9.8 | 0.1 | |
| 19851021 | 7.5 | 58 | | 12 | 6.8 | 3.7 | 1.1 | 0.2 | 12 | 0.13 | |

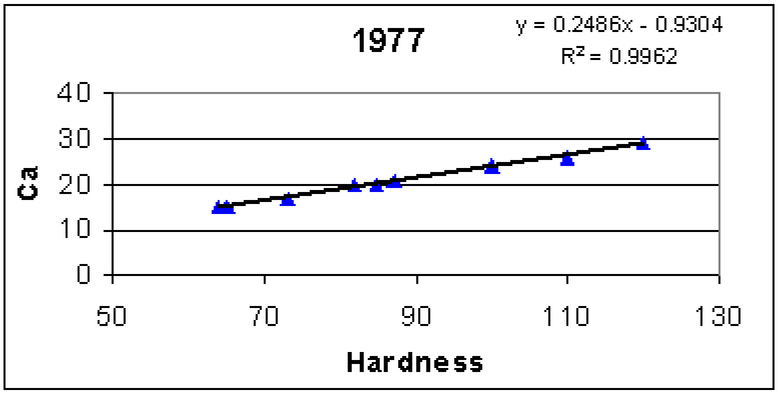
# Appendix C-6. Water Composition of St. Louis River, MN, from USGS NASQAN and Select Relationships to Water Hardness

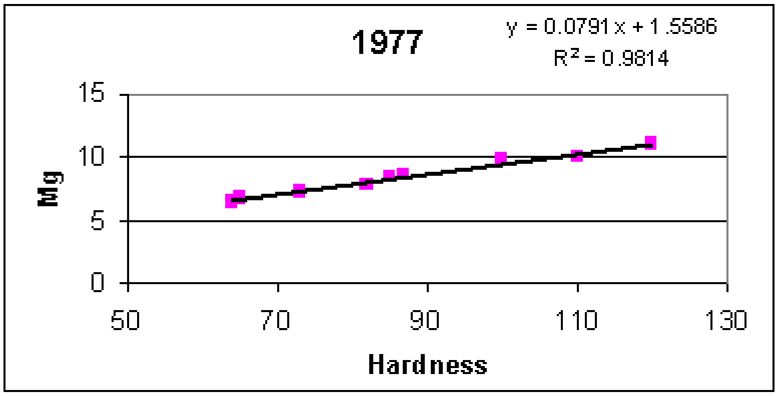
| Date | pH | Hardness | Alkalinity | Ca | Mg | Na | K | Cl | $SO_4$ | $NO_3$ | DOC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 19730222 | 6.8 | 68 | 53 | 17 | 6.3 | 11 | 1.6 | 14 | 14 | 0.19 | |
| 19730503 | 7.1 | 58 | 46 | 14 | 5.5 | 6.6 | 1.1 | 9.5 | 13 | 0.17 | |
| 19730816 | 6.9 | 70 | 51 | 17 | 6.6 | 7.6 | 1.2 | 9 | 20 | 0.01 | |
| 19731128 | 7 | 65 | 48 | 16 | 6.1 | 7.5 | 1.3 | 8.8 | 14 | | |
| 19740221 | 7 | 64 | 48 | 16 | 5.8 | 8.9 | 1.3 | 12 | 14 | | |
| 19740516 | 6.9 | 45 | 32 | 11 | 4.3 | 3.5 | 1.2 | 3.8 | 11 | | |
| 19740919 | | 88 | 60 | 21 | 8.6 | 12 | 1.8 | 17 | 23 | | |
| 19741030 | 7.3 | 83 | 62 | 23 | 6.3 | 13 | 1.3 | 16 | 23 | | |
| 19741209 | 7.4 | 86 | 62 | 22 | 7.6 | 12 | 1.6 | 15 | 18 | | |
| 19750121 | 7.3 | 74 | 66 | 18 | 7 | 10 | 1.1 | 12 | 13 | | |
| 19750303 | 7.3 | 74 | 68 | 17 | 7.6 | 10 | 1.7 | 11 | 12 | | |
| 19750407 | 7.2 | 95 | 80 | 22 | 9.7 | 11 | 2 | 14 | 16 | | |
| 19750527 | 7.5 | 63 | 50 | 15 | 6.1 | 8.5 | 1.5 | 9.2 | 12 | | |
| 19750708 | 9.2 | 58 | 43 | 14 | 5.7 | 3.2 | 1 | 3.4 | 10 | | |
| 19750818 | 7.2 | 73 | 56 | 18 | 6.9 | 12 | 1.3 | 16 | 16 | | |
| 19750929 | 7.4 | 90 | 72 | 23 | 8 | 12 | 1.5 | 13 | 20 | | |
| 19751110 | 7.1 | 90 | 63 | 22 | 8.4 | 12 | 1.7 | 15 | 24 | | |
| 19751216 | 7.6 | 87 | 61 | 22 | 7.8 | 14 | 1.6 | 16 | 28 | | |
| 19760209 | 7.5 | 72 | 59 | 18 | 6.6 | 13 | 1.6 | 13 | 18 | | |
| 19760322 | 7.7 | 78 | 65 | 19 | 7.4 | 12 | 1.4 | 11 | 17 | | |
| 19760503 | 7.6 | 59 | 43 | 14 | 5.8 | 7.9 | 1.3 | 8.6 | 15 | | |
| 19760614 | 7.5 | 94 | 75 | 22 | 9.4 | 16 | 1.9 | 20 | 20 | | |
| 19760726 | 7.4 | 93 | 80 | 22 | 9.3 | 21 | 1.9 | 25 | 24 | | |
| 19760908 | 7.5 | 82 | 78 | 18 | 9.1 | 17 | 2.5 | 9.3 | 26 | | |
| 19761019 | 7.5 | 83 | 72 | 20 | 8.1 | 21 | 1.6 | 24 | 21 | | |
| 19761129 | 7.4 | 95 | 74 | 22 | 9.7 | 25 | 1.8 | 32 | 24 | | |
| 19770110 | 7.3 | 85 | 88 | 20 | 8.4 | 17 | 1.5 | 15 | 19 | | |
| 19770214 | 8.2 | 82 | 73 | 20 | 7.8 | 18 | 1.7 | 26 | 17 | | |
| 19770404 | 7.3 | 87 | 67 | 21 | 8.5 | 20 | 2.4 | 28 | 24 | | |
| 19770516 | 7.3 | 120 | 98 | 29 | 11 | 30 | 2.8 | 26 | 36 | | |
| 19770628 | 7.8 | 100 | 75 | 24 | 9.9 | 13 | 2 | 16 | 23 | | |
| 19770808 | 7.4 | 110 | 90 | 26 | 10 | 27 | 2.2 | 32 | 28 | | |
| 19770919 | 7.4 | 73 | 44 | 17 | 7.3 | 6.6 | 1.7 | 8.9 | 17 | | |
| 19771031 | 7.6 | 64 | 47 | 15 | 6.5 | 7.9 | 1.3 | 9.7 | 22 | | 37 |
| 19771212 | 7.5 | 65 | 50 | 15 | 6.8 | 6.3 | 1.2 | 7.1 | 16 | | |
| 19780123 | 7.3 | 71 | 52 | 17 | 6.9 | 12 | 1.5 | 9.4 | 18 | | |
| 19780306 | 7.2 | 67 | 48 | 16 | 6.5 | 8.8 | 1.2 | 17 | 16 | | 32 |
| 19780417 | 7.5 | 43 | 28 | 10 | 4.3 | 4.2 | 1.8 | 5.7 | 15 | | |
| 19780530 | 7.9 | 64 | 54 | 15 | 6.4 | 5.7 | 1.5 | 7.1 | 14 | | 33 |
| 19780710 | 7.4 | 53 | 44 | 13 | 5.1 | 4.3 | 1.3 | 5.3 | 8.9 | | |
| 19780821 | 8.4 | 60 | 42 | 15 | 5.5 | 5.3 | 1.5 | 6.5 | 12 | | 36 |
| 19781002 | 7.7 | 71 | 57 | 17 | 6.9 | 8.2 | 1.1 | 9.6 | 15 | | 24 |
| 19781115 | 7.4 | 68 | 52 | 16 | 6.8 | 11 | 1.1 | 10 | 12 | | |
| 19781218 | 7.4 | 68 | 55 | 16 | 6.9 | 11 | 1 | 9.2 | 14 | | |
| 19790205 | 7.4 | 63 | 57 | 15 | 6.3 | 334.4 | 1 | 3.1 | 8 | | 12 |

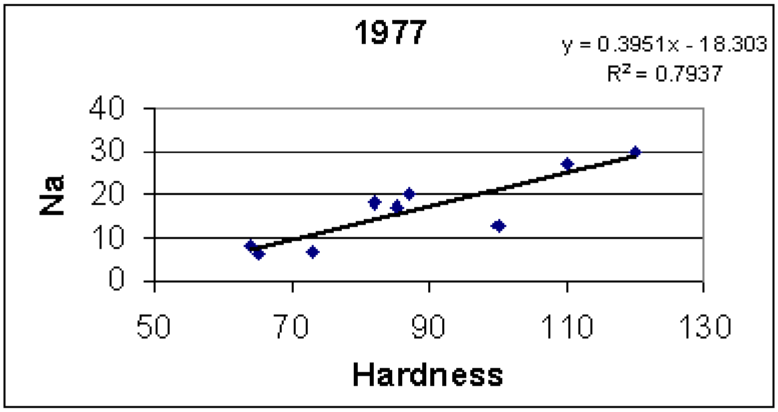
| Date | pH | Hardness | Alkalinity | Ca | Mg | Na | K | Cl | $SO_4$ | $NO_3$ | DOCD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 19790329 | 7.6 | 80 | 63 | 19 | 8 | 8.4 | 2.3 | 7.8 | 13 | | |
| 19790430 | 7.6 | 37 | 29 | 8.7 | 3.7 | 2.2 | 1.3 | 2.8 | 8.9 | | 20 |
| 19790611 | 7.2 | 47 | 34 | 11 | 4.8 | 3.1 | 0.8 | 2.8 | 9.4 | | |
| 19790723 | 7.6 | 73 | 55 | 17 | 7.3 | 3.9 | 0.9 | 3.7 | 8.9 | | 30 |
| 19790827 | 7.2 | | | | | | | | | | |
| 19791015 | 8.1 | 74 | 54 | 16 | 8.2 | 5 | 1.1 | 3.9 | 13 | 0.01 | 12 |
| 19791126 | 7.8 | 61 | 52 | 14 | 6.3 | 3.8 | 0.9 | 3.6 | 11 | 0.37 | |
| 19800121 | 7.6 | 60 | 53 | 14 | 6 | 3.8 | 0.9 | 3.2 | 9.9 | 0.15 | |
| 19800219 | 7.4 | 63 | 51 | 15 | 6.2 | 3.9 | 0.8 | 2.9 | 9.2 | 0.19 | 17 |
| 19800331 | 8.4 | 68 | 64 | 16 | 6.9 | 4.2 | 1.1 | 3.5 | 9.2 | 0.3 | |
| 19800602 | 8.3 | 84 | 72 | 19 | 8.8 | 6.4 | 1.2 | 5 | 15 | 0.01 | 21 |
| 19800630 | 8.3 | 93 | 68 | 21 | 9.9 | 7.9 | 1.4 | 6.7 | 24 | 0.02 | |
| 19800804 | 8.1 | 130 | 110 | 28 | 14 | 10 | 1.9 | 11 | 24 | 0.01 | 13 |
| 19800902 | 7.8 | 110 | 82 | 24 | 11 | 7.2 | 1.7 | 7.6 | 18 | 0.01 | |
| 19800929 | 7.6 | 73 | 54 | 16 | 8.1 | 5.7 | 1.4 | 5.8 | 14 | 0.12 | |
| 19801103 | 7 | 82 | 58 | 18 | 8.9 | 5.6 | 1.3 | 6.9 | 18 | 0.19 | 23 |
| 19801208 | | 67 | 50 | 15 | 7.2 | 4.6 | 1 | 4.1 | 11 | 0.19 | |
| 19810105 | 7.6 | 70 | 55 | 16 | 7.2 | 4.2 | 1.1 | 4.1 | 13 | 0.23 | |
| 19810209 | 7.5 | 68 | 58 | 16 | 6.9 | 4.9 | 1 | 3.5 | 8.1 | 0.27 | 14 |
| 19810309 | 7.7 | 61 | 57 | 14 | 6.2 | 5.2 | 1.8 | 5.1 | 8.6 | 0.36 | |
| 19810504 | 7.3 | 42 | 40 | 9.6 | 4.3 | 3.7 | 1.2 | 3.6 | 9.6 | 0.18 | 21 |
| 19810706 | 7.4 | 51 | 39 | 12 | 5 | 3.5 | 1.2 | 3.2 | 7.5 | 0.14 | 10 |
| 19810908 | 7.9 | 73 | 64 | 16 | 8 | 4.2 | 0.8 | 4.2 | 8.3 | 0.11 | |
| 19811020 | 7.6 | 51 | 37 | 12 | 5.2 | 4.3 | 1.2 | 4.2 | 8.9 | 0.31 | |
| 19820113 | | 62 | 52 | 14 | 6.5 | 4 | 0.9 | 3.7 | 9.3 | 0.24 | |
| 19820309 | 7.4 | 66 | 58 | 15 | 7 | 5.3 | 1 | 3.8 | 11 | 0.36 | |
| 19820420 | 7.2 | 32 | 25 | 7.5 | 3.3 | 2.1 | 1.3 | 2.3 | 6 | 0.19 | |
| 19820621 | 7.9 | 61 | 55 | 14 | 6.4 | 4.3 | 1.1 | 4 | 10 | 0.1 | |
| 19820809 | 7.4 | 66 | 54 | 15 | 6.9 | 3.9 | 0.6 | 3.5 | 9 | 0.25 | |
| 19821004 | 8 | 73 | 63 | 15 | 8.7 | 4.9 | 1 | 4.7 | 13 | 0.11 | |
| 19821207 | 7.3 | 55 | 43 | 12 | 6.1 | 4.2 | 0.8 | 3.3 | 16 | 0.24 | |
| 19830131 | 6.9 | 62 | 50 | 14 | 6.5 | 4.1 | 0.8 | 3.5 | 15 | 0.36 | |
| 19830328 | 7.5 | 68 | 56 | 15 | 7.3 | 4.5 | 1.2 | 4.1 | 15 | 0.35 | |
| 19830523 | 8.2 | 68 | 53 | 15 | 7.5 | 4 | 1.3 | 0.8 | 23 | 0.12 | |
| 19830718 | 7.6 | 67 | 53 | 15 | 7.2 | 3.7 | 1.3 | 3.7 | 22 | 0.15 | |
| 19831031 | 7.7 | 64 | 48 | 14 | 7 | 3.9 | 1.2 | 3.5 | 24 | 0.12 | |
| 19840109 | 7.4 | 57 | 50 | 13 | 6 | 3.6 | 0.9 | 3.4 | 13 | 0.23 | |
| 19840306 | 7.1 | 66 | 57 | 15 | 7 | 4.4 | 0.9 | 5.2 | 8.7 | 0.31 | |
| 19840424 | 7.2 | 51 | 39 | 11 | 5.6 | 3.1 | 1.4 | 3.2 | 14 | 0.12 | |
| 19840619 | 9.5 | 52 | 39 | 12 | 5.3 | 2.9 | 0.8 | 3.6 | 10 | 0.13 | |
| 19840822 | 6.4 | 70 | 58 | 15 | 7.9 | 4.7 | 1 | 3.8 | 17 | 0.1 | |
| 19841009 | 7.6 | 73 | | 16 | 7.9 | 4.6 | 1 | 3.7 | 15 | 0.1 | |
| 19841120 | 7.1 | 64 | | 14 | 7.1 | 3.9 | 0.9 | 3.7 | 14 | 0.24 | |
| 19850211 | 7 | 69 | | 15 | 7.7 | 4.6 | 1.1 | 4 | 11 | 0.27 | |
| 19850325 | 7.3 | 61 | | 13 | 7 | 5.6 | 2.5 | 6.6 | 16 | 0.31 | |
| 19850506 | 7.4 | 55 | | 12 | 6 | 3.6 | 1.7 | 4.2 | 14 | 0.15 | |
| 19850730 | 7.6 | 62 | | 14 | 6.6 | 3.2 | 0.9 | 4 | 9.8 | 0.1 | |
| 19851021 | 7.5 | 58 | | 12 | 6.8 | 3.7 | 1.1 | 0.2 | 12 | 0.13 | |

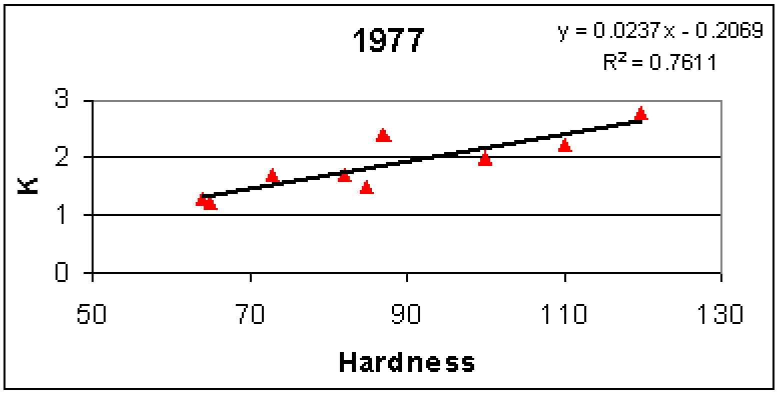
| Date | pH | Hardness | Alkalinity | Ca | Mg | Na | K | Cl | $SO_4$ | $NO_3$ | DOCD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 19851203 | 7.4 | 73 |  | 16 | 8 | 4 | 1 | 4.2 | 18 | 0.16 |  |
| 19860303 | 7.4 | 66 |  | 15 | 7 | 4 | 1 | 3.4 | 10 | 0.24 |  |
| 19860407 | 7.3 |  |  |  |  |  |  |  |  | 0.19 |  |
| 19860602 | 7.5 | 58 |  | 13 | 6.3 | 3.5 | 1 | 2.8 | 15 | 0.1 |  |
| 19860818 | 7.9 | 74 |  | 15 | 8.9 | 4.6 | 1.2 | 3.7 | 24 | 0.1 |  |
| 19861112 | 7.5 | 55 |  | 12 | 6 | 3.4 | 1.4 | 3.8 | 19 | 0.27 |  |
| 19861210 | 7.3 | 70 | 57 | 13 | 9 | 5 | 1 | 4.8 | 21 | 0.16 |  |
| 19870218 | 7 | 66 |  | 15 | 6.8 | 3.7 | 0.9 | 3.1 | 12 | 0.24 |  |
| 19870518 | 8 | 83 |  | 18 | 9.3 | 5.8 | 1.2 | 5 | 10 | 0.1 |  |
| 19870622 | 7.8 | 75 |  | 16 | 8.5 | 6.2 | 1.1 | 5.2 | 19 | 0.1 |  |
| 19870721 | 7.6 | 51 |  | 12 | 5.2 | 2.8 | 1.3 | 3.1 | 15 | 0.1 |  |
| 19871028 | 8 | 82 |  | 17 | 9.6 | 6.8 | 1.4 | 1.3 | 19 | 0.1 |  |
| 19871208 | 7.9 | 69 |  | 15 | 7.7 | 5.3 | 1.4 | 4.8 | 17 | 0.1 |  |
| 19880119 | 7.4 | 73 |  | 16 | 8 | 5.1 | 1 | 3.6 | 15 | 0.15 |  |
| 19880223 | 7.4 | 85 |  | 19 | 9.2 | 6.5 | 8.5 | 5.1 | 16 | 0.2 |  |
| 19880412 | 7.4 | 42 |  | 9.2 | 4.7 | 3 | 2.8 | 5 | 20 | 0.25 |  |
| 19880907 | 7.1 | 70 |  | 15 | 8 | 5.3 | 1.5 | 6.1 | 18 | 0.15 |  |
| 19881031 | 7.6 | 100 |  | 21 | 12 | 9 | 1.9 | 7.8 | 27 | 0.1 |  |
| 19881130 | 7.6 | 78 |  | 17 | 8.6 | 5.5 | 1.3 | 5.5 | 19 | 0.19 |  |
| 19890221 | 7.1 | 77 |  | 17 | 8.4 | 6.3 | 1.3 | 4.4 | 17 | 0.25 |  |
| 19890410 | 7.2 | 48 |  | 11 | 5 | 4.9 | 1.8 | 8.1 | 8 | 0.37 |  |
| 19890626 | 7.4 | 63 |  | 14 | 6.8 | 4.6 | 1.1 | 5 | 12 | 0.15 |  |
| 19890814 | 8.1 | 95 |  | 20 | 11 | 9.1 | 1.5 | 8.9 | 18 | 0.1 |  |
| 19891101 | 8.1 | 110 |  | 20 | 15 | 7.8 | 1.9 | 6.3 | 31 | 0.1 |  |
| 19891218 | 7.5 | 88 |  | 17 | 11 | 6.1 | 1.4 | 5 | 22 | 0.16 |  |
| 19900123 | 7.3 | 100 |  | 18 | 14 | 7.2 | 1.7 | 5.2 | 28 | 0.23 |  |
| 19900416 | 7.5 | 62 |  | 13 | 7.2 | 5.1 | 1.9 | 5.4 | 14 | 0.2 |  |
| 19900716 | 7.7 | 70 |  | 15 | 8 | 5.7 | 1.3 | 5.4 | 11 | 0.2 |  |
| 19900820 | 8.1 | 95 |  | 20 | 11 | 7.8 | 1.5 | 7.9 | 20 | 0.1 |  |
| 19901009 | 7.3 | 81 |  | 18 | 8.7 | 5.4 | 1.5 | 5.7 | 13 | 0.1 |  |
| 19910102 | 7.4 | 83 |  | 19 | 8.7 | 5.3 | 1.4 | 5 | 12 | 0.2 |  |
| 19910212 | 7.1 | 80 |  | 18 | 8.5 | 6.8 | 1.3 | 3.9 | 11 | 0.2 |  |
| 19910502 | 6.7 | 56 |  | 13 | 5.8 | 4 | 1 | 3.7 | 7.9 | 0.1 |  |
| 19910610 | 7.3 | 64 |  | 15 | 6.5 | 4 | 0.7 | 4.1 | 6.9 | 0.12 |  |
| 19910731 | 7.8 | 55 |  | 13 | 5.4 | 2.5 | 1 | 2.6 | 3.8 | 0.05 |  |
| 19910801 | 7.3 |  |  |  |  |  |  |  |  |  |  |
| 19911003 | 7.8 | 67 |  | 15 | 7.1 | 4.4 | 1 | 4.4 | 9.6 | 0.068 |  |
| 19911204 | 7.4 | 61 |  | 13 | 6.9 | 4.8 | 1 | 3.5 | 7 | 0.18 |  |
| 19920113 | 7.9 | 67 |  | 15 | 7.2 | 4.3 | 1.1 | 3.2 | 9.3 | 0.21 |  |
| 19920413 | 7.7 | 30 |  | 7.8 | 2.5 | 2.5 | 0.3 | 2.4 | 4.8 | 0.16 |  |
| 19920722 | 7.6 | 71 |  | 16 | 7.5 | 4.8 | 0.9 | 2.1 | 9.6 | 0.11 |  |
| 19921026 | 8.2 | 86 |  | 18 | 10 | 5.3 | 1.2 | 5.4 | 14 |  |  |
| 19921216 | 7.6 | 89 |  | 19 | 10 | 6 | 1.2 | 5.6 | 13 | 0.25 |  |
| 19930201 | 7.2 | 83 |  | 18 | 9.1 | 7.3 | 1.2 | 7.3 | 12 | 0.28 |  |
| 19930426 | 7.7 | 66 |  | 15 | 6.8 | 4.1 | 1.2 | 4.9 | 9.5 | 0.092 |  |
| 19930722 | 7.5 | 64 |  | 15 | 6.5 | 4 | 0.2 | 3.9 | 7.7 | 0.079 |  |
| 19931201 | 7.7 | 80 |  | 17 | 9 | 4.8 | 1 | 4 | 11 | 0.16 |  |

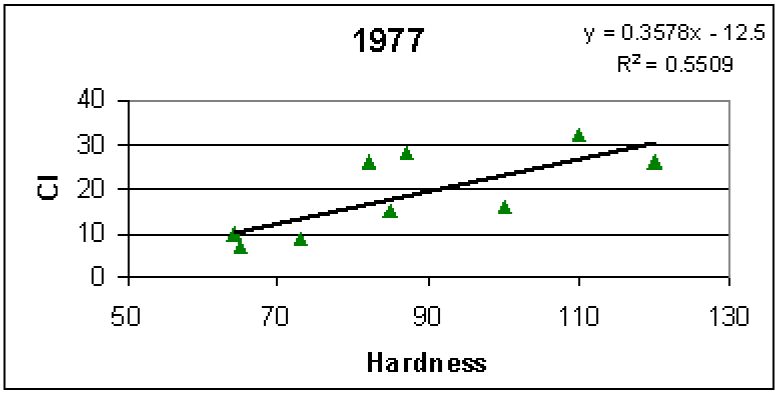
| Date | pH | Hardness | Alkalinity | Ca | Mg | Na | K | Cl | $SO_4$ | $NO_3$ | DOCD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 19940216 | 7.3 | | | | | | | | | | |
| 19940511 | 7.7 | 51 | | 11 | 5.6 | 3.7 | 1.1 | 3.4 | 9.4 | 0.076 | |
| | | | | | | | | | | | |
| MIN | 6.4 | 30 | 25 | 7.5 | 2.5 | 2.1 | 0.2 | 0.2 | 3.8 | 0.01 | 10 |
| MAX | 9.5 | 130 | 110 | 29 | 15 | 30 | 8.5 | 32 | 36 | 0.37 | 37 |
| MEAN | 7.52 | 71.11 | 56.94 | 16.16 | 7.46 | 7.09 | 1.37 | 7.39 | 15.04 | 0.17 | 22.19 |

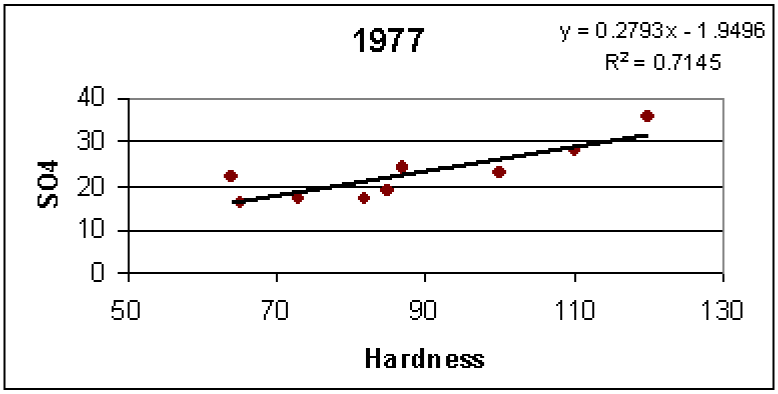

1977
y = 0.2486x - 0.9304
R² = 0.9962
Ca
0
10
20
30
40
50
70
90
110
130
Hardness


1977
y = 0.0791x + 1.5586
R² = 0.9814
Mg
0
5
10
15
50
70
90
110
130
Hardness


1977
y = 0.3951x - 18.303
R² = 0.7937
Na
0
10
20
30
40
50
70
90
110
130
Hardness


1977
y = 0.0237x - 0.2069
R² = 0.7611
K
3
2
1
0
50
70
90
110
130
Hardness


1977
y = 0.3578x - 12.5
R² = 0.5509
Cl
40
30
20
10
0
50
70
90
110
130
Hardness


1977
y = 0.2793x - 1.9496
R² = 0.7145
SO4
40
30
20
10
0
50
70
90
110
130
Hardness

# Appendix C-7. Supplementary Data for Bennett et al. (1995)

| Tank | Dose (µg Cu/L) | Conductivity (µmho/cm) | pH | Oxygen (mg/L) | Temp ($^{o}$C) | Alkalinity (as mg $CaCO_3$/L) | Hardness (as mg $CaCO_3$/L) |
|---|---|---|---|---|---|---|---|
| ***0 hours* 7/9/92** | | | | | | | |
| a | 897 | 325 | 8.62 | 7.5 | 21 | 100 | 96 |
| b | 897 | 300 | 8.6 | 7.6 | 21 | 100 | 96 |
| c | 897 | 320 | 8.6 | 7.6 | 21 | 80 | 96 |
| d | 607 | 320 | 8.62 | 7.7 | 21 | 80 | 96 |
| e | 607 | 370 | 8.62 | 7.6 | 21 | 80 | 96 |
| f | 607 | 328 | 8.64 | 7.6 | 21 | 80 | 96 |
| g | 93 | 310 | 8.64 | 7.6 | 21 | 80 | 96 |
| h | 93 | 370 | 8.69 | 7.5 | 21 | 80 | 96 |
| I | 93 | 310 | 8.6 | 7.6 | 21 | 80 | 96 |
| j | 505 | 310 | 8.62 | 7.7 | 21 | 100 | 96 |
| k | 505 | 310 | 8.65 | 7.7 | 21 | 80 | 96 |
| l | 505 | 320 | 8.69 | 7.7 | 21 | 80 | 96 |
| m | 319 | 320 | 8.69 | 7.7 | 21 | 80 | 96 |
| n | 319 | 330 | 8.68 | 7.7 | 21 | 80 | 96 |
| o | 319 | 320 | 8.67 | 7.7 | 21 | 80 | 96 |
| p | 0 | 310 | 8.62 | 7.5 | 21 | 80 | 96 |
| q | 0 | 320 | 8.63 | 7.6 | 21 | 80 | 96 |
| r | 0 | 320 | 8.6 | 7.7 | 21 | 80 | 96 |
| ***24 hours* 7/10/92** | | | | | | | |
| a | 897 | 300 | 7.78 | 8.5 | 21.5 | 60 | 104 |
| b | 897 | 305 | 7.64 | 8.4 | 22 | 80 | 100 |
| c | 897 | 305 | 7.68 | 8.5 | 22 | 90 | 100 |
| d | 607 | 300 | 7.7 | 8.4 | 21.5 | 90 | 100 |
| e | 607 | 305 | 7.65 | 8.4 | 21.5 | 80 | 100 |
| f | 607 | 305 | 7.75 | 8.4 | 21.5 | 80 | 100 |
| g | 93 | 300 | 7.77 | 9.1 | 22 | 80 | 100 |
| h | 93 | 295 | 7.76 | 9.2 | 21.5 | 80 | 108 |
| I | 93 | 295 | 7.76 | 9 | 21.5 | 85 | 100 |
| j | 505 | 300 | 7.73 | 8.8 | 22 | 90 | 84 |
| k | 505 | 300 | 7.71 | 8.8 | 21.5 | 80 | 100 |
| l | 505 | 300 | 7.73 | 8.7 | 21.5 | 80 | 100 |
| m | 319 | 300 | 7.74 | 9.1 | 21.5 | 80 | 100 |
| n | 319 | 300 | 7.52 | 8.5 | 22 | 80 | 100 |
| o | 319 | 310 | 7.79 | 8.7 | 22.5 | 80 | 100 |
| p | 0 | 305 | 7.79 | 9.1 | 22 | 80 | 100 |
| q | 0 | 305 | 7.7 | 9.1 | 22 | 80 | 104 |
| r | 0 | 300 | 7.71 | 9.1 | 22 | 80 | 104 |
| ***48 hours* 7/11/92** | | | | | | | |
| a | 897 | * | * | * | * | * | * |
| b | 897 | * | * | * | * | * | * |
| c | 897 | 320 | 8.1 | 7.2 | 21.5 | 100 | 96 |
| d | 607 | 315 | 7.91 | 6.9 | 21.5 | 100 | 96 |
| e | 607 | 310 | 7.84 | 6.8 | 21.5 | 100 | 100 |
| f | 607 | 315 | 8 | 7 | 21.5 | 100 | 104 |
| g | 93 | 300 | 8.19 | 7.7 | 21.5 | 100 | 100 |

| Tank | Dose (µg Cu/L) | Conductivity (µmho/cm) | pH | Oxygen (mg/L) | Temp ($^oC$) | Alkalinity (as mg $CaCO_3$/L) | Hardness (as mg $CaCO_3$/L)D |
|---|---|---|---|---|---|---|---|
| h | 93 | 300 | 8.13 | 7.7 | 21 | 100 | 100 |
| I | 93 | 300 | 8.16 | 7.6 | 21 | 100 | 104 |
| j | 505 | 310 | 8.1 | 7.5 | 21 | 80 | 100 |
| k | 505 | 310 | 8.12 | 7.4 | 21 | 100 | 100 |
| l | 505 | 310 | 8.13 | 7.4 | 21 | 80 | 100 |
| m | 319 | 310 | 8.12 | 7.4 | 21 | 100 | 100 |
| n | 319 | 310 | 7.8 | 6.4# | 21.5 | 100 | 100 |
| o | 319 | 310 | 8.18 | 7.3 | 22 | 100 | 96 |
| p | 0 | 300 | 8.16 | 8 | 21.5 | 80 | 100 |
| q | 0 | 300 | 8.1 | 7.9 | 21.5 | 80 | 104 |
| r | 0 | 300 | 8.21 | 8 | 21.5 | 100 | 100 |
| *72 hours* 7/12/92 | | | | | | | |
| a | 897 | * | * | * | * | * | * |
| b | 897 | * | * | * | * | * | * |
| c | 897 | * | * | * | * | * | * |
| d | 607 | 310 | 8.02 | 8.9 | 21.5 | 100 | 100 |
| e | 607 | 315 | 8.04 | 8.8 | 21.5 | 100 | 100 |
| f | 607 | 315 | 8.02 | 8.7 | 21.5 | 80 | 100 |
| g | 93 | 310 | 7.92 | 9.1 | 21.5 | 100 | 104 |
| h | 93 | 305 | 7.91 | 9.1 | 21 | 100 | 100 |
| I | 93 | 310 | 7.91 | 9 | 21 | 80 | 106 |
| j | 505 | 315 | 7.97 | 8.9 | 21.5 | 100 | 104 |
| k | 505 | 310 | 7.96 | 8.9 | 21 | 100 | 100 |
| l | 505 | 310 | 7.96 | 9 | 21 | 80 | 104 |
| m | 319 | 310 | 7.91 | 9 | 21 | 100 | 100 |
| n | 319 | 310 | 7.97 | 9 | 21 | 80 | 100 |
| o | 319 | 320 | 7.99 | 8.8 | 22 | 100 | 104 |
| p | 0 | 300 | 7.86 | 9.3 | 21.5 | 100 | 104 |
| q | 0 | 300 | 7.81 | 9.1 | 21.5 | 80 | 100 |
| r | 0 | 305 | 7.93 | 9.3 | 21.5 | 80 | 100 |
| *96 hours* 7/13/92 | | | | | | | |
| a | 897 | * | * | * | * | * | * |
| b | 897 | * | * | * | * | * | * |
| c | 897 | * | * | * | * | * | * |
| d | 607 | 320 | 8.03 | 7.3 | 21.5 | 100 | 104 |
| e | 607 | 320 | 8.07 | 7.3 | 21.5 | 100 | 100 |
| f | 607 | 325 | 8.02 | 7.2 | 21.5 | 100 | 104 |
| g | 93 | 325 | 7.95 | 7.1 | 21.5 | 120 | 104 |
| h | 93 | 315 | 8.03 | 7.5 | 21 | 100 | 100 |
| I | 93 | 310 | 8.02 | 7.4 | 21 | 100 | 100 |
| j | 505 | 320 | 8.06 | 7.4 | 21.5 | 80 | 100 |
| k | 505 | 320 | 8.05 | 7.4 | 21 | 120 | 100 |
| l | 505 | 320 | 8.03 | 7.3 | 21 | 100 | 104 |
| m | 319 | 315 | 8.05 | 7.5 | 21 | 100 | 104 |
| n | 319 | 320 | 8.06 | 7.4 | 21 | 100 | 100 |
| o | 319 | 330 | 8.08 | 7.3 | 22 | 100 | 104 |

| Tank | Dose (µg Cu/L) | Conductivity (µmho/cm) | pH | Oxygen (mg/L) | Temp ($^oC$) | Alkalinity (as mg $CaCO_3$/L) | Hardness (as mg $CaCO_3$/L)D |
|---|---|---|---|---|---|---|---|
| p | 0 | 330 | 7.78 | 8.1 | 21.5 | 80 | 96 |
| q | 0 | 325 | 7.75 | 7.9 | 21.5 | 80 | 104 |
| r | 0 | 330 | 7.86 | 8.1 | 21.5 | 80 | 100 |

* All fish dead, no water quality measured.

\# Air stone had fallen out of tank.

# Appendix C-8. Supplementary Data for Richards and Beitinger (1995)

| Acclimation Temperature | 5°C | | 12°C | | 22°C | | 32°C | |
|---|---|---|---|---|---|---|---|---|
| Replicate | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Sample size | 30 | 36 | 30 | 36 | 36 | 30 | 33 | 29 |
| pH | 8.2-8.3 | 7.8-8.2 | 8.4-8.5 | 8.2-8.4 | 8.3-8.4 | 8.1-8.5 | 8.4-8.5 | 8.4-8.5 |
| Hardness (mg/l $CaCO_3$) | 164-180 | 152-166 | 152-168 | 148-170 | 164-174 | 162-172 | 164-168 | 162-172 |
| Alkalinity (mg/l $CaCO_3$) | 125-140 | 130-140 | 130-140 | 130-140 | 140-145 | 140-145 | 135-140 | 135-145 |
| Weights of minnows (g) | 0.62-3.23 | 0.42-2.64 | 0.56-2.38 | 0.30-1.93 | 0.66-1.15 | 0.13-1.55 | 0.26-1.36 | 0.23-1.32 |
| Lengths of minnows (cm) | 3.3-5.5 | 3.2-5.2 | 3.2-4.9 | 2.8-5.1 | 1.9-4.3 | 2.4-4.6 | 3.0-4.8 | 3.3-4.8 |

## Appendix C-9. Data for the American River, CA, for July 1978 Through December 1980 (data from the City of Sacramento, CA, Water Quality Laboratory; personal communication). Units Are mg/L.

| Date | pH | Hardness | Alkalinity | Ca | Mg | Ca:Mg | Na | Cl | $SO_4$ |
|---|---|---|---|---|---|---|---|---|---|
| Jul-78 | 7.6 | 20 | 22 | 5.2 | 1.7 | 3.06 | 3.2 | 2.6 | 4 |
| Aug-78 | 7.6 | 20 | 22 | 4.9 | 1.9 | 2.58 | 3.4 | 2.8 | 5 |
| Sep-78 | 7.5 | 20 | 22 | 5.2 | 1.7 | 3.06 | 3.5 | 2.6 | 4 |
| Oct-78 | 7.3 | 20 | 22 | 5 | 1.8 | 2.78 | 3.6 | 3 | 4 |
| Nov-78 | 7.2 | 20 |  | 4.9 | 1.9 | 2.58 | 3.9 |  | 5 |
| Dec-78 |  |  |  |  |  |  |  |  |  |
| Jan-79 | 7.4 | 23 | 24 | 5.1 | 2.1 | 2.43 | 3.2 | 2.9 | 4 |
| Feb-79 | 7.5 | 24 | 25 | 6.5 | 1.9 | 3.42 | 3 | 3 | 5 |
| Mar-79 | 7.6 | 26 | 27 | 7.4 | 1.8 | 4.11 | 3.3 | 2.7 | 6 |
| Apr-79 | 7.7 | 27 | 27 | 7.5 | 2 | 3.75 | 3.6 | 2.7 | 7 |
| May-79 | 7.6 | 25 | 26 | 5.7 | 2.6 | 2.19 | 3.4 | 2.4 | 6 |
| Jun-79 | 7.7 | 22 | 24 | 5.7 | 1.9 | 3.00 | 3.1 | 2.5 | 4 |
| Jul-79 | 7.6 | 21 | 22 | 5.3 | 1.9 | 2.79 | 3 | 2.7 | 4 |
| Aug-79 | 7.5 | 21 | 22 | 5.6 | 1.7 | 3.29 | 3.2 | 2.4 | 5 |
| Sep-79 | 7.3 | 20 | 21 | 5.7 | 1.4 | 4.07 | 3.5 | 2.5 | 3 |
| Oct-79 | 7.2 | 19 | 20 | 5.5 | 1.3 | 4.23 | 3.1 | 2.8 | 3 |
| Nov-79 |  |  |  |  |  |  |  |  |  |
| Dec-79 |  |  |  |  |  |  |  |  |  |
| Jan-80 | 7.5 | 23 | 23 | 6.1 | 1.9 | 3.21 | 2.4 | 2.6 | 4 |
| Feb-80 | 7.4 | 23 | 23 | 6.1 | 1.9 | 3.21 | 2.7 | 2.3 | 2 |
| Mar-80 | 7.5 | 24 | 26 | 5.8 | 2.3 | 2.52 | 2 | 2.3 | 2 |
| Apr-80 | 7.7 | 25 | 25 | 6.4 | 2.2 | 2.91 | 1.9 | 2.5 | 3 |
| May-80 | 7.5 | 22 | 21 | 6.1 | 1.6 | 3.81 | 2.4 | 2.4 | 3 |
| Jun-80 | 7.3 | 19 | 21 | 5.1 | 1.5 | 3.40 | 2.3 | 2.4 | 2 |
| Jul-80 | 7.4 | 18 | 20 | 4.6 | 1.6 | 2.88 | 2.6 | 2.1 | 3 |
| Aug-80 | 7.5 | 18 | 21 | 5.2 | 1.2 | 4.33 | 3 | 2.7 | 2 |
| Sep-80 | 7.3 | 18 | 20 | 4.9 | 1.4 | 3.50 | 2.9 | 2.4 | 4 |
| Oct-80 | 7.3 | 18 | 20 | 5 | 1.3 | 3.85 | 3 | 2.7 | 2 |
| Mean | 7.5 | 21.4 | 22.8 | 5.6 | 1.8 | 3.2 | 3.0 | 2.6 | 3.8 |
| max | 7.7 | 27.0 | 27.0 | 7.5 | 2.6 | 4.3 | 3.9 | 3.0 | 7.0 |
| min | 7.2 | 18.0 | 20.0 | 4.6 | 1.2 | 2.2 | 1.9 | 2.1 | 2.0 |

# Appendix C-10. STORET Data for Minnesota Lakes and Rivers

| Date | pH | Hardness | Alkalinity | Ca | Mg | Ca:Mg | Na | K | Cl | SO$_4$ | NO$_3$ | TOC | DOC | Sulfide |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Embarrass River, MN | | | | | | | | | | | | | | |
| 3/22/76 | 7 | 133 | 103 | 27 | 16 | 1.69 | 2.5 | 2 | 11 | 34 | | | | |
| 4/29/76 | 6.7 | 25.3 | 23 | 5.2 | 3 | 1.73 | 2.8 | 0.7 | 2.9 | 8.4 | 0.04 | 16 | | 0.6 |
| 5/28/76 | 6.5 | | 53 | | | | | | 3.5 | 12 | | | | |
| 6/28/76 | 6.9 | 44 | 36 | 9.9 | 4.6 | 2.15 | 3.9 | 0.3 | 5 | 13 | 0.04 | 37 | | |
| 7/28/76 | 6.6 | | 76 | 5.2 | | | | | 4.8 | 7.5 | | | | |
| 8/26/76 | 6.9 | 100 | 110 | 24 | 9.9 | 2.42 | 9 | 1 | 8.4 | 5.6 | | 21 | | 0.6 |
| | | | | | | | | | | | | | | |
| Means | 6.8 | 75.58 | 66.83 | 14.26 | 8.38 | 2.00 | 4.55 | 1.00 | 5.93 | 13.42 | 0.04 | 24.67 | | 0.60 |
| max. | 7 | 133 | 110 | 27 | 16 | 2.42 | 9 | 2 | 11 | 34 | 0.04 | 37 | | 0.6 |
| min. | 6.5 | 25.3 | 23 | 5.2 | 3 | 1.69 | 2.5 | 0.3 | 2.9 | 5.6 | 0.04 | 16 | | 0.6 |
| | | | | | | | | | | | | | | |
| S. Kawishiwi River, MN | | | | | | | | | | | | | | |
| 10/16/75 | 6.4 | 21 | 14 | 4.9 | 2.1 | 2.33 | 1.3 | 0.4 | 0.5 | 4.4 | 0.01 | 12 | | 0.2 |
| 11/6/75 | 6.9 | 24 | 19 | 5.5 | 2.5 | 2.20 | 1.2 | 0.4 | 0.6 | 4.1 | | | | |
| 12/11/75 | | 39 | 23 | 10 | 3.4 | 2.94 | 1.4 | 0.4 | 1.5 | | | | | 0.2 |
| 1/9/76 | 6.6 | 29 | 24 | 6.2 | 3.2 | 1.94 | 1.6 | 0.8 | 2.3 | 7 | | | | |
| 2/4/76 | 6.3 | 24 | 20 | 5.2 | 2.7 | 1.93 | 1.7 | 0.6 | 0.9 | 6.3 | 0.16 | 16 | | 0 |
| 3/9/76 | 6.9 | 23 | 23 | 5.7 | 2.2 | 2.59 | 1.5 | 0.5 | 0.9 | 4.9 | | | | 1 |
| 4/23/76 | 6.6 | 14 | 8 | 3.4 | 1.3 | 2.62 | 0.9 | 0.4 | 0.7 | 4.8 | | | | 0.2 |
| 5/25/76 | 6.8 | 16 | 11 | 4 | 1.5 | 2.67 | 0.9 | 0.4 | 0.7 | 4.8 | | | | |
| 6/25/76 | 6.6 | | 16 | | | | | | 1.1 | 3.3 | | | | 1.8 |
| 7/23/76 | 6.7 | | 19 | | | | | | 1.2 | 4.4 | | | | 0.5 |
| | | | | | | | | | | | | | | |
| Means | 6.6 | 23.75 | 17.70 | 5.61 | 2.36 | 2.40 | 1.31 | 0.49 | 1.04 | 4.89 | 0.09 | 14.00 | | 0.56 |
| max. | 6.9 | 39 | 24 | 10 | 3.4 | 2.94 | 1.7 | 0.8 | 2.3 | 7 | 0.16 | 16 | | 1.8 |
| min. | 6.3 | 14 | 8 | 3.4 | 1.3 | 1.93 | 0.9 | 0.4 | 0.5 | 3.3 | 0.01 | 12 | | 0 |
| | | | | | | | | | | | | | | |
| Colby Lake, MN | | | | | | | | | | | | | | |
| LCY2 | | | | | | | | | | | | | | |
| 6/17/96 | 8.5 | 56 | 33 | 13 | 5.7 | 2.28 | 4.3 | 1.5 | 6.3 | 22 | 0.25 | 17 | | |
| 6/17/96 | 6.8 | | | | | | | | | | 0.25 | 17 | | |
| 6/17/96 | 6.9 | 71 | 33 | 17 | 7 | 2.43 | 4.3 | 1.4 | 9.4 | 22 | | 18 | | |
| LCY1 | | | | | | | | | | | | | | |
| 6/17/96 | 6.8 | 54 | 33 | 12 | 5.8 | 2.07 | 3.9 | 1.4 | 6.6 | 26 | 0.3 | 16 | | |
| 6/17/96 | 6.8 | | | | | | | | | | | 16 | | |
| 6/17/96 | 6.5 | 41 | 34 | 11 | 3.2 | 3.44 | 3.6 | 1.3 | 6.8 | 22 | 0.33 | 17 | | |
| 6/17/96 | 7.4 | 83 | 39 | 21 | 7.3 | 2.88 | | | 7.8 | 52 | 0.18 | | | |
| | | | | | | | | | | | | | | |
| Means | 7.1 | 55.50 | 33.25 | 13.25 | 5.43 | 2.55 | 4.03 | 1.40 | 7.28 | 23.00 | 0.28 | 16.83 | | |
| max. | 8.5 | 71 | 34 | 17 | 7 | 3.44 | 4.3 | 1.5 | 9.4 | 26 | 0.33 | 18 | | |
| min. | 6.5 | 41 | 33 | 11 | 3.2 | 2.07 | 3.6 | 1.3 | 6.3 | 22 | 0.25 | 16 | | |
| | | | | | | | | | | | | | | |
| Cloquet Lake, MN | | | | | | | | | | | | | | |
| 7/13/76 | 6.4 | 17 | 11 | 4 | 1.8 | 2.22 | | | 1.7 | 7.6 | 0 | 38 | | |
| | | | | | | | | | | | | | | |
| Lake One, MN | | | | | | | | | | | | | | |
| 10/16/75 | 7.2 | 27 | 21 | 6.9 | 2.3 | 3.00 | | | 1.2 | 5.6 | 0.02 | 22 | | |
| | | | | | | | | | | | | | | |
| Greenwood Lake, MN | | | | | | | | | | | | | | |
| 7/6/76 | 6.7 | 10 | 15 | 2.8 | 0.7 | 4.00 | 0.1 | 0.3 | 0.2 | 4.2 | 0 | 11 | | |

# Appendix D. Saltwater Conversion Factors for Dissolved Values

# Appendix D
# Saltwater Conversion Factors for Dissolved Values

**February 14, 2007**

U.S. Environmental Protection Agency
Office of Water
Office of Science and Technology
Washington, D.C.

# ACKNOWLEDGMENTS

Larry Brooke and Tyler Linton
(primary authors)
Great Lakes Environmental Center
1295 King Avenue
Columbus, OH 43212

Jennifer Mitchell and Cindy Roberts
(authors and document coordinators)
U.S. Environmental Protection Agency
Washington, DC

## Saltwater Conversion Factors for Converting Nominal or Total Copper Concentrations to Dissolved Copper Concentrations

The U.S. EPA changed its policy in 1993 of basing water quality criteria for metals from a total metal criteria to a dissolved metal criteria. The policy states "the use of dissolved metal to set and measure compliance with water quality standards is the recommended approach, because dissolved metal more closely approximates the bioavailable fraction of metal in the water column than does total recoverable metal" (Prothro 1993). All of the criteria for metals to this date were based upon total metal and very few data were available with dissolved concentrations of the metals. A problem was created by the new policy of how to derive dissolved metal concentrations for studies in which this form of the metal was not measured. The U.S. EPA attempted to develop correction factors for each metal for which criteria exist for both fresh- and saltwater (Lussier et al. 1995; Stephan 1995). In the case of saltwater, a correction for copper was not derived.

Several saltwater studies are available that report nominal, total, and dissolved concentrations of copper in laboratory water (Table 1) from site-specific water effect ratio (WER) studies. These studies show relatively consistent ratios for the nominal-to-dissolved concentrations and for the total-to-dissolved concentrations. Calculation of a mean ratio (conversion factor) to convert nominal and total copper concentrations to dissolved copper permits the use of the results for critical studies without dissolved copper measurements.

Three studies, each with multiple tests per study, were useful for deriving the conversion factors. One study was conducted for the lower Hudson River in the New York/New Jersey Harbor (SAIC 1993). The tests were conducted with harbor site water and with EPA Environmental Research Laboratory - Narragansett water from Narragansett Bay, Massachusetts. Only the tests with laboratory water were used for this exercise. Three series of 48-hour static tests were conducted with various animals. Salinity ranged from 28 to 32 ppt during all the tests. Series 1 tests were not used to calculate ratios for dissolved-to-total or dissolved-to-nominal copper concentrations, because in many instances, concentrations of measured copper did not increase as nominal concentrations increased. Of the series 2 tests, only the coot clam (*Mulinia lateralis*) tests were successful and used to calculate ratios. Three replicate tests without ultraviolet (UV) light present and one test with UV light present were reported with total and dissolved copper measurements made at 0 hr and 48 hr (end) of the tests. Dissolved-to-total and dissolved-to-nominal ratios were calculated for the four tests each with two time intervals. The mean ratio for the dissolved-to-total measurements is 0.943 and the mean ratio for the dissolved-to-nominal is 0.917. A third series of static tests was conducted by SAIC and the mussel (*Mytilus sp.*) test was the only successful test. Again the tests were conducted as three replicate tests without UV light and a fourth with UV light. The mean test ratio for dissolved-to-total copper was 0.863 and the dissolved-to-nominal mean test ratio was 0.906.

The summer flounder (*Paralichthys dentatus*) was exposed to copper in laboratory water for 96 hours in a static test (CH2MHill 1999a). The water was collected from Narragansett Bay and diluted with laboratory reverse osmosis water to dilute the solution to 22 ppt salinity. Three tests were run with copper concentrations measured at the start of the tests as total recoverable and dissolved copper. Five exposure concentrations were used to conduct the tests. Only the two lowest concentrations were used to derive ratios for dissolved-to-total and dissolved-to-nominal copper mean ratios. These concentrations were at the approximate 500 µg/L or lower concentrations, and are in the range of most copper concentrations routinely tested in the laboratory. The mean dissolved-to-total and dissolved-to-nominal ratios were 0.947 and 0.836, respectively.

Three 48-hour static tests were conducted with the blue mussel (*Mytilus edulis*) in water from the same source and treated in the same manner as the summer flounder tests (CH2MHill 1999b). Salinity was diluted to 20 ppt. Exposures were made at eight concentrations of copper and total and dissolved copper concentrations were measured only at the start of the tests. Mean ratios for the dissolved-to-total and dissolved-to-nominal copper were calculated by combining the ratios calculated for each of the test concentrations. The mean dissolved-to-total and dissolved-to-nominal ratios were 0.979 and 0.879, respectively.

A study was conducted by the City of San Jose, CA to develop a WER for San Francisco Bay in which copper was used as a toxicant and the concentrations used in the laboratory exposures were measured as total and dissolved copper (Environ. Serv. Dept., City of San Jose 1998). Mussels and the purple sea urchin (*Strongylocentrotus purpuratus*) were used as the test organisms. Tests were conducted in filtered natural sea water from San Francisco Bay that was diluted to a salinity of 28 ppt. The mussel test was of 48-hour duration and the purple sea urchin test was of 96-hour duration. Five concentrations of copper were used in the toxicity tests with the concentrations measured at the start of each test. (During each test, a single concentration of copper was measured at the termination of the test and this value was not used in the calculations.) Twenty-two tests were conducted during a 13-month period with the mussel and two tests were conducted with the purple sea urchin. The mean dissolved-to-total and dissolved-to-nominal ratios for the mussel tests were 0.836 and 0.785, respectively. The mean dissolved-to-total and dissolved-to-nominal ratios for the purple sea urchin were 0.883 and 0.702, respectively.

For some of the tests, control concentrations had measured concentrations of total and dissolved copper. These values were not used to calculate ratios for dissolved-to-total and dissolved-to-nominal copper concentrations. All mean ratios were calculated as the arithmetic mean and not as a geometric mean of the available ratios. When the data are normally distributed, the arithmetic mean is the appropriate measure of central tendency (Parkhurst 1998) and is a better estimator than the geometric mean. All concentrations of copper used to calculate ratios should be time-weighted averages (Stephan 1995). In all instances of data used to calculate ratios, the concentrations were identical to time-weighted values because either only one value was available or if two were available they were of equal weight.

Based on the information presented above the overall ratio for correcting total copper concentrations to dissolved copper concentrations is 0.909 based upon the results of six sets of studies. This is comparable to its equivalent factor in freshwater, which is 0.960 ± 0.037 (Stephan 1995). When it is necessary to convert nominal copper concentrations to dissolved copper concentrations the conversion factor is 0.838 based upon the same studies. The means of both conversion factors have standard deviations of less than ten percent of the means (Table 1).

**Table D-1. Summary of Saltwater Copper Ratios**

| Species | Mean Dissolved-to-Total Ratio | Mean Dissolved-to-Nominal Ratio | Reference |
|---|---|---|---|
| Coot clam, *Mulinia lateralis* | 0.943 | 0.917 | SAIC 1993 |
| Summer flounder, *Paralichthys dentatus* | 0.947 | 0.836 | CH2MHill 1999a |
| Blue mussel, *Mytilus sp* | 0.863 | 0.906 | SAIC 1993 |
| Blue mussel, *Mytilus edulis* | 0.979 | 0.879 | CH2MHill 1999b |
| Blue mussel, *Mytilus sp* | 0.836 | 0.785 | Environ. Serv. Dept., City of San Jose 1998 |
| Purple sea urchin, *Strongylocentrotus purpuratus* | 0.883 | 0.702 | Environ. Serv. Dept., City of San Jose 1998 |
| Arithmetic Mean | 0.909 | 0.838 | |
| Standard Deviation | ±0.056 | ±0.082 | |

## References

CH2MHill. 1999a. Bioassay report: Acute toxicity of copper to summer flounder (*Paralichthys dentatus*). Final report prepared for U.S. Navy. November 1999. CH2MHill, Norfolk, Virginia. 26 p.

CH2MHill. 1999b. Bioassay report: Acute toxicity of copper to blue mussel (*Mytilus edulis*). Final report prepared for U.S. Navy. November 1999. CH2MHill, Norfolk, Virginia. 41 p.

Environmental Services Department, City of San Jose. 1998. Development of a site-specific water quality criterion for copper in south San Francisco Bay. Environmental Services Department, City of San Jose, San Jose/Santa Clara Water Pollution Control Plant, 4245 Zanker Road, San Jose, CA. 171 pp. May.

Lussier, S.M., W.S. Boothman, S. Poucher, D. Champlin and A. Helmsteter. 1995. Derivation of conversion factors for dissolved saltwater aquatic life criteria for metals. Draft report to the U.S. EPA, Office of Water. U.S. EPA, Narragansett, RI. March 31, 1995.

Parkhurst, D.F. 1998. Arithmetic versus geometric means for environmental concentration data. Environ. Sci. Technol./News. 32:92A-95A.

Prothro, M. 1993. Memorandum concerning "Office of Water Policy and Technical Guidance on Interpretation and Implementation of Aquatic Life Metals Criteria." October 1.

SAIC. 1993. Toxicity testing to support the New York/New Jersey Harbor site-specific copper criteria study. Final Report to U.S. EPA, Office of Wastewater Enforcement and Compliance (Contract No. 68-C8-0066. Work Assignment C-4-94). Science Applications International Corporation, Narragansett, RI.

Stephan, C.E. 1995. Derivation of conversation factors for the calculation of dissolved freshwater aquatic life criteria for metals. Report. March 11, 1995. U.S. EPA, Duluth, MN.

# Appendix E. BLM Input Data and Notes

# Appendix E. BLM Table

| | Model Output | | Model Input | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BLM Data Label | Critical Accumulation | Hard-ness (mg/L) | Temp (ºC) | pH | Dissolved LC50 (µg/L) | DOC (mg/L) | Humic Acid (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | Cl (mg/L) | Alkalinity (mg/L) | S (mg/L) | Notes |
| LUVA01S | 1.1869 | 290 | 25 | 6.57 | 124.8 | 0.5 | 10 | 47.8602 | 41.47 | 89.821 | 7.178 | 278.4 | 6.5081 | 235 | 0.0003 | 1,2,3,4,5 |
| LUVA02S | 2.1707 | 290 | 25 | 7.29 | 259.2 | 0.5 | 10 | 47.8602 | 41.47 | 89.821 | 7.178 | 278.4 | 6.5081 | 235 | 0.0003 | 1,2,3,4,5 |
| LUVA03S | 2.0991 | 290 | 25 | 8.25 | 480 | 0.5 | 10 | 47.8602 | 41.47 | 89.821 | 7.178 | 278.4 | 6.5081 | 235 | 0.0003 | 1,2,3,4,5 |
| CADE01F | 27.6903 | 44.9 | 15 | 7.7 | 1920 | 1.1 | 10 | 13.1965 | 2.911001 | 1.27 | 0.56 | 3.32 | 1.2 | 42.7 | 0.0003 | 1,2,3,6,7,8 |
| CADE02F | 26.6895 | 44.9 | 15 | 7.7 | 1344 | 1.1 | 10 | 13.1965 | 2.911001 | 1.27 | 0.56 | 3.32 | 1.2 | 42.7 | 0.0003 | 1,2,3,6,7,8 |
| JUPL01F | 0.1537 | 21 | 15 | 7.20 | 14.4 | 1.1 | 10 | 6.0583 | 1.7462 | 4.5302 | 0.7 | 2.8706 | 5.468 | 26 | 0.0003 | 1,3,6,7,9,10 |
| LIVI01F | 0.0570 | 21 | 15 | 7.2 | 7.68 | 1.1 | 10 | 6.0583 | 1.7462 | 4.5302 | 0.7 | 2.8706 | 5.468 | 26 | 0.0003 | 1,3,6,7,9,10 |
| PHIN01F | 0.4378 | 44.9 | 15 | 7.7 | 39.36 | 1.1 | 10 | 13.1965 | 2.911001 | 1.27 | 0.56 | 3.32 | 1.2 | 42.7 | 0.0003 | 1,2,3,6,7,8 |
| PHIN02F | 0.3410 | 44.9 | 15 | 7.7 | 35.52 | 1.1 | 10 | 13.1965 | 2.911001 | 1.27 | 0.56 | 3.32 | 1.2 | 42.7 | 0.0003 | 1,2,3,6,7,8 |
| ACPE01S | 0.1147 | 96 | 25 | 8.35 | 25.92 | 0.5 | 10 | 15.8434 | 13.728 | 29.734 | 2.3762 | 92.159 | 2.1544 | 102 | 0.0003 | 1,2,3,4,6,7,20 |
| ACPE02S | 0.1556 | 68 | 25 | 8.35 | 27.84 | 0.5 | 10 | 11.2224 | 9.724 | 21.061 | 1.6831 | 65.279 | 1.526 | 108 | 0.0003 | 1,2,3,4,6,7,20 |
| UTIM01S | 8.2925 | 39 | 23 | 7.4 | 82.56 | 0.5 | 10 | 6.43638 | 5.577 | 12.079 | 0.9653 | 37.439 | 0.8752 | 32.5 | 0.0003 | 1,2,3,4,6,11 |
| UTIM02S | 8.0633 | 90 | 23 | 7.6 | 191.04 | 0.5 | 10 | 13.9716 | 12.11764 | 26.253 | 2.098 | 81.372 | 1.9022 | 65 | 0.0003 | 1,2,3,4,12 |
| UTIM03S | 1.3555 | 92 | 25 | 8.1 | 72.96 | 0.5 | 10 | 29.0614 | 4.73839 | 30.798 | 1.6408 | 46.006 | 32.716 | 77 | 0.0003 | 1,2,3,4,6,7,53 |
| UTIM04S | 1.4793 | 86 | 25 | 8.2 | 81.6 | 0.5 | 10 | 27.1661 | 4.429364 | 28.79 | 1.5338 | 43.005 | 30.583 | 78 | 0.0003 | 1,2,3,4,6,7,53 |
| UTIM05S | 0.5289 | 90 | 25 | 8 | 39.36 | 0.5 | 10 | 28.4296 | 4.635381 | 30.129 | 1.6052 | 45.006 | 32.005 | 78 | 0.0003 | 1,2,3,4,6,7,53 |
| UTIM06S | 1.2514 | 90 | 24 | 8.2 | 75.84 | 0.5 | 10 | 14.8532 | 12.87 | 13.938 | 1.1138 | 43.199 | 1.0099 | 99 | 0.0003 | 1,2,3,4,5,6,7 |
| UTIM07S | 1.3009 | 90 | 25 | 7.9 | 69.12 | 0.5 | 10 | 28.4296 | 4.635381 | 30.129 | 1.6052 | 45.006 | 32.005 | 99 | 0.0003 | 1,2,3,4,6,7,53 |
| UTIM08S | 0.7111 | 86 | 25 | 7.9 | 36.48 | 0.5 | 10 | 14.193 | 12.298 | 13.318 | 1.0643 | 41.279 | 0.965 | 59 | 0.0003 | 1,2,3,4,5,6,7 |
| CEDU01S | 0.1132 | 52 | 24.5 | 7.5 | 18.24 | 1.1 | 10 | 15.2833 | 3.371316 | 1.5 | 0.57 | 3.8 | 1.4 | 55 | 0.0003 | 1,2,3,6,7,8 |
| CEDU02S | 0.0941 | 52 | 24.5 | 7.5 | 16.32 | 1.1 | 10 | 15.2833 | 3.371316 | 1.5 | 0.57 | 3.8 | 1.4 | 55 | 0.0003 | 1,2,3,6,7,8 |
| CEDU03S | 0.0751 | 45 | 25 | 7.72 | 25 | 1.5 | 10 | 11.0991 | 4.2075 | 9.5 | 1.6 | 46 | 34 | 39.7 | 0.0003 | 1,2,6,7,16 |
| CEDU04S | 0.0400 | 45 | 25 | 7.72 | 17 | 1.5 | 10 | 11.0991 | 4.2075 | 9.5 | 1.6 | 46 | 34 | 39.7 | 0.0003 | 1,2,6,7,16 |
| CEDU05S | 0.1046 | 45 | 25 | 7.72 | 30 | 1.5 | 10 | 11.0991 | 4.2075 | 9.5 | 1.6 | 46 | 34 | 39.7 | 0.0003 | 1,2,6,7,16 |
| CEDU06S | 0.0700 | 45 | 25 | 7.72 | 24 | 1.5 | 10 | 11.0991 | 4.2075 | 9.5 | 1.6 | 46 | 34 | 39.7 | 0.0003 | 1,2,6,7,16 |
| CEDU07S | 0.0920 | 45 | 25 | 7.72 | 28 | 1.5 | 10 | 11.0991 | 4.2075 | 9.5 | 1.6 | 46 | 34 | 39.7 | 0.0003 | 1,2,6,7,16 |
| CEDU08S | 0.1184 | 45 | 25 | 7.72 | 32 | 1.5 | 10 | 11.0991 | 4.2075 | 9.5 | 1.6 | 46 | 34 | 39.7 | 0.0003 | 1,2,6,7,16 |
| CEDU09S | 0.0651 | 45 | 25 | 7.72 | 23 | 1.5 | 10 | 11.0991 | 4.2075 | 9.5 | 1.6 | 46 | 34 | 39.7 | 0.0003 | 1,2,6,7,16 |
| CEDU10S | 0.0517 | 45 | 25 | 7.72 | 20 | 1.5 | 10 | 11.0991 | 4.2075 | 9.5 | 1.6 | 46 | 34 | 39.7 | 0.0003 | 1,2,6,7,16 |
| CEDU11S | 0.0476 | 45 | 25 | 7.72 | 19 | 1.5 | 10 | 11.0991 | 4.2075 | 9.5 | 1.6 | 46 | 34 | 39.7 | 0.0003 | 1,2,6,7,16 |
| CEDU12S | 0.0194 | 94.1 | 25 | 8.15 | 26 | 2 | 10 | 23.2094 | 8.79835 | 5.2449 | 1.6 | 20.054 | 6.1705 | 69.6 | 0.0003 | 1,2,6,7,17 |
| CEDU13S | 0.0144 | 94.1 | 25 | 8.15 | 21 | 2 | 10 | 23.2094 | 8.79835 | 5.2449 | 1.6 | 20.054 | 6.1705 | 69.6 | 0.0003 | 1,2,6,7,17 |
| CEDU14S | 0.0206 | 94.1 | 25 | 8.15 | 27 | 2 | 10 | 23.2094 | 8.79835 | 5.2449 | 1.6 | 20.054 | 6.1705 | 69.6 | 0.0003 | 1,2,6,7,17 |

# Appendix E.  BLM Table

| | Model Output | | Model Input | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BLM Data Label | Critical Accumulation | Hard-ness (mg/L) | Temp (ºC) | pH | Dissolved LC50 (µg/L) | DOC (mg/L) | Humic Acid (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | Cl (mg/L) | Alkalinity (mg/L) | S (mg/L) | Notes |
| CEDU15S | 0.0338 | 94.1 | 25 | 8.15 | 37 | 2 | 10 | 23.2094 | 8.79835 | 5.2449 | 1.6 | 20.054 | 6.1705 | 69.6 | 0.0003 | 1,2,6,7,17 |
| CEDU16S | 0.0294 | 94.1 | 25 | 8.15 | 34 | 2 | 10 | 23.2094 | 8.79835 | 5.2449 | 1.6 | 20.054 | 6.1705 | 69.6 | 0.0003 | 1,2,6,7,17 |
| CEDU17S | 0.0428 | 179 | 25 | 8.31 | 67 | 2.3 | 10 | 50.1069 | 13.12323 | 14.32 | 2.4 | 22.673 | 10.979 | 140.1 | 0.0003 | 1,2,6,7,18 |
| CEDU18S | 0.0164 | 179 | 25 | 8.31 | 38 | 2.3 | 10 | 50.1069 | 13.12323 | 14.32 | 2.4 | 22.673 | 10.979 | 140.1 | 0.0003 | 1,2,6,7,18 |
| CEDU19S | 0.0579 | 179 | 25 | 8.31 | 78 | 2.3 | 10 | 50.1069 | 13.12323 | 14.32 | 2.4 | 22.673 | 10.979 | 140.1 | 0.0003 | 1,2,6,7,18 |
| CEDU20S | 0.0627 | 179 | 25 | 8.31 | 81 | 2.3 | 10 | 50.1069 | 13.12323 | 14.32 | 2.4 | 22.673 | 10.979 | 140.1 | 0.0003 | 1,2,6,7,18 |
| CEDU21S | 0.0283 | 97.6 | 25 | 8 | 28 | 2 | 10 | 24.0727 | 9.1256 | 5.44 | 1.6 | 20.8 | 6.4 | 74.2 | 0.0003 | 1,2,6,7,17 |
| CEDU22S | 0.1218 | 182 | 25 | 8 | 84 | 2.3 | 10 | 50.9467 | 13.34317 | 14.56 | 2.4 | 23.053 | 11.163 | 144.3 | 0.0003 | 1,2,6,7,18 |
| CEDU23S | 0.0510 | 57.1 | 25 | 8.18 | 12.864 | 0.5 | 10 | 9.42352 | 8.1653 | 17.685 | 1.4133 | 54.815 | 1.2814 | 81 | 0.0003 | 1,2,3,4,6,7,20 |
| CEDU24R | 0.0377 | 80 | 20 | 7.6 | 5.5396825 | 0.5 | 10 | 13.2028 | 11.44 | 24.778 | 1.9801 | 76.799 | 1.7953 | 53 | 0.0003 | 1,2,6,7,20,21 |
| DAMA01S | 0.0221 | 39 | 20 | 7.8 | 8.736 | 1.1 | 10 | 10.9867 | 2.7776 | 5.8136 | 0.7 | 7.9394 | 7.7684 | 51 | 0.0003 | 1,2,3,6,7,9,10 |
| DAMA02S | 0.0315 | 39 | 20 | 7.8 | 11.232 | 1.1 | 10 | 10.9867 | 2.7776 | 5.8136 | 0.7 | 7.9394 | 7.7684 | 51 | 0.0003 | 1,2,3,6,7,9,10 |
| DAMA03S | 0.0147 | 38 | 20 | 7.79 | 6.336 | 1.1 | 10 | 10.7129 | 2.7203 | 5.7423 | 0.7 | 7.6578 | 7.6406 | 50 | 0.0003 | 1,2,3,6,7,9,10 |
| DAMA04S | 0.0253 | 38 | 20 | 7.79 | 9.504 | 1.1 | 10 | 10.7129 | 2.7203 | 5.7423 | 0.7 | 7.6578 | 7.6406 | 50 | 0.0003 | 1,2,3,6,7,9,10 |
| DAMA05S | 0.1799 | 39 | 20 | 6.9 | 11.232 | 1.1 | 10 | 10.9867 | 2.7776 | 5.8136 | 0.7 | 7.9394 | 7.7684 | 30 | 0.0003 | 1,2,3,6,7,9,10 |
| DAMA06S | 0.0786 | 39 | 20 | 6.9 | 6.432 | 1.1 | 10 | 10.9867 | 2.7776 | 5.8136 | 0.7 | 7.9394 | 7.7684 | 30 | 0.0003 | 1,2,3,6,7,9,10 |
| DAMA07S | 0.0312 | 26 | 20 | 7.6 | 8.736 | 1.1 | 10 | 7.4273 | 2.0327 | 4.8867 | 0.7 | 4.2786 | 6.107 | 24 | 0.0003 | 1,2,3,6,7,9,10 |
| DAMA08S | 0.0123 | 27 | 20 | 7.7 | 4.992 | 1.1 | 10 | 7.7011 | 2.09 | 4.958 | 0.7 | 4.5602 | 6.2348 | 24 | 0.0003 | 1,2,3,6,7,9,10 |
| DAMA09S | 0.4278 | 170 | 20 | 7.8 | 39.552 | 0.5 | 10 | 27.9433 | 24.23527 | 52.507 | 4.1961 | 162.74 | 3.8045 | 115 | 0.0003 | 3,4,22,23 |
| DAMA10S | 0.0443 | 170 | 20 | 7.8 | 10.08 | 0.5 | 10 | 27.9433 | 24.23527 | 52.507 | 4.1961 | 162.74 | 3.8045 | 115 | 0.0003 | 3,4,22,23 |
| DAMA11S | 0.1330 | 170 | 20 | 7.8 | 19.776 | 0.5 | 10 | 27.9433 | 24.23527 | 52.507 | 4.1961 | 162.74 | 3.8045 | 115 | 0.0003 | 3,4,22,23 |
| DAMA12S | 0.0990 | 170 | 20 | 7.8 | 16.608 | 0.5 | 10 | 27.9433 | 24.23527 | 52.507 | 4.1961 | 162.74 | 3.8045 | 115 | 0.0003 | 3,4,22,23 |
| DAMA13S | 0.9670 | 170 | 20 | 7.8 | 67.872 | 0.5 | 10 | 27.9433 | 24.23527 | 52.507 | 4.1961 | 162.74 | 3.8045 | 115 | 0.0003 | 3,4,22,23 |
| DAMA14S | 0.2716 | 170 | 20 | 7.8 | 30.048 | 0.5 | 10 | 27.9433 | 24.23527 | 52.507 | 4.1961 | 162.74 | 3.8045 | 115 | 0.0003 | 3,4,22,23 |
| DAMA15S | 0.0160 | 109.9 | 21 | 6.93 | 6.816 | 2.4 | 10 | 40.0 | 2.43 | 85.1 | 1.23 | 10 | 106 | 12.5 | 0.0003 | 1,2,3,6,7,24 |
| DAMA16S | 0.0298 | 109.9 | 21 | 6.93 | 15.744 | 3.4 | 10 | 40.0 | 2.43 | 85.1 | 1.23 | 10 | 106 | 12.5 | 0.0003 | 1,2,3,6,7,24 |
| DAMA17S | 0.0393 | 109.9 | 21 | 7.43 | 38.304 | 3.4 | 10 | 40.0 | 2.43 | 85.1 | 1.23 | 10 | 106 | 13.875 | 0.0003 | 1,2,3,6,7,19,24 |
| DAMA18S | 0.0219 | 109.9 | 21 | 7.43 | 17.952 | 2.4 | 10 | 40.0 | 2.43 | 85.1 | 1.23 | 10 | 106 | 13.875 | 0.0003 | 1,2,3,6,7,19,24 |
| DAMA19S | 0.0111 | 109.9 | 21 | 7.82 | 18.144 | 2.4 | 10 | 40.0 | 2.43 | 85.1 | 1.23 | 10 | 106 | 14.5 | 0.0003 | 1,2,3,6,7,19,24 |
| DAMA20S | 0.0189 | 109.9 | 21 | 7.82 | 38.112 | 3.4 | 10 | 40.0 | 2.43 | 85.1 | 1.23 | 10 | 106 | 14.5 | 0.0003 | 1,2,3,6,7,19,24 |
| DAMA21S | 0.0898 | 109.9 | 21 | 6.93 | 44.16 | 4.4 | 10 | 40.0 | 2.43 | 85.1 | 1.23 | 10 | 106 | 12.5 | 0.0003 | 1,2,3,6,7,24 |
| DAMA22S | 0.1076 | 109.9 | 21 | 6.93 | 69.024 | 6.1 | 10 | 40.0 | 2.43 | 85.1 | 1.23 | 10 | 106 | 12.5 | 0.0003 | 1,2,3,6,7,24 |
| DAMA23S | 0.0458 | 109.9 | 21 | 7.43 | 54.912 | 4.4 | 10 | 40.0 | 2.43 | 85.1 | 1.23 | 10 | 106 | 13.875 | 0.0003 | 1,2,3,6,7,19,24 |
| DAMA24S | 0.0288 | 109.9 | 21 | 7.82 | 65.088 | 4.4 | 10 | 40.0 | 2.43 | 85.1 | 1.23 | 10 | 106 | 14.5 | 0.0003 | 1,2,3,6,7,19,24 |

# Appendix E. BLM Table

| | Model Output | | Model Input | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BLM Data Label | Critical Accumulation | Hard-ness (mg/L) | Temp (ºC) | pH | Dissolved LC50 (μg/L) | DOC (mg/L) | Humic Acid (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | Cl (mg/L) | Alkalinity (mg/L) | S (mg/L) | Notes |
| DAMA25S | 0.1143 | 52 | 18.2 | 7.8 | 24.96 | 1.1 | 10 | 14 | 3.5 | 12 | 2.9 | 23 | 11 | 45 | 0.0003 | 1,2,3,6,7,9,25 |
| DAMA26S | 0.0917 | 105 | 20.3 | 7.9 | 28.8 | 1.1 | 10 | 29 | 6.8 | 29 | 5.3 | 57 | 21 | 79 | 0.0003 | 1,2,3,6,7,9,25 |
| DAMA27S | 0.1053 | 106 | 19.7 | 8.1 | 36.48 | 1.1 | 10 | 29 | 6.8 | 29 | 5.3 | 57 | 21 | 82 | 0.0003 | 1,2,3,6,7,9,25 |
| DAMA28S | 0.1538 | 207 | 19.9 | 8.3 | 66.24 | 1.1 | 10 | 58 | 13 | 62 | 8.2 | 127 | 40 | 166 | 0.0003 | 1,2,3,6,7,9,25 |
| DAMA29S | 0.0062 | 7.1 | 24 | 8.55 | 4.608 | 0.5 | 10 | 1.15182 | 1.027387 | 3.5102 | 2.8052 | 6.8159 | 2.5434 | 56 | 0.0003 | 1,2,3,4,6,7,56 |
| DAMA30S | 0.2536 | 20.6 | 24 | 6.97 | 7.104 | 0.5 | 10 | 3.39973 | 2.9458 | 2.5478 | 2.1356 | 19.776 | 1.9363 | 60 | 0.0003 | 1,2,3,4,6,7,56 |
| DAMA31S | 0.0119 | 23 | 24 | 8.52 | 6.24 | 0.5 | 10 | 3.79581 | 3.289 | 2.8446 | 2.3845 | 22.08 | 2.1619 | 64 | 0.0003 | 1,2,3,4,6,7,56 |
| DAPC01S | 0.0087 | 48 | 18 | 8.03 | 10.944 | 2.288 | 10 | 14.1077 | 3.111984 | 1.36 | 0.57 | 3.55 | 1.25 | 42 | 0.0003 | 1,2,3,6,7,15,26 |
| DAPC02S | 0.0052 | 48 | 18 | 8.03 | 8.6976 | 2.816 | 10 | 14.1077 | 3.111984 | 1.36 | 0.57 | 3.55 | 1.25 | 42 | 0.0003 | 1,2,3,6,7,15,26 |
| DAPC03S | 0.0043 | 48 | 18 | 8.01 | 6.9504 | 2.728 | 10 | 14.1077 | 3.111984 | 1.36 | 0.57 | 3.55 | 1.25 | 44 | 0.0003 | 1,2,3,6,7,15,26 |
| DAPC04S | 0.0057 | 44 | 18 | 8.04 | 10.368 | 3.08 | 10 | 12.932 | 2.852652 | 1.24 | 0.57 | 3.25 | 1.15 | 42 | 0.0003 | 1,2,3,6,7,15,26 |
| DAPC05S | 0.0879 | 31 | 18 | 6.66 | 53.184 | 12.2094 | 10 | 7.37407 | 3.063455 | 1.6792 | 0.5 | 6.3292 | 1.2917 | 27 | 0.0003 | 1,2,3,6,7,27,28 |
| DAPC06S | 0.0490 | 29 | 18 | 6.97 | 53.088 | 11.3373 | 10 | 6.89832 | 2.865813 | 1.5708 | 0.5 | 5.9208 | 1.2083 | 27 | 0.0003 | 1,2,3,6,7,27,28 |
| DAPC07S | 0.0285 | 28 | 18 | 7.2 | 51.168 | 11.3373 | 10 | 6.66045 | 2.766992 | 1.5167 | 0.5 | 5.7167 | 1.1667 | 22 | 0.0003 | 1,2,3,6,7,27,28 |
| DAPC08S | 0.0268 | 88 | 18 | 7.01 | 93.312 | 24.4188 | 10 | 20.9464 | 8.5194 | 16.466 | 1.8787 | 22.629 | 18.986 | 20 | 0.0003 | 1,2,3,6,7,27,29 |
| DAPC09S | 0.0187 | 100 | 18 | 7.55 | 191.04 | 29.6514 | 10 | 23.9296 | 9.4686 | 21.207 | 2.1631 | 25.98 | 23.28 | 20 | 0.0003 | 1,2,3,6,7,27,29 |
| DAPC10S | 0.0701 | 82 | 18 | 6.99 | 204.48 | 27.9072 | 10 | 19.4548 | 8.0448 | 14.095 | 1.7365 | 20.953 | 16.84 | 18 | 0.0003 | 1,2,3,6,7,27,29 |
| DAPC11S | 0.0460 | 84 | 18 | 7.01 | 158.4 | 27.9072 | 10 | 19.952 | 8.203 | 14.885 | 1.7839 | 21.512 | 17.555 | 17 | 0.0003 | 1,2,3,6,7,27,29 |
| DAPC12S | 0.0100 | 16 | 18 | 7.39 | 34.08 | 11.6124 | 10 | 4.13844 | 1.379481 | 0.16 | 0.3 | 6.72 | 0.32 | 11 | 0.0003 | 1,2,3,6,7,27,28 |
| DAPC13S | 0.0137 | 151 | 18 | 7.76 | 75.648 | 12.5801 | 10 | 36.7872 | 14.39533 | 10.786 | 1.4 | 62.018 | 19.684 | 44 | 0.0003 | 1,2,3,6,7,27,28 |
| DAPC14S | 0.0053 | 96 | 18 | 8.1 | 108.48 | 27.0956 | 10 | 22.0888 | 9.939946 | 6.8571 | 1.4 | 19.911 | 4.2667 | 91 | 0.0003 | 1,2,3,6,7,27,28 |
| DAPC15S | 0.0137 | 26 | 18 | 7.24 | 73.344 | 24.1925 | 10 | 7.37925 | 1.844812 | 0.26 | 0.3 | 11.624 | 2.6 | 4 | 0.0003 | 1,2,3,6,7,27,28 |
| DAPC16S | 0.0564 | 84 | 18 | 7.08 | 81.312 | 12.5801 | 10 | 20.4644 | 8.008 | 6 | 1.4 | 34.5 | 10.95 | 13 | 0.0003 | 1,2,3,6,7,27,28 |
| DAPC17S | 0.0633 | 92 | 18 | 7.22 | 176.64 | 20.3217 | 10 | 22.4134 | 8.770667 | 6.5714 | 1.4 | 37.786 | 11.993 | 19 | 0.0003 | 1,2,3,6,7,27,28 |
| DAPC18S | 0.0056 | 47 | 18 | 8.03 | 8.928 | 2.728 | 10 | 13.8137 | 3.047151 | 1.33 | 0.57 | 3.47 | 1.23 | 42.5 | 0.0003 | 1,2,3,6,7,15,26 |
| DAPC19S | 0.0119 | 97 | 18 | 8.03 | 17.088 | 2.728 | 10 | 34 | 2.9 | 1.3 | 0.57 | 51.3 | 1.2 | 42.5 | 0.0003 | 1,2,3,6,7,15,30 |
| DAPC20S | 0.0160 | 147 | 18 | 8.03 | 22.752 | 2.728 | 10 | 54 | 2.9 | 1.3 | 0.57 | 99.3 | 1.2 | 42.5 | 0.0003 | 1,2,3,6,7,15,30 |
| DAPC21S | 0.0168 | 247 | 18 | 8.03 | 26.208 | 2.728 | 10 | 94 | 2.9 | 1.3 | 0.57 | 147.3 | 1.2 | 42.5 | 0.0003 | 1,2,3,6,7,15,30 |
| DAPC22S | 0.0171 | 97 | 18 | 8.03 | 24.192 | 2.728 | 10 | 13.6 | 15.2 | 1.3 | 0.57 | 51.3 | 1.2 | 42.5 | 0.0003 | 1,2,3,6,7,15,30 |
| DAPC23S | 0.0155 | 147 | 18 | 8.03 | 24.096 | 2.728 | 10 | 13.6 | 27.5 | 1.3 | 0.57 | 99.3 | 1.2 | 42.5 | 0.0003 | 1,2,3,6,7,15,30 |
| DAPC24S | 0.0133 | 247 | 18 | 8.03 | 24.096 | 2.728 | 10 | 13.6 | 51.9 | 1.3 | 0.57 | 147.3 | 1.2 | 42.5 | 0.0003 | 1,2,3,6,7,15,30 |
| SCSP01S | 0.1034 | 52 | 24.5 | 7.5 | 17.28 | 1.1 | 10 | 15.2833 | 3.371316 | 1.47 | 0.57 | 3.84 | 1.36 | 55 | 0.0003 | 1,2,3,6,7,8 |
| GAPS01F | 0.1153 | 44.9 | 15 | 7.7 | 21.12 | 1.1 | 10 | 13.1965 | 2.911001 | 1.27 | 0.57 | 3.32 | 1.17 | 42.7 | 0.0003 | 1,2,3,6,7,8 |
| GAPS02F | 0.0888 | 44.9 | 15 | 7.7 | 18.24 | 1.1 | 10 | 13.1965 | 2.911001 | 1.27 | 0.57 | 3.32 | 1.17 | 42.7 | 0.0003 | 1,2,3,6,7,8 |

## Appendix E. BLM Table

|  | Model Output |  | Model Input |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BLM Data Label | Critical Accumulation | Hardness (mg/L) | Temp (ºC) | pH | Dissolved LC50 (µg/L) | DOC (mg/L) | Humic Acid (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | Cl (mg/L) | Alkalinity (mg/L) | S (mg/L) | Notes |
| HYAZ01S | 0.1511 | 290 | 25 | 6.23 | 16.32 | 0.5 | 10 | 47.8602 | 41.47 | 89.821 | 7.178 | 278.4 | 6.5081 | 235 | 0.0003 | 1,2,3,4,5,13 |
| HYAZ02S | 0.1074 | 290 | 25 | 7.51 | 23.04 | 0.5 | 10 | 47.8602 | 41.47 | 89.821 | 7.178 | 278.4 | 6.5081 | 235 | 0.0003 | 1,2,3,4,5,13 |
| HYAZ03S | 0.2392 | 290 | 25 | 8.38 | 83.52 | 0.5 | 10 | 47.8602 | 41.47 | 89.821 | 7.178 | 278.4 | 6.5081 | 235 | 0.0003 | 1,2,3,4,5,13 |
| HYAZ04S | 0.0794 | 20.5 | 21 | 7.15 | 23.328 | 2.8 | 10 | 5.1 | 1.9 | 5.3 | 0.8 | 9.3 | 10.0 | 6.7 | 0.0003 | 3,31 |
| HYAZ05S | 0.0768 | 20.5 | 21 | 7.15 | 22.848 | 2.8 | 10 | 5.1 | 1.9 | 5.3 | 0.8 | 9.3 | 10.0 | 6.7 | 0.0003 | 3,31 |
| HYAZ06S | 0.2314 | 20.6 | 21 | 7.14 | 7.872 | 0.5 | 10 | 5.3 | 1.8 | 5.5 | 0.8 | 7.0 | 9.7 | 11.0 | 0.0003 | 3,31 |
| HYAZ07S | 0.3312 | 20.6 | 21 | 7.14 | 9.6 | 0.5 | 10 | 5.3 | 1.8 | 5.5 | 0.8 | 7.0 | 9.7 | 11.0 | 0.0003 | 3,31 |
| ACLY01S | 29.5658 | 42 | 18.5 | 7.0 | 7968 | 1.1 | 10 | 12.3442 | 2.722986 | 1.3 | 0.57 | 3.4 | 1.2 | 47 | 0.0003 | 1,2,3,6,7,8 |
| CHDE01S | 25.2731 | 44 | 20 | 7.40 | 709.44 | 0.5 | 10 | 6.99 | 6.06 | 13.1 | 1.05 | 40.7 | 0.951 | 32.5 | 0.0003 | 1,2,3,4,32,33 |
| SCPL01S | 2.9865 | 167 | 22 | 7.6 | 153.6 | 0.5 | 10 | 27.5609 | 23.881 | 51.724 | 4.1335 | 160.32 | 3.7478 | 115 | 0.0003 | 1,2,3,4,6,7,20 |
| ONAP01S | 0.9139 | 169 | 12 | 8 | 67.2 | 0.5 | 10 | 27.891 | 24.167 | 52.344 | 4.183 | 162.24 | 3.7927 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| ONCL01S | 1.0007 | 169 | 12 | 8.1 | 76.8 | 0.5 | 10 | 27.891 | 24.167 | 52.344 | 4.183 | 162.24 | 3.7927 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| ONCL02S | 0.5538 | 169 | 12 | 8.25 | 57.6 | 0.5 | 10 | 27.891 | 24.167 | 52.344 | 4.183 | 162.24 | 3.7927 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| ONCL03F | 2.8512 | 205 | 13.7 | 7.73 | 367 | 3.3 | 10 | 49.8 | 19.6 | 4 | 0.64 | 10 | 0.44 | 178 | 0.0003 | 1,2,6,7,34 |
| ONCL04F | 1.5731 | 69.9 | 13.7 | 8.54 | 186 | 1.5 | 10 | 18.4 | 5.8 | 1.405 | 0.2248 | 3.5126 | 0.1546 | 174 | 0.0003 | 1,2,6,7,35 |
| ONCL05F | 0.4400 | 18 | 13.7 | 8.07 | 36.8 | 0.75 | 10 | 4.8 | 1.5 | 0.3618 | 0.0579 | 0.9045 | 0.0398 | 183 | 0.0003 | 1,2,6,7,35 |
| ONCL06F | 1.9714 | 204 | 13.7 | 7.61 | 232 | 3.3 | 10 | 64.7 | 10.3 | 4.1005 | 0.6561 | 10.251 | 0.4511 | 77.9 | 0.0003 | 1,2,6,7,35 |
| ONCL07F | 5.2514 | 83 | 13.7 | 7.4 | 162 | 1.7 | 10 | 20.4 | 7.8 | 1.6683 | 0.2669 | 4.1709 | 0.1835 | 70 | 0.0003 | 1,2,6,7,35 |
| ONCL08F | 1.2778 | 31.4 | 13.7 | 8.32 | 73.6 | 0.94 | 10 | 7.9 | 2.7 | 0.6312 | 0.101 | 1.5779 | 0.0694 | 78.3 | 0.0003 | 1,2,6,7,35 |
| ONCL09F | 0.3591 | 160 | 13.7 | 7.53 | 91 | 2.8 | 10 | 57.5 | 4.0 | 3.2161 | 0.5146 | 8.0402 | 0.3538 | 26.0 | 0.0003 | 1,2,6,7,35 |
| ONCL10F | 0.3318 | 74.3 | 13.7 | 7.57 | 44.4 | 1.5 | 10 | 24.7 | 3.1 | 1.4935 | 0.239 | 3.7337 | 0.1643 | 22.7 | 0.0003 | 1,2,6,7,35 |
| ONCL11F | 0.1192 | 26.4 | 13.7 | 7.64 | 15.7 | 0.87 | 10 | 6.0 | 2.8 | 0.5307 | 0.0849 | 1.3266 | 0.0584 | 20.1 | 0.0003 | 1,2,6,7,35 |
| ONGO01F | 1.3932 | 83.1 | 7.15 | 7.63 | 137.28 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONGO02F | 0.3615 | 83.1 | 7.15 | 7.63 | 83.52 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONGO03F | 3.5018 | 83.1 | 7.15 | 7.63 | 191.04 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONKI01R | 4.9807 | 33 | 13.5 | 7.29 | 157.44 | 2.496 | 10 | 8.77741 | 2.698479 | 7.3188 | 1.15 | 6.1426 | 6.8124 | 29 | 0.0003 | 1,2,3,6,7,27,36 |
| ONKI02F | 0.4054 | 25 | 12 | 7.30 | 31.68 | 1.3 | 10 | 6.8 | 1.8 | 5.0 | 0.6 | 4.2 | 6 | 24 | 0.0003 | 3,37 |
| ONKI03F | 0.9203 | 20 | 9.4 | 7.29 | 44.16 | 1.3 | 10 | 5.7845 | 1.6889 | 4.4589 | 0.7 | 2.589 | 5.3402 | 22 | 0.0003 | 1,2,3,6,7,10,38 |
| ONKI04F | 0.1617 | 31.1 | 13.3 | 7.30 | 49 | 3.2 | 10 | 8.01999 | 2.695987 | 5.12 | 0.653 | 4 | 4.5 | 29.6 | 0.0003 | 1,2,6,7,39 |
| ONKI05F | 0.1736 | 31.1 | 13.3 | 7.30 | 51 | 3.2 | 10 | 8.01999 | 2.695987 | 5.12 | 0.653 | 4 | 4.5 | 29.6 | 0.0003 | 1,2,6,7,39 |
| ONKI06F | 0.1461 | 31.6 | 15.7 | 7.50 | 58 | 3.2 | 10 | 8.14893 | 2.739331 | 5.12 | 0.653 | 3.5 | 4.2 | 30.4 | 0.0003 | 1,2,6,7,39 |
| ONKI07F | 0.4829 | 31 | 15.3 | 7.20 | 78 | 3.2 | 10 | 7.99421 | 2.687318 | 5.12 | 0.653 | 2.3 | 3.1 | 29.7 | 0.0003 | 1,2,6,7,39 |
| ONMY01S | 1.3925 | 169 | 12 | 8.2 | 105.6 | 0.5 | 10 | 27.891 | 24.167 | 52.344 | 4.183 | 162.24 | 3.7927 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| ONMY02S | 0.5765 | 169 | 12 | 7.95 | 48 | 0.5 | 10 | 27.891 | 24.167 | 52.344 | 4.183 | 162.24 | 3.7927 | 117 | 0.0003 | 1,2,3,4,6,7,20 |

# Appendix E. BLM Table

| | Model Output | | Model Input | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BLM Data Label | Critical Accumulation | Hard-ness (mg/L) | Temp (ºC) | pH | Dissolved LC50 (µg/L) | DOC (mg/L) | Humic Acid (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | Cl (mg/L) | Alkalinity (mg/L) | S (mg/L) | Notes |
| ONMY03S | 0.7648 | 169 | 12 | 7.95 | 57.6 | 0.5 | 10 | 27.891 | 24.167 | 52.344 | 4.183 | 162.24 | 3.7927 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| ONMY04R | 0.1249 | 44.1 | 11.5 | 7.7 | 40 | 2 | 10 | 9.07 | 4.1 | 4.75 | 1.02 | 3.3 | 1.56 | 49.7 | 0.0003 | 40 |
| ONMY05R | 0.0917 | 44.6 | 11.5 | 7.8 | 19 | 0.99 | 10 | 7.37 | 6.1 | 6.24 | 0.8 | 1.31 | 3.82 | 53.1 | 0.0003 | 40 |
| ONMY06R | 0.0376 | 38.7 | 12 | 7.62 | 3.4 | 0.33 | 10 | 2.37 | 8.65 | 13.7 | 0.15 | 0.36 | 20.3 | 40 | 0.0003 | 51 |
| ONMY07R | 0.1465 | 39.3 | 12 | 7.61 | 8.1 | 0.36 | 10 | 14.1 | 1.8 | 13.2 | 0.1 | 0.36 | 19.9 | 41.7 | 0.0003 | 51 |
| ONMY08R | 0.1881 | 89.5 | 12 | 8.21 | 17.2 | 0.345 | 10 | 15 | 11.85 | 10.05 | 1 | 0.36 | 6.73 | 97.5 | 0.0003 | 51 |
| ONMY09R | 0.5172 | 89.67 | 12 | 8.15 | 32 | 0.345 | 10 | 28.9 | 3.15 | 32.5 | 0.5 | 0.36 | 45.2 | 97.25 | 0.0003 | 51 |
| ONMY10F | 0.3824 | 23 | 12.2 | 7.1 | 26.88 | 1.4 | 10 | 6.1 | 1.8 | 4.4 | 0.4 | 5.8 | 6 | 22 | 0.0003 | 3,37 |
| ONMY11F | 0.1589 | 23 | 12.2 | 7.1 | 16.32 | 1.4 | 10 | 6.1 | 1.8 | 4.4 | 0.4 | 5.8 | 6 | 22 | 0.0003 | 3,37 |
| ONMY12F | 0.1059 | 23 | 12.2 | 7.4 | 17.28 | 1.3 | 10 | 6.8 | 1.8 | 5.0 | 0.6 | 4.2 | 6 | 22 | 0.0003 | 3,37 |
| ONMY13F | 0.4633 | 23 | 12.2 | 7.1 | 27.84 | 1.3 | 10 | 6.8 | 1.8 | 5.0 | 0.6 | 4.2 | 6 | 22 | 0.0003 | 3,37 |
| ONMY14F | 0.4998 | 194 | 12.8 | 7.84 | 169 | 3.3 | 10 | 55.1 | 13.7 | 4 | 0.64 | 10 | 0.44 | 174 | 0.0003 | 1,2,6,7,34 |
| ONMY15F | 0.1118 | 194 | 12.8 | 7.84 | 85.3 | 3.3 | 10 | 55.1 | 13.7 | 4 | 0.64 | 10 | 0.44 | 174 | 0.0003 | 1,2,6,7,34 |
| ONMY16F | 0.1069 | 194 | 12.8 | 7.84 | 83.3 | 3.3 | 10 | 55.1 | 13.7 | 4 | 0.64 | 10 | 0.44 | 174 | 0.0003 | 1,2,6,7,34 |
| ONMY17F | 0.1627 | 194 | 12.8 | 7.84 | 103 | 3.3 | 10 | 55.1 | 13.7 | 4 | 0.64 | 10 | 0.44 | 174 | 0.0003 | 1,2,6,7,34 |
| ONMY18F | 1.5525 | 194 | 12.8 | 7.84 | 274 | 3.3 | 10 | 55.1 | 13.7 | 4 | 0.64 | 10 | 0.44 | 174 | 0.0003 | 1,2,6,7,34 |
| ONMY19F | 0.2605 | 194 | 12.8 | 7.84 | 128 | 3.3 | 10 | 55.1 | 13.7 | 4 | 0.64 | 10 | 0.44 | 174 | 0.0003 | 1,2,6,7,34 |
| ONMY20F | 0.9538 | 194 | 12.8 | 7.84 | 221 | 3.3 | 10 | 55.1 | 13.7 | 4 | 0.64 | 10 | 0.44 | 174 | 0.0003 | 1,2,6,7,34 |
| ONMY21F | 0.4717 | 194 | 12.8 | 7.84 | 165 | 3.3 | 10 | 55.1 | 13.7 | 4 | 0.64 | 10 | 0.44 | 174 | 0.0003 | 1,2,6,7,34 |
| ONMY22F | 0.7244 | 194 | 12.8 | 7.84 | 197 | 3.3 | 10 | 55.1 | 13.7 | 4 | 0.64 | 10 | 0.44 | 174 | 0.0003 | 1,2,6,7,34 |
| ONMY23F | 4.6605 | 194 | 12.8 | 7.84 | 514 | 3.3 | 10 | 55.1 | 13.7 | 4 | 0.64 | 10 | 0.44 | 174 | 0.0003 | 1,2,6,7,34 |
| ONMY24F | 1.1894 | 194 | 12.8 | 7.84 | 243 | 3.3 | 10 | 55.1 | 13.7 | 4 | 0.64 | 10 | 0.44 | 174 | 0.0003 | 1,2,6,7,34 |
| ONMY25F | 0.0613 | 9.2 | 15.5 | 6.96 | 2.688 | 0.5 | 10 | 2.3 | 0.7 | 2 | 0.2 | 4.6 | 2.1 | 11 | 0.0003 | 3,41 |
| ONMY26F | 0.3626 | 31 | 15.3 | 7.2 | 68 | 3.2 | 10 | 7.99421 | 2.687318 | 5.12 | 0.653 | 2.3 | 3.1 | 29.7 | 0.0003 | 1,2,6,7,39 |
| ONMY27F | 0.0770 | 36.1 | 11.4 | 7.6 | 18 | 1.31 | 10 | 4.03 | 7.13 | 1.56 | 0.26 | 1.49 | 0.88 | 36.6 | 0.0003 | 40 |
| ONMY28F | 0.8944 | 36.2 | 11.5 | 6.1 | 12 | 1.36 | 10 | 3.93 | 7.27 | 1.57 | 0.28 | 1.47 | 0.87 | 8.5 | 0.0003 | 40 |
| ONMY29F | 0.5568 | 20.4 | 11.7 | 7.5 | 5.7 | 0.15 | 10 | 3.13 | 2.77 | 2.62 | 0.25 | 0.36 | 1.48 | 23 | 0.0003 | 40 |
| ONMY30F | 0.2504 | 45.2 | 11.7 | 7.7 | 35 | 1.23 | 10 | 9.7 | 4.43 | 5.33 | 0.97 | 3.41 | 1.47 | 50 | 0.0003 | 40 |
| ONMY31F | 1.1775 | 45.4 | 11.8 | 6.3 | 18 | 1.22 | 10 | 9.7 | 4.43 | 5.02 | 0.98 | 3.37 | 1.37 | 10.9 | 0.0003 | 40 |
| ONMY32F | 0.5318 | 41.9 | 12.3 | 7.9 | 17 | 0.33 | 10 | 6.6 | 5.97 | 5.89 | 0.63 | 1.11 | 3.37 | 48.3 | 0.0003 | 40 |
| ONMY33F | 1.2884 | 214 | 7.64 | 7.94 | 96.96 | 0.27 | 10 | 49.4 | 24.1 | 10.3 | 1.75 | 18.9 | 5.28 | 198 | 0.0003 | 1,2,3,6,7,54,55 |
| ONMY34F | 3.8957 | 220 | 7.74 | 7.92 | 295.68 | 0.36 | 10 | 51.2 | 25.5 | 8.36 | 2.1 | 24 | 4.64 | 197 | 0.0003 | 1,2,3,6,7,54,55 |
| ONMY35F | 4.4437 | 105 | 7.77 | 7.82 | 89.28 | 0.1 | 10 | 23.1 | 11.8 | 3.54 | 3.22 | 17.1 | 2.91 | 94.1 | 0.0003 | 1,2,3,6,7,54,55 |
| ONMY36F | 1.9096 | 98.2 | 8.49 | 7.89 | 34.464 | 0.045 | 10 | 22.3 | 11.2 | 3.58 | 0.9 | 11.5 | 2.85 | 87.9 | 0.0003 | 1,2,3,6,7,54,55 |

## Appendix E. BLM Table

| | Model Output | | Model Input | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BLM Data Label | Critical Accumulation | Hard-ness (mg/L) | Temp (ºC) | pH | Dissolved LC50 (µg/L) | DOC (mg/L) | Humic Acid (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | Cl (mg/L) | Alkalinity (mg/L) | S (mg/L) | Notes |
| ONMY37F | 1.7297 | 104 | 16.3 | 7.83 | 52.224 | 0.28 | 10 | 22.4 | 11.4 | 3.76 | 2.72 | 12.4 | 3.01 | 97.6 | 0.0003 | 1,2,3,6,7,54,55 |
| ONNE01F | 3.1060 | 83.1 | 7.15 | 7.63 | 182.4 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONNE02F | 3.5466 | 83.1 | 7.15 | 7.63 | 192 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONNE03F | 0.5132 | 83.1 | 7.15 | 7.63 | 96 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONNE04F | 0.6617 | 83.1 | 7.15 | 7.63 | 105.6 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONNE05F | 1.0574 | 83.1 | 7.15 | 7.63 | 124.8 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONNE06F | 1.6007 | 83.1 | 7.15 | 7.63 | 144 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONNE07F | 4.0021 | 83.1 | 7.15 | 7.63 | 201.6 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONNE08F | 2.2920 | 83.1 | 7.15 | 7.63 | 163.2 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONNE09F | 3.1060 | 83.1 | 7.15 | 7.63 | 182.4 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONNE10F | 5.4103 | 83.1 | 7.15 | 7.63 | 230.4 | 2.58 | 10 | 22.3428 | 6.313221 | 10.259 | 7.5024 | 25.1 | 9.994 | 62.5 | 0.0003 | 1,2,3,6,7,52 |
| ONTS01F | 0.2050 | 23 | 12.2 | 7.4 | 24.96 | 1.3 | 10 | 6.8 | 1.8 | 5.0 | 0.6 | 4.2 | 6 | 22 | 0.0003 | 3,37 |
| ONTS02F | 0.1161 | 23 | 12.2 | 7.4 | 18.24 | 1.3 | 10 | 6.8 | 1.8 | 5.0 | 0.6 | 4.2 | 6 | 22 | 0.0003 | 3,37 |
| ONTS03F | 0.7109 | 23 | 12.2 | 7.1 | 36.48 | 1.4 | 10 | 6.1 | 1.8 | 4.4 | 0.4 | 5.8 | 6 | 22 | 0.0003 | 3,37 |
| ONTS04F | 0.3750 | 23 | 12.2 | 7.1 | 24.96 | 1.3 | 10 | 6.8 | 1.8 | 5.0 | 0.6 | 4.2 | 6 | 22 | 0.0003 | 3,37 |
| ONTS05F | 0.3517 | 13 | 12 | 7.15 | 9.792 | 0.5 | 10 | 2.14546 | 1.859 | 4.0264 | 0.3218 | 12.48 | 0.2917 | 12 | 0.0003 | 1,2,3,4,6,7,20 |
| ONTS06F | 0.8340 | 46 | 12 | 7.55 | 23.136 | 0.5 | 10 | 7.59162 | 6.578 | 14.247 | 1.1386 | 44.159 | 1.0323 | 35 | 0.0003 | 1,2,3,4,6,7,20 |
| ONTS07F | 0.9241 | 182 | 12 | 8.12 | 79.2 | 0.5 | 10 | 30.0364 | 26.026 | 56.37 | 4.5048 | 174.72 | 4.0844 | 125 | 0.0003 | 1,2,3,4,6,7,20 |
| ONTS08F | 0.3954 | 359 | 12 | 8.49 | 123.264 | 0.5 | 10 | 59.2477 | 51.337 | 111.19 | 8.8858 | 344.64 | 8.0566 | 243 | 0.0003 | 1,2,3,4,6,7,20 |
| ONTS09F | 1.1161 | 36.6 | 12 | 7.71 | 7.4 | 0.055 | 10 | 6.36 | 4.73 | 4.84 | 0.22 | 0.94 | 2.79 | 40.8 | 0.0003 | 51 |
| ONTS10F | 0.8313 | 34.6 | 12 | 7.79 | 12.5 | 0.19 | 10 | 7.82 | 3.17 | 9.98 | 0.11 | 0.73 | 8.34 | 40.6 | 0.0003 | 51 |
| ONTS11F | 0.8622 | 38.3 | 12 | 7.71 | 14.3 | 0.24 | 10 | 6.33 | 5.1 | 5.27 | 0.6 | 0.99 | 2.96 | 43.6 | 0.0003 | 51 |
| ONTS12F | 1.7785 | 35.7 | 12 | 7.74 | 18.3 | 0.17 | 10 | 8.15 | 3.38 | 10 | 0.37 | 0.76 | 9.1 | 43.3 | 0.0003 | 51 |
| SACO01F | 2.9901 | 214 | 7.64 | 7.94 | 218.88 | 0.27 | 10 | 49.4 | 24.1 | 10.3 | 1.75 | 18.9 | 5.28 | 198 | 0.0003 | 1,2,3,6,7,54,55 |
| SACO02F | 2.6420 | 220 | 7.74 | 7.92 | 198.72 | 0.36 | 10 | 51.2 | 25.5 | 8.36 | 2.1 | 24 | 4.64 | 197 | 0.0003 | 1,2,3,6,7,54,55 |
| SACO03F | 3.2456 | 105 | 7.77 | 7.82 | 63.936 | 0.1 | 10 | 23.1 | 11.8 | 3.54 | 3.22 | 17.1 | 2.91 | 94.1 | 0.0003 | 1,2,3,6,7,54,55 |
| SACO04F | 2.6405 | 98.2 | 8.49 | 7.89 | 48 | 0.045 | 10 | 22.3 | 11.2 | 3.58 | 0.9 | 11.5 | 2.85 | 87.9 | 0.0003 | 1,2,3,6,7,54,55 |
| SACO05F | 3.0680 | 104 | 16.3 | 7.83 | 85.44 | 0.28 | 10 | 22.4 | 11.4 | 3.76 | 2.72 | 12.4 | 3.01 | 97.6 | 0.0003 | 1,2,3,6,7,54,55 |
| ACAL01F | 9.7513 | 54 | 10.5 | 7.3 | 137.28 | 1.1 | 10 | 15.0937 | 3.6371 | 6.8831 | 0.7 | 12.163 | 9.6854 | 43 | 0.0003 | 1,2,3,6,7,9,10 |
| GIEL01S | 2.6186 | 173 | 22 | 8.05 | 192 | 0.5 | 10 | 28.5511 | 24.739 | 53.583 | 4.282 | 166.08 | 3.8824 | 117 | 0.0003 | 1,2,3,6,7,20 |
| NOCR01F | 29.9790 | 72.2 | 25 | 7.50 | 81216 | 1.5 | 10 | 17.8079 | 6.7507 | 15.26 | 1.6 | 73.841 | 54.15 | 42.5 | 0.0003 | 2,3,6,7,16,42 |
| PIPR01S | 11.3981 | 103 | 22 | 7.4 | 297.6 | 0.5 | 10 | 28.4667 | 7.773195 | 27.778 | 2.6358 | 29.602 | 53.021 | 65 | 0.0003 | 1,2,3,4,6,48 |
| PIPR02S | 4.9570 | 103 | 22 | 7.4 | 115.2 | 0.5 | 10 | 28.4667 | 7.773195 | 27.778 | 2.6358 | 29.602 | 53.021 | 65 | 0.0003 | 1,2,3,4,6,48 |
| PIPR03S | 9.4256 | 263 | 22 | 7.4 | 374.4 | 0.5 | 10 | 72.6868 | 19.84806 | 36.487 | 3.4623 | 77.901 | 130.77 | 65 | 0.0003 | 1,2,3,4,6,48 |

## Appendix E.  BLM Table

| | Model Output | | Model Input | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BLM Data Label | Critical Accumulation | Hard-ness (mg/L) | Temp (ºC) | pH | Dissolved LC50 (µg/L) | DOC (mg/L) | Humic Acid (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | Cl (mg/L) | Alkalinity (mg/L) | S (mg/L) | Notes |
| PIPR04S | 1.2005 | 52 | 24.5 | 7.4 | 52.8 | 1.1 | 10 | 15.2833 | 3.371316 | 1.47 | 0.57 | 3.84 | 1.36 | 55 | 0.0003 | 1,2,3,6,7,8 |
| PIPR05S | 3.0479 | 52 | 24.5 | 7.4 | 81.6 | 1.1 | 10 | 15.2833 | 3.371316 | 1.47 | 0.57 | 3.84 | 1.36 | 55 | 0.0003 | 1,2,3,6,7,8 |
| PIPR06S | 0.1314 | 290 | 25 | 6.27 | 14.4 | 0.5 | 10 | 47.8602 | 41.47 | 89.821 | 7.178 | 278.4 | 6.5081 | 235 | 0.0003 | 1,2,3,4,5 |
| PIPR07S | 0.3064 | 290 | 25 | 7.14 | 42.24 | 0.5 | 10 | 47.8602 | 41.47 | 89.821 | 7.178 | 278.4 | 6.5081 | 235 | 0.0003 | 1,2,3,4,5 |
| PIPR08S | 0.5392 | 290 | 25 | 8.6 | 192 | 0.5 | 10 | 47.8602 | 41.47 | 89.821 | 7.178 | 278.4 | 6.5081 | 235 | 0.0003 | 1,2,3,4,5 |
| PIPR09S | 0.0890 | 19 | 22 | 7.06 | 4.6272 | 0.6 | 10 | 4.9 | 1.64 | 3.7 | 0.78 | 9.6 | 5.8 | 11.17 | 0.0003 | 3,49 |
| PIPR10S | 0.2665 | 19.5 | 22 | 7.25 | 7.872 | 0.4 | 10 | 5.2 | 1.64 | 5.36 | 0.79 | 2.45 | 8.6 | 12.7 | 0.0003 | 3,49 |
| PIPR11S | 0.5716 | 16.5 | 22 | 6.36 | 30.3072 | 3.3 | 10 | 4.1 | 1.54 | 2.82 | 0.76 | 9.4 | 4.7 | 8.46 | 0.0003 | 3,49 |
| PIPR12S | 0.2950 | 17 | 22 | 6.42 | 20.2176 | 3.1 | 10 | 4.2 | 1.56 | 2.74 | 0.74 | 7.4 | 4.6 | 3.4 | 0.0003 | 3,49 |
| PIPR13S | 0.4162 | 19 | 22 | 6.38 | 34.5312 | 4.3 | 10 | 5 | 1.62 | 7.04 | 0.72 | 10.2 | 12.2 | 7.83 | 0.0003 | 3,49 |
| PIPR14S | 0.2640 | 17 | 22 | 7.15 | 57.4368 | 3.4 | 10 | 4.2 | 1.54 | 2.9 | 1 | 7.4 | 4.7 | 8.74 | 0.0003 | 3,49 |
| PIPR15S | 0.0477 | 17 | 22 | 7.16 | 4.6368 | 0.8 | 10 | 4.5 | 1.46 | 2.68 | 0.78 | 10.9 | 3.8 | 9.3 | 0.0003 | 3,49 |
| PIPR16S | 0.1770 | 17.5 | 22 | 7.13 | 67.4688 | 5.1 | 10 | 4.6 | 1.48 | 2.62 | 0.77 | 10.5 | 3.5 | 8.95 | 0.0003 | 3,49 |
| PIPR17S | 0.0787 | 18.5 | 22 | 7.06 | 80.2464 | 10.5 | 10 | 5 | 1.54 | 2.64 | 0.8 | 10.7 | 3.5 | 8.29 | 0.0003 | 3,49 |
| PIPR18S | 0.1907 | 18.5 | 22 | 6.90 | 174.72 | 15.6 | 10 | 4.9 | 1.5 | 3.54 | 0.99 | 7 | 5.2 | 9.52 | 0.0003 | 3,49 |
| PIPR19S | 3.2305 | 173 | 22 | 8.25 | 278.4 | 0.5 | 10 | 28.5511 | 24.739 | 53.583 | 4.282 | 166.08 | 3.8824 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| PIPR20S | 7.4512 | 173 | 22 | 8.1 | 604.8 | 0.5 | 10 | 28.5511 | 24.739 | 53.583 | 4.282 | 166.08 | 3.8824 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| PIPR21S | 4.8297 | 173 | 22 | 8.15 | 384 | 0.5 | 10 | 28.5511 | 24.739 | 53.583 | 4.282 | 166.08 | 3.8824 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| PIPR22S | 7.6122 | 173 | 22 | 7.3 | 374.4 | 0.5 | 10 | 28.5511 | 24.739 | 53.583 | 4.282 | 166.08 | 3.8824 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| PIPR23S | 7.2327 | 166 | 5 | 8.05 | 432 | 0.5 | 10 | 27.3959 | 23.738 | 51.415 | 4.1088 | 159.36 | 3.7253 | 132.5 | 0.0003 | 1,2,3,4,6,7,20 |
| PIPR24S | 3.4469 | 159 | 12 | 8.35 | 285.12 | 0.5 | 10 | 26.2406 | 22.737 | 49.247 | 3.9355 | 152.64 | 3.5682 | 135 | 0.0003 | 1,2,3,4,6,7,20 |
| PIPR25S | 2.8678 | 168 | 22 | 8.3 | 298.56 | 0.5 | 10 | 27.7259 | 24.024 | 52.034 | 4.1583 | 161.28 | 3.7702 | 142.5 | 0.0003 | 1,2,3,4,6,7,20 |
| PIPR26S | 3.3686 | 167 | 32 | 8.45 | 492.48 | 0.5 | 10 | 27.5609 | 23.881 | 51.724 | 4.1335 | 160.32 | 3.7478 | 140 | 0.0003 | 1,2,3,4,6,7,20 |
| PIPR27S | 0.5950 | 45.54059 | 22 | 7.93 | 53.958366 | 1.1 | 10 | 13.4911 | 2.888065 | 1.6093 | 0.391 | 3.362 | 1.4181 | 42.037464 | 0.0003 | 43,44 |
| PIPR28S | 4.0104 | 45.54059 | 22 | 7.93 | 165.17867 | 1.1 | 10 | 13.4911 | 2.888065 | 91.27 | 0.391 | 3.362 | 143.23 | 42.037464 | 0.0003 | 43,44 |
| PIPR29S | 0.7241 | 44.53969 | 22 | 7.98 | 59.464322 | 1.1 | 10 | 13.1946 | 2.824591 | 1.6093 | 0.391 | 3.362 | 1.4181 | 42.037464 | 0.0003 | 43,44 |
| PIPR30S | 4.0805 | 44.53969 | 22 | 7.98 | 146.45842 | 1.1 | 10 | 13.1946 | 2.824591 | 45.98 | 0.391 | 3.362 | 72.324 | 44.039248 | 0.0003 | 43,44 |
| PIPR31S | 1.8188 | 44.53969 | 22 | 7.99 | 82.038741 | 1.1 | 10 | 13.1946 | 2.824591 | 1.6093 | 0.391 | 3.362 | 1.4181 | 42.53791 | 0.0003 | 43,44 |
| PIPR32S | 4.9213 | 45.54059 | 22 | 7.96 | 124.4346 | 1.1 | 10 | 13.4911 | 2.888065 | 1.6093 | 0.391 | 3.362 | 36.871 | 43.038356 | 0.0003 | 43,44 |
| PIPR33S | 3.9367 | 45.04014 | 22 | 7.79 | 103.759 | 1.1 | 10 | 13.3428 | 2.856328 | 1.6093 | 0.391 | 3.362 | 1.4181 | 46.041032 | 0.0003 | 43,44 |
| PIPR34S | 5.7875 | 45.04014 | 22 | 7.81 | 167.3225 | 1.1 | 10 | 13.3428 | 2.856328 | 47.589 | 0.391 | 99.42 | 1.4181 | 46.041032 | 0.0003 | 43,44 |
| PIPR35S | 3.2914 | 138.1231 | 22 | 7.785 | 120.015 | 1.1 | 10 | 12.892 | 25.75825 | 1.6093 | 0.391 | 3.362 | 72.324 | 43.038356 | 0.0003 | 43,44 |
| PIPR36S | 5.7959 | 151.1347 | 22 | 7.78 | 169.418 | 1.1 | 10 | 14.1065 | 28.18476 | 1.6093 | 0.391 | 99.42 | 1.4181 | 43.038356 | 0.0003 | 43,44 |
| PIPR37S | 3.4870 | 138.1231 | 22 | 8.02 | 268.224 | 1.1 | 10 | 12.892 | 25.75825 | 1.6093 | 0.391 | 3.362 | 1.4181 | 149.13291 | 0.0003 | 43,44 |

# Appendix E.  BLM Table

| | Model Output | | Model Input | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BLM Data Label | Critical Accumulation | Hard-ness (mg/L) | Temp (ºC) | pH | Dissolved LC50 (µg/L) | DOC (mg/L) | Humic Acid (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | Cl (mg/L) | Alkalinity (mg/L) | S (mg/L) | Notes |
| PIPR38S | 9.2068 | 139.124 | 22 | 7.775 | 242.443 | 1.1 | 10 | 51.1778 | 2.779812 | 1.6093 | 0.391 | 99.42 | 1.4181 | 43.038356 | 0.0003 | 43,44 |
| PIPR39S | 4.7038 | 47.04192 | 22 | 7.78 | 113.3475 | 1.1 | 10 | 13.4268 | 4.010325 | 1.6093 | 0.391 | 3.362 | 1.4181 | 43.038356 | 0.0003 | 43,44 |
| PIPR40S | 3.1754 | 37.033 | 22 | 7.785 | 77.8764 | 0.88 | 10 | 11.022 | 3.281175 | 2.9887 | 0.391 | 3.362 | 1.4181 | 43.038356 | 0.0003 | 43,45 |
| PIPR41S | 5.3335 | 60.05352 | 22 | 7.795 | 128.016 | 1.1 | 10 | 15.2304 | 5.954725 | 1.6093 | 0.391 | 17.771 | 1.4181 | 43.038356 | 0.0003 | 43,44 |
| PIPR42S | 6.4718 | 76.06779 | 22 | 7.8 | 151.13 | 1.1 | 10 | 18.8376 | 7.413025 | 1.6093 | 0.391 | 32.179 | 1.7727 | 42.037464 | 0.0003 | 43,44 |
| PIPR43S | 6.4642 | 103.0919 | 22 | 7.805 | 166.624 | 1.1 | 10 | 25.05 | 10.2081 | 2.0691 | 0.391 | 60.036 | 1.7727 | 43.038356 | 0.0003 | 43,44 |
| PIPR44S | 7.0015 | 103.0919 | 22 | 7.78 | 163.83 | 1.1 | 10 | 32.064 | 4.010325 | 1.8392 | 0.391 | 58.115 | 1.7727 | 40.03568 | 0.0003 | 43,44 |
| PIPR45S | 5.9820 | 107.0954 | 22 | 7.79 | 157.48 | 1.1 | 10 | 18.2364 | 15.43368 | 1.6093 | 0.391 | 61.957 | 1.7727 | 43.038356 | 0.0003 | 43,44 |
| PIPR46S | 7.4331 | 134.1195 | 22 | 7.8 | 199.7075 | 1.1 | 10 | 32.2644 | 13.00318 | 1.6093 | 0.391 | 88.854 | 1.7727 | 43.038356 | 0.0003 | 43,44 |
| PIPR47S | 6.0725 | 45.04014 | 22 | 7.815 | 128.524 | 1.1 | 10 | 14.028 | 2.18745 | 1.3794 | 0.391 | 3.362 | 1.0636 | 41.036572 | 0.0003 | 43,44 |
| PIPR48S | 7.2713 | 46.04103 | 22 | 7.82 | 150.876 | 1.1 | 10 | 14.028 | 2.18745 | 6.2072 | 1.5639 | 5.7635 | 7.0906 | 42.037464 | 0.0003 | 43,44 |
| PIPR49S | 5.4175 | 45.04014 | 22 | 7.82 | 131.064 | 1.1 | 10 | 14.028 | 2.18745 | 15.173 | 1.5639 | 10.566 | 15.245 | 41.036572 | 0.0003 | 43,44 |
| PIPR50S | 6.2395 | 45.04014 | 22 | 7.81 | 160.2105 | 1.1 | 10 | 14.2284 | 2.18745 | 35.174 | 1.5639 | 21.613 | 36.162 | 41.036572 | 0.0003 | 43,44 |
| PIPR51S | 6.2194 | 44.03925 | 22 | 7.82 | 182.88 | 1.1 | 10 | 15.03 | 2.18745 | 62.992 | 1.5639 | 40.825 | 70.906 | 40.03568 | 0.0003 | 43,44 |
| PIPR52S | 4.9667 | 45.04014 | 22 | 7.81 | 180.848 | 1.1 | 10 | 14.4288 | 2.18745 | 101.39 | 1.9549 | 59.076 | 107.78 | 41.036572 | 0.0003 | 43,44 |
| PIPR53S | 6.1183 | 46.04103 | 22 | 7.81 | 176.784 | 1.1 | 10 | 14.2284 | 2.18745 | 57.015 | 19.158 | 40.825 | 71.97 | 42.037464 | 0.0003 | 43,44 |
| PIPR54S | 5.7931 | 189.1686 | 22 | 7.82 | 188.9125 | 1.1 | 10 | 55.11 | 15.79825 | 1.6093 | 0.782 | 152.25 | 1.0636 | 42.037464 | 0.0003 | 43,44 |
| PIPR55S | 5.2814 | 46.04103 | 22 | 7.865 | 125.603 | 1.1 | 10 | 14.6292 | 3.15965 | 1.3794 | 0.391 | 3.362 | 1.0636 | 42.037464 | 0.0003 | 43,44 |
| PIPR56S | 3.8765 | 75.0669 | 22 | 7.87 | 117.348 | 1.1 | 10 | 24.4488 | 5.954725 | 1.3794 | 0.391 | 30.739 | 1.0636 | 41.036572 | 0.0003 | 43,44 |
| PIPR57S | 3.7460 | 46.04103 | 22 | 7.865 | 114.554 | 1.1 | 10 | 14.4288 | 3.15965 | 19.771 | 0.391 | 12.488 | 18.436 | 41.036572 | 0.0003 | 43,44 |
| PIPR58S | 3.8963 | 74.06601 | 22 | 7.85 | 126.492 | 1.1 | 10 | 24.4488 | 6.07625 | 18.392 | 0.391 | 38.903 | 18.436 | 42.037464 | 0.0003 | 43,44 |
| PIPR59S | 5.1820 | 133.1186 | 22 | 7.85 | 172.72 | 1.1 | 10 | 41.082 | 11.6664 | 18.392 | 0.391 | 98.94 | 18.436 | 42.037464 | 0.0003 | 43,44 |
| PIPR60S | 5.0050 | 76.06779 | 22 | 7.85 | 167.3225 | 1.1 | 10 | 24.048 | 6.07625 | 47.589 | 0.782 | 58.115 | 52.116 | 43.038356 | 0.0003 | 43,44 |
| PIPR61S | 6.3379 | 134.1195 | 22 | 7.84 | 226.695 | 1.1 | 10 | 40.8816 | 11.6664 | 49.198 | 0.782 | 118.63 | 51.052 | 43.038356 | 0.0003 | 43,44 |
| PIPR62S | 6.5522 | 52.04638 | 22 | 7.96 | 84.201 | 0.3 | 10 | 12.024 | 4.13185 | 1.6093 | 0.391 | 10.566 | 1.7727 | 42.037464 | 0.0003 | 43,46 |
| PIPR63S | 7.7846 | 51.04549 | 22 | 7.96 | 97.79 | 0.3 | 10 | 11.2224 | 3.8888 | 2.7588 | 0.782 | 10.566 | 3.5453 | 41.036572 | 0.0003 | 43,46 |
| PIPR64S | 5.4254 | 50.0446 | 22 | 7.945 | 70.0786 | 0.3 | 10 | 11.022 | 3.767275 | 5.9773 | 1.5639 | 12.007 | 8.1542 | 41.036572 | 0.0003 | 43,46 |
| PIPR65S | 5.7632 | 51.04549 | 22 | 7.965 | 81.5848 | 0.3 | 10 | 11.2224 | 3.8888 | 11.955 | 2.3459 | 15.369 | 15.245 | 42.037464 | 0.0003 | 43,46 |
| PIPR66S | 5.0152 | 51.04549 | 22 | 7.96 | 77.4319 | 0.3 | 10 | 11.2224 | 3.767275 | 23.22 | 3.1279 | 21.613 | 30.135 | 41.036572 | 0.0003 | 43,46 |
| PIPR67S | 5.9195 | 53.04728 | 22 | 7.97 | 110.871 | 0.3 | 10 | 11.2224 | 3.767275 | 46.899 | 4.6918 | 33.62 | 59.207 | 41.537018 | 0.0003 | 43,46 |
| PIPR68S | 5.4017 | 53.04728 | 22 | 7.96 | 151.892 | 0.3 | 10 | 11.6232 | 3.8888 | 117.94 | 7.0377 | 68.201 | 141.81 | 42.037464 | 0.0003 | 43,46 |
| PIPR69S | 4.1225 | 52.04638 | 22 | 7.94 | 175.26 | 0.3 | 10 | 11.4228 | 3.767275 | 236.79 | 10.948 | 128.24 | 279.72 | 43.038356 | 0.0003 | 43,46 |
| PIPR70S | 6.6575 | 47.04192 | 25 | 7.82 | 145.288 | 1.1 | 10 | 13.9359 | 2.983276 | 1.6093 | 0.391 | 3.362 | 1.4181 | 42.53791 | 0.0003 | 43,44 |
| PIPR71S | 4.6725 | 47.04192 | 20 | 7.82 | 111.76 | 1.1 | 10 | 13.9359 | 2.983276 | 1.6093 | 0.391 | 3.362 | 1.4181 | 43.038356 | 0.0003 | 43,44 |

# Appendix E. BLM Table

| BLM Data Label | Model Output | Hard-ness (mg/L) | Model Input | | | | | | | | | | | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Critical Accumulation | | Temp (ºC) | pH | Dissolved LC50 (µg/L) | DOC (mg/L) | Humic Acid (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | Cl (mg/L) | Alkalinity (mg/L) | S (mg/L) | |
| PIPR72S | 2.3613 | 47.04192 | 15 | 7.82 | 79.1845 | 1.1 | 10 | 13.9359 | 2.983276 | 1.6093 | 0.391 | 3.362 | 1.4181 | 42.53791 | 0.0003 | 43,44 |
| PIPR73S | 1.1782 | 47.04192 | 10 | 7.82 | 60.0075 | 1.1 | 10 | 13.9359 | 2.983276 | 1.6093 | 0.391 | 3.362 | 1.4181 | 42.53791 | 0.0003 | 43,44 |
| PIPR74S | 7.6860 | 140.1249 | 22 | 8.03 | 370.078 | 0.3 | 10 | 29.058 | 12.03098 | 25.059 | 4.3008 | 60.036 | 25.881 | 98.087416 | 0.0003 | 43,46 |
| PIPR75S | 10.9585 | 88.0785 | 22 | 7.965 | 292.1 | 0.3 | 10 | 19.038 | 7.04845 | 14.943 | 2.7369 | 37.943 | 17.017 | 63.056196 | 0.0003 | 43,46 |
| PIPR76S | 7.9470 | 59.05263 | 22 | 7.89 | 101.473 | 0.3 | 10 | 12.024 | 4.61795 | 9.1959 | 0.782 | 23.054 | 9.9268 | 39.034788 | 0.0003 | 43,46 |
| PIPR77S | 6.9448 | 41.03657 | 22 | 7.825 | 62.5094 | 0.3 | 10 | 8.2164 | 3.038125 | 7.5866 | 2.7369 | 13.928 | 6.3815 | 29.025868 | 0.0003 | 43,46 |
| PIPR78S | 5.9976 | 27.02408 | 22 | 7.745 | 42.0624 | 0.3 | 10 | 5.6112 | 1.822875 | 4.598 | 2.3459 | 8.6452 | 4.2544 | 23.020516 | 0.0003 | 43,46 |
| PIPR79S | 9.0570 | 43.03836 | 22 | 7.885 | 172.466 | 1.1 | 10 | 10.4208 | 2.67355 | 1.6093 | 0.782 | 2.8817 | 1.4181 | 42.037464 | 0.0003 | 43,44 |
| PIPR80S | 0.7034 | 25.0223 | 22 | 7.565 | 12.4333 | 0.3 | 10 | 6.68596 | 2.02764 | 3.4485 | 1.1729 | 4.3226 | 4.9634 | 16.014272 | 0.0003 | 43,46 |
| PIPR81S | 7.0672 | 107.0954 | 22 | 8.105 | 271.272 | 0.3 | 10 | 28.6924 | 8.631893 | 14.254 | 1.9549 | 19.212 | 16.308 | 80.07136 | 0.0003 | 43,46 |
| PIPR82S | 4.9660 | 87.0776 | 22 | 7.055 | 71.12 | 0.3 | 10 | 23.3293 | 7.018455 | 13.564 | 1.9549 | 19.212 | 15.954 | 58.051736 | 0.0003 | 43,46 |
| PIPR83S | 5.1028 | 85.07582 | 22 | 7.33 | 79.629 | 0.3 | 10 | 22.793 | 6.857111 | 13.794 | 1.9549 | 19.212 | 15.954 | 58.051736 | 0.0003 | 43,46 |
| PIPR84S | 5.4229 | 88.0785 | 22 | 7.605 | 99.53625 | 0.3 | 10 | 23.5975 | 7.099127 | 13.564 | 1.9549 | 19.212 | 15.954 | 59.052628 | 0.0003 | 43,46 |
| PIPR85S | 6.5439 | 87.0776 | 22 | 7.745 | 132.715 | 0.3 | 10 | 23.3293 | 7.018455 | 14.484 | 1.9549 | 18.731 | 15.954 | 59.052628 | 0.0003 | 43,46 |
| PIPR86S | 5.4310 | 87.0776 | 22 | 8.07 | 137.16 | 0.3 | 10 | 23.3293 | 7.018455 | 12.644 | 1.9549 | 18.731 | 15.954 | 59.052628 | 0.0003 | 43,46 |
| PIPR87S | 5.4306 | 87.0776 | 22 | 8.375 | 182.245 | 0.3 | 10 | 23.3293 | 7.018455 | 13.334 | 1.9549 | 18.731 | 15.954 | 59.052628 | 0.0003 | 43,46 |
| PIPR88S | 5.7955 | 87.0776 | 22 | 8.73 | 268.9225 | 0.3 | 10 | 23.3293 | 7.018455 | 14.254 | 1.9549 | 18.731 | 14.89 | 59.052628 | 0.0003 | 43,46 |
| PIPR89S | 6.9862 | 87.0776 | 22 | 8.115 | 188.976 | 0.3 | 10 | 23.3293 | 7.018455 | 12.874 | 1.9549 | 18.731 | 15.954 | 59.052628 | 0.0003 | 43,46 |
| PIPR90S | 8.5781 | 251.2239 | 22 | 7.2 | 662.559 | 0.3 | 10 | 67.127 | 20.35751 | 57.475 | 4.6918 | 72.524 | 62.397 | 150.1338 | 0.0003 | 43,46 |
| PIPR91S | 9.0461 | 252.2248 | 22 | 7.575 | 904.875 | 0.3 | 10 | 67.3945 | 20.43861 | 57.475 | 4.6918 | 70.603 | 62.043 | 164.14629 | 0.0003 | 43,46 |
| PIPR92S | 8.7054 | 252.2248 | 22 | 7.915 | 995.68 | 0.3 | 10 | 67.3945 | 20.43861 | 57.475 | 4.6918 | 73.484 | 62.043 | 150.1338 | 0.0003 | 43,46 |
| PIPR93S | 6.4404 | 251.2239 | 22 | 8.275 | 891.54 | 0.3 | 10 | 67.127 | 20.35751 | 57.475 | 4.6918 | 73.484 | 62.043 | 143.12756 | 0.0003 | 43,46 |
| PIPR94S | 8.4348 | 200.1784 | 22 | 8.05 | 757.6185 | 0.3 | 10 | 53.5426 | 16.18781 | 37.243 | 3.5188 | 49.47 | 46.798 | 128.11418 | 0.0003 | 43,46 |
| PIPR95S | 8.0730 | 140.1249 | 22 | 7.95 | 404.8125 | 0.3 | 10 | 37.4414 | 11.35479 | 22.99 | 2.3459 | 28.817 | 25.172 | 99.088308 | 0.0003 | 43,46 |
| PIPR96S | 8.8271 | 90.08028 | 22 | 8.045 | 262.128 | 0.3 | 10 | 24.1338 | 7.260471 | 14.254 | 1.9549 | 18.731 | 15.599 | 65.05798 | 0.0003 | 43,46 |
| PIPR97S | 2.3840 | 19.01695 | 22 | 7.525 | 20.447 | 0.3 | 10 | 5.08133 | 1.541007 | 3.4485 | 0.782 | 0.9606 | 4.9634 | 19.016948 | 0.0003 | 43,46 |
| PIPR98S | 2.6680 | 34.03033 | 22 | 7.53 | 23.1648 | 0.3 | 10 | 9.0929 | 2.757591 | 3.4485 | 0.782 | 9.6058 | 4.6089 | 20.01784 | 0.0003 | 43,46 |
| PIPR99S | 4.5268 | 51.04549 | 22 | 7.54 | 34.9885 | 0.3 | 10 | 13.6394 | 4.136386 | 3.4485 | 0.782 | 16.81 | 4.6089 | 21.018732 | 0.0003 | 43,46 |
| PIPR100S | 3.5167 | 29.02587 | 22 | 7.585 | 27.94 | 0.3 | 10 | 7.75571 | 2.352063 | 3.4485 | 0.782 | 5.2832 | 4.6089 | 22.019624 | 0.0003 | 43,46 |
| PIPR101S | 3.1703 | 30.02676 | 22 | 7.605 | 26.67 | 0.3 | 10 | 8.02315 | 2.433168 | 1.3794 | 0.782 | 4.3226 | 2.4817 | 23.020516 | 0.0003 | 43,46 |
| PIPR102S | 1.9033 | 27.02408 | 22 | 7.55 | 20.32 | 0.3 | 10 | 7.22084 | 2.189852 | 10.345 | 1.1729 | 5.2832 | 13.118 | 20.01784 | 0.0003 | 43,46 |
| PIPR103S | 2.9068 | 27.02408 | 22 | 7.525 | 26.67 | 0.3 | 10 | 7.22084 | 2.189852 | 20.691 | 1.5639 | 10.566 | 26.59 | 20.01784 | 0.0003 | 43,46 |
| PIPR104S | 6.9464 | 90.08028 | 22 | 7.995 | 182.88 | 0.3 | 10 | 24.1338 | 7.260471 | 14.254 | 1.9549 | 19.212 | 15.954 | 63.056196 | 0.0003 | 43,46 |
| PIPR105S | 4.3303 | 60.05352 | 22 | 8.11 | 96.6724 | 0.3 | 10 | 16.0463 | 4.866337 | 11.955 | 1.5639 | 3.8423 | 17.372 | 58.051736 | 0.0003 | 43,46 |

## Appendix E.  BLM Table

| BLM Data Label | Model Output | Hard-ness (mg/L) | Model Input | | | | | | | | | | | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Critical Accumulation | | Temp (ºC) | pH | Dissolved LC50 (µg/L) | DOC (mg/L) | Humic Acid (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | Cl (mg/L) | Alkalinity (mg/L) | S (mg/L) | |
| PIPR106S | 6.1231 | 120.107 | 22 | 8.09 | 182.88 | 0.3 | 10 | 32.0926 | 9.732674 | 11.955 | 1.5639 | 33.62 | 17.372 | 59.052628 | 0.0003 | 43,46 |
| PIPR107S | 5.3380 | 180.1606 | 22 | 8.09 | 190.6905 | 0.3 | 10 | 48.1389 | 14.59901 | 11.955 | 1.5639 | 62.438 | 17.017 | 58.051736 | 0.0003 | 43,46 |
| PIPR108S | 4.7175 | 91.08117 | 22 | 8.125 | 127.0635 | 0.3 | 10 | 24.3369 | 7.380611 | 11.955 | 1.5639 | 19.212 | 15.954 | 59.052628 | 0.0003 | 43,46 |
| PIPR109S | 5.7327 | 90.08028 | 22 | 8.155 | 148.59 | 0.3 | 10 | 24.0695 | 7.299505 | 2.299 | 6.2557 | 15.85 | 6.027 | 60.05352 | 0.0003 | 43,46 |
| PIPR110S | 6.5363 | 93.08296 | 22 | 8.135 | 223.52 | 0.3 | 10 | 24.8718 | 7.542822 | 35.864 | 3.9098 | 27.377 | 49.989 | 62.055304 | 0.0003 | 43,46 |
| PIPR111S | 6.7795 | 92.08206 | 22 | 8.145 | 283.1465 | 0.3 | 10 | 24.6043 | 7.461717 | 71.728 | 7.4287 | 41.305 | 102.81 | 61.054412 | 0.0003 | 43,46 |
| PIPR112S | 5.0174 | 91.08117 | 22 | 8.19 | 150.241 | 0.3 | 10 | 24.402 | 7.341142 | 14.484 | 15.248 | 18.731 | 17.372 | 62.055304 | 0.0003 | 43,46 |
| PIPR113S | 6.2630 | 144.1284 | 22 | 8.38 | 644.525 | 0.3 | 10 | 38.5111 | 11.67921 | 34.485 | 3.1279 | 12.488 | 42.189 | 138.1231 | 0.0003 | 43,46 |
| PIPR114S | 5.5141 | 292.2605 | 22 | 8.27 | 697.5475 | 0.3 | 10 | 78.092 | 23.68284 | 34.485 | 3.1279 | 87.893 | 57.079 | 137.1222 | 0.0003 | 43,46 |
| PIPR115S | 5.1749 | 440.3925 | 22 | 8.225 | 752.475 | 0.3 | 10 | 117.673 | 35.68647 | 34.485 | 3.1279 | 175.31 | 41.125 | 133.11864 | 0.0003 | 43,46 |
| PIPR116S | 5.8459 | 217.1936 | 22 | 8.31 | 653.415 | 0.3 | 10 | 58.0341 | 17.59992 | 34.485 | 3.1279 | 46.588 | 43.253 | 133.11864 | 0.0003 | 43,46 |
| PIPR117S | 6.1591 | 218.1945 | 22 | 8.305 | 646.3665 | 0.3 | 10 | 58.3016 | 17.68102 | 6.8969 | 1.5639 | 38.903 | 9.5723 | 140.12488 | 0.0003 | 43,46 |
| PIPR118S | 5.9250 | 212.1891 | 22 | 8.345 | 939.8 | 0.3 | 10 | 56.6969 | 17.19439 | 103.45 | 7.8197 | 65.319 | 124.79 | 143.12756 | 0.0003 | 43,46 |
| PIPR119S | 8.2172 | 92.08206 | 22 | 8.125 | 253.365 | 0.3 | 10 | 24.6701 | 7.421814 | 14.254 | 1.9549 | 19.212 | 16.663 | 63.056196 | 0.0003 | 43,46 |
| PIPR120F | 0.3052 | 48 | 25 | 8.03 | 109.44 | 2.64 | 10 | 14.1077 | 3.111984 | 1.35 | 0.57 | 3.54 | 1.25 | 44 | 0.0003 | 1,2,3,6,7,15,26 |
| PIPR121F | 0.3617 | 45 | 25 | 8.04 | 116.16 | 2.64 | 10 | 13.2259 | 2.917485 | 1.27 | 0.57 | 3.33 | 1.17 | 44 | 0.0003 | 1,2,3,6,7,15,26 |
| PIPR122F | 0.1755 | 46 | 25 | 7.98 | 84.96 | 2.64 | 10 | 13.5198 | 2.982318 | 1.3 | 0.57 | 3.4 | 1.2 | 41 | 0.0003 | 1,2,3,6,7,15,26 |
| PIPR123F | 3.4889 | 30 | 25 | 6.82 | 418.56 | 10.4652 | 10 | 7.1362 | 2.964634 | 1.625 | 0.5 | 6.125 | 1.25 | 21 | 0.0003 | 1,2,3,6,7,27,28 |
| PIPR124F | 1.8656 | 37 | 25 | 7.28 | 495.36 | 11.3373 | 10 | 8.80131 | 3.656382 | 2.0042 | 0.5 | 7.5542 | 1.5417 | 21 | 0.0003 | 1,2,3,6,7,27,28 |
| PIPR125F | 2.8066 | 87 | 25 | 7.11 | 1522.56 | 31.3956 | 10 | 20.6978 | 8.4403 | 16.071 | 1.855 | 22.35 | 18.629 | 20 | 0.0003 | 1,2,3,6,7,27,29 |
| PIPR126F | 3.1774 | 73 | 25 | 6.94 | 1083.84 | 24.4188 | 10 | 17.2174 | 7.3329 | 10.539 | 1.5232 | 18.439 | 13.619 | 18 | 0.0003 | 1,2,3,6,7,27,29 |
| PIPR127F | 1.4538 | 84 | 25 | 7.07 | 528 | 14.5155 | 10 | 20.4644 | 8.008 | 6 | 1.4 | 34.5 | 10.95 | 12 | 0.0003 | 1,2,3,6,7,27,28 |
| PIPR128F | 1.0075 | 66 | 25 | 6.97 | 960.96 | 32.9018 | 10 | 16.0792 | 6.292 | 4.7143 | 1.4 | 27.107 | 8.6036 | 12 | 0.0003 | 1,2,3,6,7,27,28 |
| PIPR129F | 1.2809 | 43.9 | 25 | 7.4 | 88.32 | 2 | 10 | 12.9026 | 2.846168 | 1.24 | 0.57 | 3.24 | 1.14 | 42.4 | 0.0003 | 1,2,6,7,8,14,15 |
| PIPR130F | 0.0860 | 47.04192 | 22 | 8.1 | 27.94 | 1.1 | 10 | 13.9359 | 2.983276 | 1.6093 | 0.391 | 3.362 | 1.4181 | 42.53791 | 0.0003 | 43,44 |
| PIPR131F | 1.1899 | 243.2168 | 22 | 8.01 | 105.7275 | 1.1 | 10 | 92.7261 | 2.884195 | 47.129 | 0.391 | 3.362 | 143.23 | 43.038356 | 0.0003 | 43,44 |
| PIPR132F | 0.1230 | 255.7279 | 22 | 8.01 | 40.0558 | 1.1 | 10 | 14.1661 | 53.5752 | 1.6093 | 0.391 | 3.362 | 143.23 | 43.538802 | 0.0003 | 43,44 |
| PIPR133F | 0.4522 | 47.04192 | 22 | 8.1 | 64.262 | 1.1 | 10 | 13.9359 | 2.983276 | 47.589 | 0.391 | 3.362 | 72.324 | 43.538802 | 0.0003 | 43,44 |
| PIPR134F | 0.3833 | 45.04014 | 22 | 8.02 | 49.01565 | 1.1 | 10 | 13.3428 | 2.856328 | 1.6093 | 0.391 | 3.362 | 1.4181 | 43.038356 | 0.0003 | 43,44 |
| PIPR135F | 0.3216 | 45.04014 | 22 | 8.65 | 67.7164 | 1.1 | 10 | 13.3428 | 2.856328 | 1.6093 | 0.391 | 3.362 | 1.4181 | 47.041924 | 0.0003 | 43,44 |
| PIPR136F | 0.1834 | 45.54059 | 22 | 7.3 | 18.669 | 1.1 | 10 | 13.4911 | 2.888065 | 1.6093 | 0.391 | 3.362 | 1.4181 | 44.039248 | 0.0003 | 43,44 |
| PIPR137F | 0.1256 | 49.04371 | 22 | 6.63 | 6.1468 | 1.1 | 10 | 14.5289 | 3.110224 | 1.6093 | 0.391 | 3.362 | 1.4181 | 49.043708 | 0.0003 | 43,44 |
| PIPR138F | 0.2961 | 45.04014 | 22 | 7.16 | 20.447 | 1.1 | 10 | 13.3428 | 2.856328 | 1.6093 | 0.391 | 3.362 | 15.599 | 26.023192 | 0.0003 | 43,44 |
| PIPR139F | 2.8408 | 43.03836 | 22 | 7.93 | 93.36405 | 1.1 | 10 | 12.7498 | 2.72938 | 1.6093 | 0.391 | 3.362 | 1.4181 | 41.036572 | 0.0003 | 43,44 |

# Appendix E. BLM Table

| BLM Data Label | Model Output | Hard- ness (mg/L) | Model Input | | | | | | | | | | | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Critical Accumulation | | Temp (ºC) | pH | Dissolved LC50 (µg/L) | DOC (mg/L) | Humic Acid (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | Cl (mg/L) | Alkalinity (mg/L) | S (mg/L) | |
| PIPR140F | 0.0373 | 45.54059 | 22 | 7.91 | 245.364 | 6.1 | 83.7705 | 13.4911 | 2.888065 | 1.6093 | 0.391 | 3.362 | 1.4181 | 44.039248 | 0.0003 | 43,47 |
| PIPR141F | 1.3667 | 45.04014 | 22 | 7.94 | 72.3392 | 1.1 | 10 | 13.3428 | 2.856328 | 1.6093 | 0.391 | 3.362 | 1.4181 | 43.038356 | 0.0003 | 43,44 |
| PIPR142F | 0.0310 | 45.04014 | 22 | 7.95 | 229.8065 | 6.1 | 83.7705 | 13.3428 | 2.856328 | 1.6093 | 0.391 | 3.362 | 1.4181 | 43.038356 | 0.0003 | 43,47 |
| PIPR143F | 0.1023 | 45.54059 | 22 | 7.94 | 195.453 | 3.6 | 72.5 | 13.4911 | 2.888065 | 1.6093 | 0.391 | 3.362 | 1.4181 | 44.039248 | 0.0003 | 43,47 |
| PIPR144F | 0.1038 | 45.04014 | 22 | 7.91 | 109.347 | 2.35 | 57.8723 | 13.3428 | 2.856328 | 1.6093 | 0.391 | 3.362 | 1.4181 | 42.037464 | 0.0003 | 43,47 |
| PIPR145F | 1.9076 | 44.03925 | 22 | 7.87 | 78.0034 | 1.1 | 10 | 13.0463 | 2.792854 | 1.6093 | 0.391 | 3.362 | 1.4181 | 42.037464 | 0.0003 | 43,44 |
| PIPR146F | 0.4905 | 44.03925 | 22 | 7.84 | 45.52315 | 1.1 | 10 | 13.0463 | 2.792854 | 1.6093 | 0.391 | 3.362 | 19.145 | 17.015164 | 0.0003 | 43,44 |
| PIPR147F | 1.3078 | 22.52007 | 22 | 6.01 | 4.3815 | 0.3 | 10 | 6.01736 | 1.824876 | 3.4485 | 0.391 | 3.362 | 4.2544 | 15.01338 | 0.0003 | 43,46 |
| PIPR148F | 1.5995 | 24.02141 | 22 | 7.02 | 12.4333 | 0.3 | 10 | 6.41852 | 1.946535 | 3.6784 | 0.391 | 3.362 | 4.9634 | 17.015164 | 0.0003 | 43,46 |
| PIPR149F | 2.4015 | 23.02052 | 22 | 8 | 26.8605 | 0.3 | 10 | 6.15108 | 1.865429 | 4.1382 | 0.782 | 3.362 | 4.9634 | 17.51561 | 0.0003 | 43,46 |
| PIPR150F | 2.3670 | 21.51918 | 22 | 9.01 | 51.3334 | 0.3 | 10 | 5.74992 | 1.743771 | 4.598 | 1.5639 | 3.362 | 4.9634 | 19.016948 | 0.0003 | 43,46 |
| PTLU01S | 4.0390 | 173 | 22 | 8.3 | 364.8 | 0.5 | 10 | 28.5511 | 24.739 | 53.583 | 4.282 | 166.08 | 3.8824 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| PTLU02S | 9.0637 | 173 | 22 | 7.25 | 460.8 | 0.5 | 10 | 28.5511 | 24.739 | 53.583 | 4.282 | 166.08 | 3.8824 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| PTOR01F | 0.2752 | 25 | 7.8 | 7.3 | 22.08 | 1.1 | 10 | 7.1535 | 1.9754 | 4.8154 | 0.7 | 3.997 | 5.9792 | 25 | 0.0003 | 1,2,3,6,7,9,10 |
| PTOR02F | 0.1587 | 54 | 11.5 | 7.3 | 17.28 | 1.1 | 10 | 15.0937 | 3.6371 | 6.8831 | 0.7 | 12.163 | 9.6854 | 43 | 0.0003 | 1,2,3,6,7,9,10 |
| XYTE01S | 2.6511 | 173 | 22 | 8.15 | 211.2 | 0.5 | 10 | 28.5511 | 24.739 | 53.583 | 4.282 | 166.08 | 3.8824 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| XYTE02S | 4.5011 | 173 | 22 | 8.05 | 326.4 | 0.5 | 10 | 28.5511 | 24.739 | 53.583 | 4.282 | 166.08 | 3.8824 | 117 | 0.0003 | 1,2,3,4,6,7,20 |
| POAC01S | 2.2126 | 167 | 22 | 8 | 153.6 | 0.5 | 10 | 27.5609 | 23.881 | 51.724 | 4.1335 | 160.32 | 3.7478 | 115 | 0.0003 | 1,2,3,4,6,7,20 |
| LEMA01R | 25.6628 | 85 | 20.2 | 7.3 | 2200 | 1.1 | 10 | 23.9 | 6.5 | 0.64 | 0.46 | 4.32 | 1.5 | 82 | 0.0003 | 50 |
| LEMA02F | 25.8381 | 45 | 20 | 7.5 | 1056 | 1.1 | 10 | 13.2259 | 2.917485 | 1.3 | 0.57 | 3.4 | 1.2 | 43 | 0.0003 | 1,2,3,6,7,8 |
| LEMA03F | 27.6113 | 25.9 | 19 | 7.03 | 960 | 1.5 | 10 | 6.38814 | 2.42165 | 5.4743 | 1.6 | 26.489 | 19.425 | 27.1 | 0.0003 | 1,2,3,6,7,16 |
| LEMA04F | 22.5658 | 85 | 21.85 | 7.45 | 1300 | 1.1 | 10 | 23.9 | 6.5 | 0.64 | 0.46 | 4.32 | 1.5 | 82 | 0.0003 | 50 |
| ETFL01S | 5.5744 | 170 | 20 | 7.8 | 316.8 | 0.5 | 10 | 27.9 | 24.2 | 52.5 | 4.2 | 163 | 3.80 | 115 | 0.0003 | 1,3,4,22 |
| ETFL02S | 5.7421 | 170 | 20 | 7.8 | 327.36 | 0.5 | 10 | 27.9 | 24.2 | 52.5 | 4.2 | 163 | 3.80 | 115 | 0.0003 | 1,3,4,22 |
| ETFL03S | 5.8278 | 170 | 20 | 7.9 | 358.08 | 0.5 | 10 | 27.9 | 24.2 | 52.5 | 4.2 | 163 | 3.80 | 115 | 0.0003 | 1,3,4,22 |
| ETFL04S | 6.4920 | 170 | 20 | 7.8 | 376.32 | 0.5 | 10 | 27.9 | 24.2 | 52.5 | 4.2 | 163 | 3.80 | 115 | 0.0003 | 1,3,4,22 |
| ETLE01S | 3.7314 | 167 | 22 | 8 | 249.6 | 0.5 | 10 | 27.5609 | 23.881 | 51.724 | 4.1335 | 160.32 | 3.7478 | 115 | 0.0003 | 1,2,3,4,6,7,20 |
| ETNI01S | 7.8536 | 170 | 20 | 7.8 | 473.28 | 0.5 | 10 | 27.9 | 24.2 | 52.5 | 4.2 | 163 | 3.80 | 115 | 0.0003 | 1,3,4,22 |
| ETNI02S | 7.7256 | 170 | 20 | 7.8 | 463.68 | 0.5 | 10 | 27.9 | 24.2 | 52.5 | 4.2 | 163 | 3.80 | 115 | 0.0003 | 1,3,4,22 |
| ETNI03S | 9.1617 | 170 | 20 | 7.8 | 577.92 | 0.5 | 10 | 27.9 | 24.2 | 52.5 | 4.2 | 163 | 3.80 | 115 | 0.0003 | 1,3,4,22 |
| ETNI04S | 8.5329 | 170 | 20 | 7.8 | 526.08 | 0.5 | 10 | 27.9 | 24.2 | 52.5 | 4.2 | 163 | 3.80 | 115 | 0.0003 | 1,3,4,22 |
| ETRU01S | 0.4735 | 167 | 22 | 8.2 | 57.6 | 0.5 | 10 | 27.5609 | 23.881 | 51.724 | 4.1335 | 160.32 | 3.7478 | 115 | 0.0003 | 1,2,3,4,6,7,20 |
| BUBO01S | 1.7185 | 167 | 22 | 7.9 | 115.2 | 0.5 | 10 | 27.5609 | 23.881 | 51.724 | 4.1335 | 160.32 | 3.7478 | 115 | 0.0003 | 1,2,3,4,6,7,20 |

# Appendix F. Regression Plots

## Appendix F. Analyses of Chronic Data

The following pages contain figures and other information related to the regression and probability distribution analyses that were performed to calculate chronic EC20s. The initial parameter estimates are shown in the tables below. In the figures that follow, circles denote measured responses and solid lines denote estimated regression lines.

### Probability Distribution Analysis

| Species | Study | Test | Endpoint | Final Estimates | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Control Value | EC50 | Standard Deviation | EC20 | EC10 |
| Snail, *Campeloma decisum (Test 1)* | Arthur and Leonard 1970 | LC | Survival | 0.925 | 14.50 | 0.192 | 8.73 | 7.01 |
| Snail, *Campeloma decisum (Test 2)* | Arthur and Leonard 1970 | LC | Survival | 0.875 | 11.80 | 0.339 | 10.94 | 9.16 |
| Cladoceran, *Daphnia pulex* | Winner 1985 | LC | Survival | 1.00 | 4.57 | 0.260 | 2.83 | 2.24 |
| Cladoceran, *Daphnia pulex* | Winner 1985 | LC | Survival | 0.900 | 11.3 | 0.111 | 9.16 | 8.28 |
| Caddisfly, *Clistoronia magnifica* | Nebeker et al. 1984b | LC | Emergence (adult 1st gen) | 0.750 | 20.0 | 0.300 | 7.67 | 5.63 |
| Bluegill (larval), *Lepomis macrochirus* | Benoit 1975 | ELS | Survival | 0.880 | 39.8 | 0.250 | 27.15 | 21.60 |

### Logistic Regression Analysis

| Species | Study | Test | Endpoint | Final Estimates | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Control Value | EC50 | Slope | EC20 | EC10 |
| Cladoceran, *Ceriodaphnia dubia* | Carlson et al. 1986 | LC | Reproduction | 13.10 | 14.6 | 1.36 | 9.17 | 7.28 |
| Cladoceran, *Daphnia magna* | Chapman et al. Manuscript | LC | Reproduction | 171.5 | 16.6 | 1.40 | 12.58 | 10.63 |
| Cladoceran, *Daphnia magna* | Chapman et al. Manuscript | LC | Reproduction | 192.1 | 28.4 | 1.59 | 19.89 | 16.34 |
| Cladoceran, *Daphnia magna* | Chapman et al. Manuscript | LC | Reproduction | 88.0 | 15.8 | 1.00 | 6.06 | 3.64 |
| Rainbow trout, *Oncorhynchus mykiss* | Seim et al. 1984 | ELS | Biomass | 137.6 | 40.7 | 1.69 | 27.77 | 22.16 |
| Rainbow trout, *Oncorhynchus mykiss* | Besser et al. 2001 | ELS | Biomass | 1224 | 29.2 | 1.99 | 20.32 | 16.74 |
| Chinook salmon, *Oncorhynchus tshawytscha* | Chapman 1975, 1982 | ELS | Biomass | 0.901 | 9.55 | 1.27 | 5.92 | 4.47 |
| Fathead minnow, *Pimephales promelas* | Lind et al. manuscript | ELS | Biomass | 108.4 | 11.4 | 4.00 | 9.38 | 8.67 |

## Evaluation of the Chronic Data Available for Freshwater Species

Following is a species-by-species discussion of each chronic test on copper evaluated for this document. Also presented are the results of regression analysis and probability distribution analysis of each dataset that was from an acceptable chronic test and contained sufficient acceptable data. For each such dataset, this appendix contains a figure that presents the data and regression/probability distribution line.

*Brachionus calyciflorus*. The chronic toxicity of copper was ascertained in 4-day renewal tests conducted at regular intervals throughout the life of the freshwater rotifer, *B. calyciflorus* (Janssen et al. 1994). The goal of this study was to develop and examine the use of this rotifer as a viable test organism. The effect of copper on the age-specific survivorship and fertility of *B. calyciflorus* was determined, but no individual replicate data were provided and only three copper concentrations were tested, which precludes these data from further regression analysis. Chronic limits based on the intrinsic rate of natural increase were 2.5 µg/L total copper (NOAEC) and 5.0 µg/L total copper (LOAEC). The chronic value determined via traditional hypothesis testing is 3.54 µg/L total copper (Table 2a).

*Campeloma decisum*. Adult *C. campeloma* were exposed to five concentrations of total copper and a control (Lake Superior water) under flow-through conditions in two 6-week studies conducted by Arthur and Leonard (1970). Adult survival in the two separate chronic copper toxicity test trials was markedly reduced in the two highest copper concentrations, 14.8 and 28.0 µg/L, respectively. The authors reported that growth, as determined from cast exoskeleton, was not measurable for this test species, although the authors did observe that the adult snails would not consume food at the two highest copper concentrations. Control survival was 80 percent or greater. Chronic values of 10.88 µg/L total copper were obtained for survival based on the geometric mean of the NOAEC and LOAEC of 8.0 and 14.8 µg/L, respectively, in both tests. The corresponding EC20s were 8.73 and 10.94 µg/L (Table 2a).

*Ceriodaphnia dubia*. The chronic toxicity of copper to *C. dubia* was determined in ambient river water collected upstream of known point-source discharges of domestic and industrial wastes as part of a water effect ratio study (Carlson et al. 1986). In this study, survival and young production of *C. dubia* were assessed using a 7-day life-cycle test. Organisms were not affected at total copper concentrations ranging from 3 to 12 µg/L (5 to 10 µg/L dissolved copper). There was a 62.7 percent reduction in survival and 97 percent reduction in the mean number of young produced per female at 32 µg/L total copper (27 µg/L dissolved copper). No daphnids survived to produce young at 91 µg/L total copper. Control survival during the study was 80 percent, which included one male. The chronic value EC20 selected for *C. dubia* in this study, 9.17 µg/L derived from a nonlinear regression evaluation, was based on mean number of young produced (reproduction).

The effects of water hardness on the chronic toxicity of copper to *C. dubia* were assessed by Belanger et al. (1989) using 7-day life-cycle tests. *C. dubia* 2 to 8 hours old were exposed to copper in ambient surface water from the New and Clinch Rivers, Virginia. Mean water hardness levels were 179 and 94 mg/L as $CaCO_3$, respectively. Test water was renewed on days 3 and 5. The corresponding chronic values for reproduction based on the NOAEC and LOAEC approach were 7.9 and <19.3 µg/L dissolved copper, respectively. The EC20 value for number of young (neonates) produced in Clinch River water (water hardness of 94 mg/L as $CaCO_3$) was 19.36 µg/L dissolved copper. The EC20 for young produced in New River water was not calculated. The chronic values were converted to total copper using the freshwater conversion factor for copper 0.96 (e.g., 7.897/0.96). The resulting total chronic values for the New and Clinch rivers are 8.23 and 20.17 µg/L, respectively.

Copper was one of 12 toxicants examined by Oris et al. (1991) in their comparisons between a 4-day survival and reproduction toxicity test utilizing *C. dubia* and a standard 7-day life-cycle test for the species. The reported 7-day chronic values for survival and reproduction (mean total young per living female) in two tests based on the traditional hypothesis testing techniques were 24.5 and 34.6 µg/L total copper. Comparable point estimates for these 7-day tests could not be calculated using regression analysis.

*Daphnia magna*. Blaylock et al. (1985) reported the average numbers of young produced for six broods of *D. magna* in a 14-day chronic exposure to copper. A significant reduction was observed in the mean number of young per female at a concentration of 30 µg/L total copper, the highest copper concentration tested. At this concentration, young were not produced at brood intervals 5 and 6. Reproduction was not affected at 10 µg/L total copper. The chronic value determined for this study (17.32 µg/L total copper) was based on the geometric mean of the NOAEC, 10 µg/L, and LOAEC, 30 µg/L.

Van Leeuwen et al. (1988) conducted a standard 21-day life-cycle test with *D. magna*. The water hardness was 225 mg/L as $CaCO_3$. Carapace length was significantly reduced at 36.8 µg/L total copper, although survival was 100 percent at this concentration. Carapace length was not affected at 12.6 µg/L total copper. No daphnids survived at 110 µg/L concentration. The highest concentration not significantly different from the control for survival was 36.8 µg/L. The lowest concentration significantly different from the control based on survival was 110 µg/L, resulting in a chronic value of 63.6 µg/L for survival. The chronic value based on carapace length was 21.50 µg/L. The 21-day EC10 as reported by the author was 5.9 µg/L total copper.

Chronic (21-day) renewal toxicity tests were conducted using *D. magna* to determine the relationship between water hardness (nominal values of 50, 100, and 200 mg/L as $CaCO_3$, respectively) and the toxicity of total copper (Chapman et al. unpublished manuscript). All test daphnids were <1 day old at the start of the tests. The dilution water was well water from the Western Fish Toxicology Station (WFTS), Corvallis, Oregon. Test endpoints were reproduction (total and live young produced per female) and adult survival. The survival of control animals was 100 percent at nominal water hardness levels of 50 and 200 mg/L as $CaCO_3$, and 80 percent at a hardness of 100 mg/L as $CaCO_3$. The chronic values for total young produced per female (fecundity) based on the geometric mean of the NOAEC and LOAEC were 13.63, 29.33, and 9.53 µg/L at the nominal hardness levels of 50, 100, and 200 mg/L as $CaCO_3$, respectively. The corresponding EC20 values for reproduction calculated using nonlinear regression analysis were 12.58, 19.89, and 6.06 µg/L total copper. The chronic toxicity of copper to *D. magna* was somewhat ameliorated from an increase in water hardness from 50 to 100 mg/L as $CaCO_3$, but slightly increased from 100 to 200 mg/L as $CaCO_3$.

*Daphnia pulex*. Winner (1985) evaluated the effects of water hardness and humic acid on the chronic toxicity (42-day) of copper to *D. pulex*. Contrary to the expectation that sublethal endpoints are more sensitive indicators of chronic toxicity, reproduction was not a sensitive indicator of copper stress in this species. Water hardness also had little effect on the chronic toxicity of copper (similar to *D. magna* trends), but humic acid significantly reduced chronic toxicity of copper when added to the varying water types. The survival chronic values based on the NOAEC and LOAEC values for the three low to no humic acid studies were 4.90, 7.07, and 12.25 µg/L total copper at hardnesses of 57.5, 115, and 230 (0.15 mg/L HA) µg/L as $CaCO_3$, respectively. The EC20 values calculated for the low and high hardness studies using nonlinear regression techniques were 2.83 and 9.16 µg/L at hardness values of 57.5 and 230 (0.15 mg/L HA) µg/L as $CaCO_3$, respectively.

*Clistoronia magnifica*. The effects of copper on the lifecycle of the caddisfly, *C. magnifica*, were examined in Nebeker et al. (1984b). The test included continuous exposure of first-generation aquatic larvae and pupae through to a third generation of larvae. A significant reduction in adult emergence occurred at 13.0 µg/L total copper from first-generation larvae. No observed adverse effect to adult emergence occurred at 8.3 µg/L total copper. Percent larval survival was close to the control value of 80 percent. The chronic value based on hypothesis testing was 10.39 µg/L total copper. The corresponding EC20 value for adult emergence was 7.67 µg/L total copper.

*Oncorhynchus mykiss*. The growth and survival of developing *O. mykiss* embryos continuously and intermittently exposed to copper for up to 85 days post-fertilization was examined by Seim et al. (1984). Results only from the continuous exposure study are considered here for deriving a chronic value. A flow-through apparatus was used to deliver six concentrations and a control (untreated well water; average of 3 µg/L copper) to a single incubation chamber. Continuous copper exposure of steelhead embryos in the incubation chambers was begun 6 days post-fertilization. At 7 weeks post-fertilization, when all control fish had hatched and reached swim-up stage, subsamples of approximately 100 alevins were transferred to aquaria and the same exposure pattern continued. Dissolved oxygen remained near saturation throughout the study. Water hardness averaged 120 mg/L as $CaCO_3$. Survival of steelhead embryos and alevins exposed continuously to total copper concentrations in the range of 3 (controls) to 30 µg/L was greater than 90 percent or greater. Survival was reduced at 57 µg/L and completely inhibited at 121 µg/L. A similar effect on survival was observed for embryos and alevins exposed to a mean of 51 (peak 263) and 109 (peak 465) µg/L of copper in the intermittent exposure, respectively. The adverse effect of continuous copper exposure on growth (measured on a dry weight basis) was observed at concentrations as low as 30 µg/L. (There was a 30 percent reduction in growth during the intermittent exposure at 16 µg/L.) The chronic limits for survival of embryos and alevin steelhead trout exposed continuously to copper were 16 and 31 µg/L, respectively (geometric mean = 22.27 µg/L). The EC20 for biomass for the continuous exposure was 27.77 µg/L.

Besser et al. (2001) conducted an ELS toxicity test with copper and the rainbow trout, *O. mykiss*, starting with eyed embryos and continuing for 30 days after the fish reached the swim-up stage. The total test period was 58 days. The test was conducted in ASTM moderately hard reconstituted water with a hardness of approximately 160 to 180 mg/L as $CaCO_3$. Twenty-five eyed embryos were held in each of four replicate egg cups at each concentration. Survival was monitored daily. At the end of the test, surviving fish in each replicate chamber were weighed (dry weight). Dry weights were used to determine growth and biomass of surviving fish. The no observed effect concentrations (NOECs) for survival and biomass were both 12 µg/L and the lowest observed effect concentrations (LOECs) for survival and biomass was also the same for both endpoints, 22 µg/L. The chronic values for biomass and survival based on the geometric mean of the NOEC and LOEC were 16.25 µg/L. The corresponding EC20 for biomass was 20.32 µg/L.

*Oncorhynchus tshawytscha*. The draft manuscript prepared by Chapman (1975/1982) provides the results from a 4-month egg through fry partial chronic test conducted to determine the effects of copper on survival and growth of *O. tshawytscha*. Continuous exposure occurred from several hours post-fertilization through hatch, swim-up, and feeding fry stages. The test was terminated after 14 weeks post-hatch. The dilution water was WFTS well water. Because of the influence of the nearby Willamette River on the hardness of this well water, reverse osmosis water was mixed periodically with ambient well water to attain a consistent hardness. The typical hardness of this well water was approximately 23 mg/L as $CaCO_3$. Control survival exceeded 90 percent for the test. The measured total copper concentrations during the test were 1.2 (control), 7.4, 9.4, 11.7, 15.5, and 20.2 µg/L, respectively. Copper adversely affected survival at 11.7 µg/L copper and higher, and growth was reduced at all copper concentrations tested compared with the growth of control fish. The chronic limits for copper in this study were estimated to be less than 7.4 µg/L. The EC20 value estimated for biomass is 5.92 µg/L total copper based on a logistic nonlinear regression model.

*Salmo trutta*. McKim et al. (1978) examined the survival and growth (expressed as standing crop) of embryo-larval and early juvenile brown trout to copper. The most sensitive exposure was with embryos exposed for 72 days. The NOAEC and LOAEC, as obtained from the figure, were 20.8 and 43.8 µg/L total copper, respectively. Data were not available to calculate point estimates at the 20 percent effect level using regression analysis. The chronic value selected for this species was 29.91 µg/L total copper (geometric mean of 20.8 and 43.8 µg/L total copper).

*Salvelinus fontinalis*. Sauter et al. (1976) examined the effects of copper on selected freshwater fish species at different hardness levels (softwater at 37.5 mg/L as $CaCO_3$; hardwater at 187 mg/L as $CaCO_3$) during a series of partial life-cycle (PLC) tests. The species tested were brook trout (*Salvelinus fontinalis*), channel catfish (*Ictalurus punctatus*), and walleye (*Stizostedion vitreum*). Because of the poor embryo and larval survival of control animals (in all cases less than 70 percent), results from tests with channel catfish and walleye were not included in Table 2a. One of the replicate control chambers from the PLC tests conducted with brook trout in hard water also exhibited poor hatchability (48 percent) and survival (58 percent) between 31 and 60 days of exposure. Therefore, the data for brook trout in hard water were not included in the subsequent EC20 (regression) analysis either.

The softwater test with brook trout was conducted using untreated well water with an average water hardness of 35 mg/L as $CaCO_3$. This PLC exposure consisted of six copper concentrations and a control. Hatchability was determined by examining randomly selected groups of 100 eggs from each replicate exposure tank. Growth and survival of fry were determined by impartially reducing the total sample size to 50 fry per tank and assessing their progress over 30 day intervals up to 60 days post-hatch. The chronic limits based on the growth (wet weight and total length) of larval brook trout after 60 days of exposure to copper in soft water were <5 and 5 µg/L. The resultant chronic value for soft water based on hypothesis testing was <5 µg/L. The corresponding EC20 values based on total length, wet weight, and biomass (the product of wet weight and survival) for brook trout in the soft-water exposures after 60 days were not amenable to nonlinear regression analysis.

McKim et al. (1978) examined survival and growth (expressed as standing crop) of embryo-larval and early juvenile brook trout exposed to copper. The embryo exposure was for 16 days, and the larval-early-juveniles exposure lasted 60 days. The NOAEC and LOAEC were 22.3 and 43.5 µg/L total copper, respectively. Data were not available to calculate point estimates at the 20 percent effect level using regression analysis. The chronic value for this species was 31.15 µg/L total copper (geometric mean of 22.3 and 43.5 µg/L total copper).

*Salvelinus namaycush*. McKim et al. (1978) examined the survival and growth (expressed as standing crop) of embryo-larval and early juvenile lake trout exposed to copper. The embryo exposure was for 27 days, and the larval-early-juveniles exposure lasted 66 days. The NOAEC and LOAEC were 22.0 and 43.5 µg/L total copper, respectively. Data were not available to calculate point estimates at the 20 percent effect level using regression analysis. The chronic value for this species was 30.94 µg/L total copper (geometric mean of 22.0 and 43.5 µg/L total copper).

*Esox lucius*. McKim et al. (1978) examined the survival and growth (expressed as standing crop) of embryo-larval and early juvenile northern pike exposed to copper. The embryo exposure was for 6 days, and the larval-early-juveniles exposure lasted 34 days. The NOAEC and LOAEC were 34.9 and 104.4 µg/L total copper, respectively. The authors attributed the higher tolerance of *E. lucius* to copper to the very short embryonic exposure period compared with salmonids and white sucker, *Catostomus* *commersoni*. Data were not available to calculate point estimates at the 20 percent effect level using regression analysis. The chronic value for this species was 60.36 µg/L total copper (geometric mean of 34.9 and 104.4 µg/L total copper).

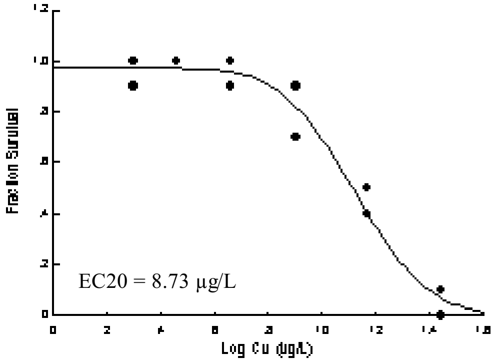
*Pimephales notatus*. An experimental design similar to that described by Mount and Stephan (1967) and Mount (1968) was used to examine the chronic effect of copper on the bluntnose minnow, *P. notatus* (Horning and Neiheisel 1979). Measured total copper concentrations were 4.3 (control), 18.0, 29.9, 44.1, 71.8, and 119.4 µg/L, respectively. The experimental dilution water was a mixture of spring water and demineralized City of Cincinnati tap water. Dissolved oxygen was kept at 5.9 mg/L or greater throughout the test. Total water hardness ranged from 172 to 230 mg/L as $CaCO_3$. The test was initiated with 22 6-week-old fry. The fish were later separated according to sex and thinned to a sex ratio of 5 males and 10 females per duplicated test chamber. Growth (total length) was significantly reduced in parental and first ($F_1$) generation *P. notatus* after 60 days of exposure to the highest concentration of copper tested (119.4 µg/L). Survival of parental *P. notatus* exposed to this same high test concentration was also lower (87 percent) at the end of the test compared with the other concentrations (range of 93 to 100 percent). Copper at concentrations of 18 µg/L and greater significantly reduced the number of eggs produced per female. The number of females available to reproduce was generally the same up to about 29.9 µg/L of copper. The chronic limits were based on an NOAEC and LOAEC of <18 and 18 µg/L for number of eggs produced per female. An EC20 was not estimated by nonlinear regression; nevertheless, in this case an EC20 is likely to be substantially below 18 µg/L.

*Pimephales promelas*. The results from a 30-day ELS toxicity test to determine the chronic toxicity of copper to *P. promelas* using dilution water from Lake Superior (hardness ranging from 40 to 50 mg/L as $CaCO_3$) was included in Table 2a from a manuscript prepared by Lind et al. in 1978. In this experiment, five test concentrations and a control were supplied by a continuous-flow diluter. The exposure began with embryos 1 day post-fertilization. Pooled results from fish dosed in replicate exposure chambers were given for mean percentage embryo survival to hatch, mean percentage fish survival after hatch, and mean fish wet weight after 30 days. The percentage of embryo survival to hatch was not affected by total copper concentrations as high as 52.1 µg/L total copper. Survival after hatch, however, was compromised at 26.2 µg/L, and mean wet weight of juvenile fathead minnows was significantly reduced at 13.1 µg/L of copper. The estimated EC20 value for biomass was 9.376 µg/L total copper.

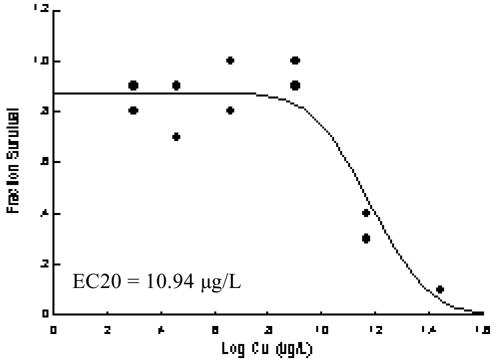
*Catastomus commersoni*. McKim et al. (1978) examined the survival and growth (expressed as standing crop) of embryo-larval and early juvenile white sucker exposed to copper. The embryo exposure was for 13 days, and the larval-early-juvenile exposure lasted 27 days. The NOAEC and LOAEC were 12.9 and 33.8 µg/L total copper, respectively. The resulting chronic value based on hypothesis testing for this species was 20.88 µg/L total copper (geometric mean of 12.9 and 33.8 µg/L total copper).

*Lepomis macrochirus*. Results from a 22-month copper life-cycle toxicity test with bluegill (*L. macrochirus*) were reported by Benoit (1975). The study included a 90-day embryo-larval survival and growth component. The tests were conducted at the U.S. EPA National Water Quality Laboratory in Duluth, Minnesota, using Lake Superior water as the dilution water (average water hardness = 45 mg/L as $CaCO_3$). The test was initiated in December 1969 with 2-year-old juvenile *L. macrochirus*. In May 1971, the fish were sexed and randomly reduced to three males and seven females per tank. Spawning commenced on 10 June 1971. The 90-day embryo-larval exposure was initiated when 12 lots of 50 newly hatched larvae from one of the two control groups were randomly selected and transferred to duplicate grow-out chambers at 1 of 6 total copper concentrations: 3 (control), 12, 21, 40, 77, and 162 µg/L, respectively. In the 22-month juvenile through adult exposure, survival, growth, and reproduction were unaffected at 77 µg/L of copper and below. No spawning occurred at 162 µg/L. Embryo hatchability and survival of 4-day-old larvae at 77 µg/L did not differ significantly from those of controls. However, after 90 days of exposure, survival of larval *L. macrochirus* at 40 and 77 µg/L was significantly lower than for controls, and no larvae survived at 162 µg/L. Growth remained unaffected at 77 µg/L. Based on the 90-day survival of bluegill larvae, the chronic limits were estimated to be 21 and 40 µg/L (geometric mean = 28.98 µg/L). The corresponding EC20 for embryo-larval survival was 27.15 µg/L.

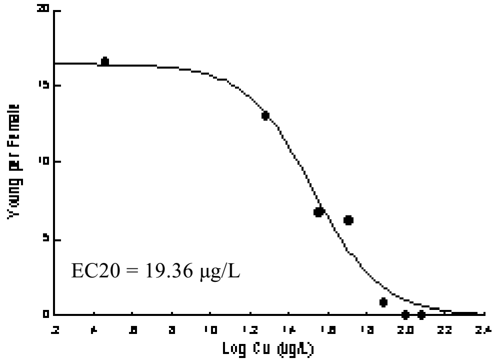
### *Campeloma decisum* (Test 1), Life-cycle, Arthur and Leonard 1970



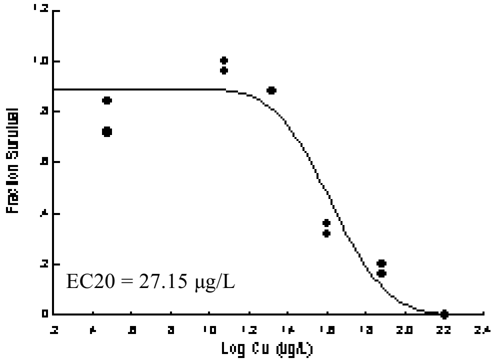
### *Campeloma decisum* (Test 2), Life-cycle, Arthur and Leonard 1970



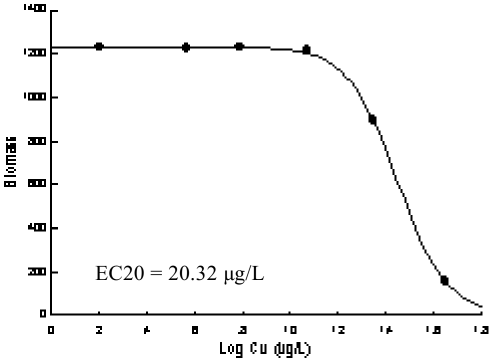
### *Ceriodaphnia dubia* (Clinch River), Life-cycle, Belanger et al. 1989



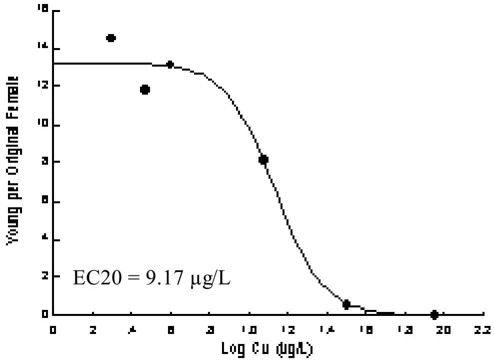
### *Lepomis macrochirus*, Early Life-stage, Benoit 1975



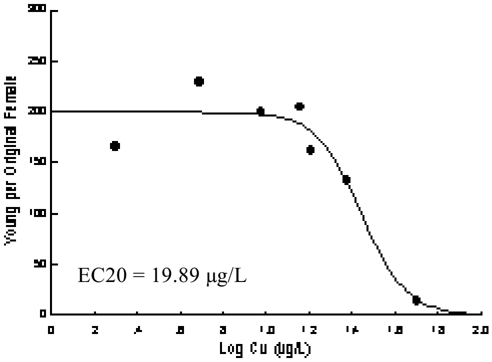
### *Oncorhynchus mykiss*, Early Life-Stage, Besser et al. 2001



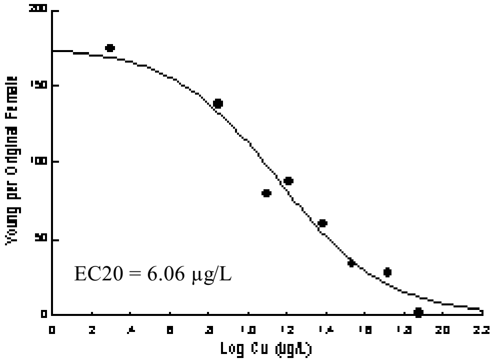
### *Ceriodaphnia dubia*, Life-cycle, Carlson et al. 1986



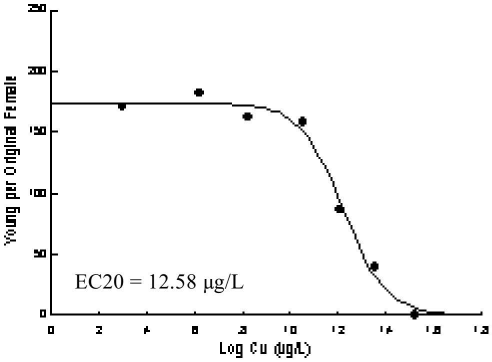
## *Daphnia magna* (Hardness 104), Life-cycle, Chapman et al. Manuscript



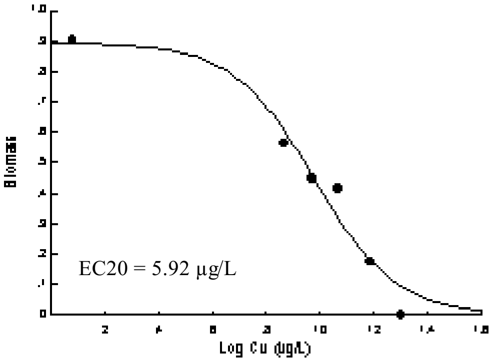
## *Daphnia magna* (Hardness 211), Life-cycle, Chapman et al. Manuscript



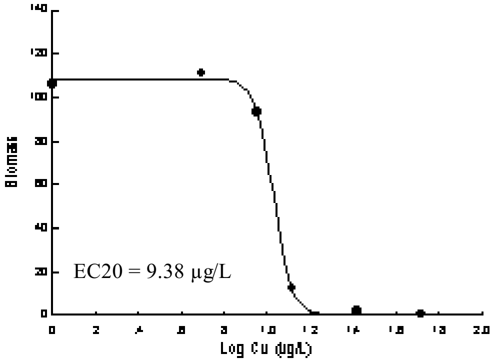
## *Daphnia magna* (Hardness 51), Life-cycle, Chapman et al. Manuscript



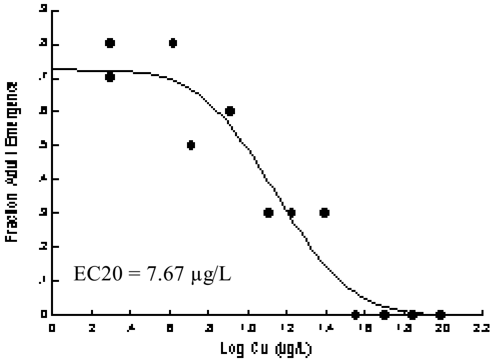
### *Oncorhynchus tshawytscha*, Early Life-Stage, Chapman 1975 & 1982



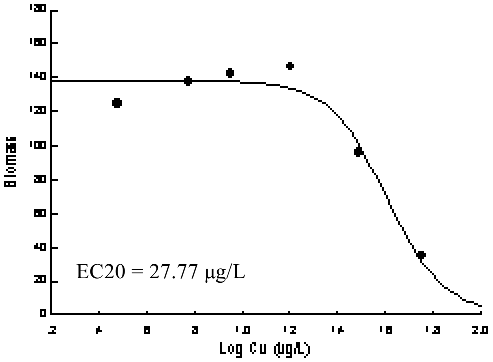
### *Pimephales promelas*, Early Life-stage, Lind et al. 1978



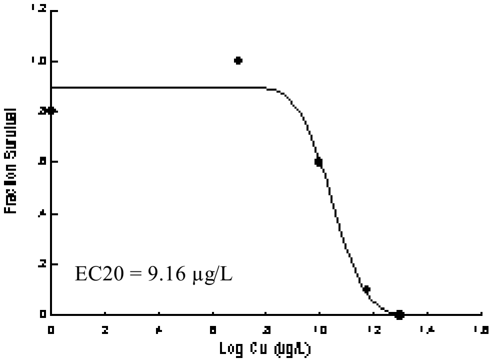
### *Clistoronia magnifica*, Life-cycle, Nebeker et al. 1984a



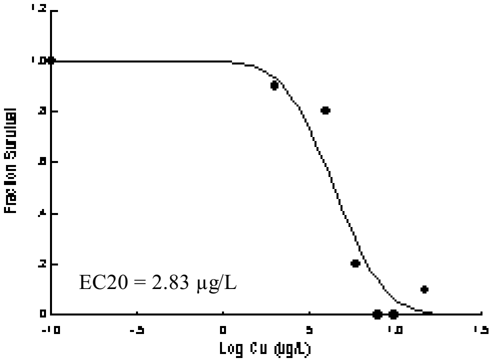
### *Oncorhynchus mykiss,* Early Life-stage, Seim et al. 1984



### *Daphnia pulex* (Hardness 230 HA 0.15), Life-cycle, Winner 1985



### *Daphnia pulex (Hardness 57)*, Life-cycle, Winner 1985



# Appendix G. Example Water Quality Criteria Values Using the BLM and the Hardness Equation

Appendix G: Representative water quality criteria values using the BLM and the Hardness equation approaches for waters with a range in pH, Hardness, and DOC concentrations. The BLM calculation assumed that alkalinity was correlated with pH, and that other major ions were correlated with hardness based on observed correlations in EPA synthetic water recipes.

| pH | Hardness | DOC | Hardness Equation Based Water Quality Criterion for Cu[1] | BLM Based Instantaneous Water Quality Criterion for Cu |
|---|---|---|---|---|
| | mg/L $CaCO_3$ | mg / L | µg / L | µg / L |
| 6.5 | 40 | 2 | 5.9 | 1.6 |
| | | 4 | 5.9 | 3.3 |
| | | 8 | 5.9 | 6.8 |
| | | 16 | 5.9 | 14.3 |
| | 80 | 2 | 11.3 | 1.9 |
| | | 4 | 11.3 | 3.8 |
| | | 8 | 11.3 | 7.7 |
| | | 16 | 11.3 | 16.0 |
| | 159 | 2 | 21.7 | 2.3 |
| | | 4 | 21.7 | 4.5 |
| | | 8 | 21.7 | 9.2 |
| | | 16 | 21.7 | 18.9 |
| | 317 | 2 | 41.5 | 2.8 |
| | | 4 | 41.5 | 5.6 |
| | | 8 | 41.5 | 11.4 |
| | | 16 | 41.5 | 23.1 |
| 7.0 | 40 | 2 | 5.9 | 3.9 |
| | | 4 | 5.9 | 8.0 |
| | | 8 | 5.9 | 16.4 |
| | | 16 | 5.9 | 34.3 |
| | 80 | 2 | 11.3 | 4.4 |
| | | 4 | 11.3 | 8.8 |
| | | 8 | 11.3 | 18.0 |
| | | 16 | 11.3 | 37.0 |
| | 159 | 2 | 21.7 | 5.1 |
| | | 4 | 21.7 | 10.3 |
| | | 8 | 21.7 | 20.7 |
| | | 16 | 21.7 | 42.4 |
| | 317 | 2 | 41.5 | 6.2 |
| | | 4 | 41.5 | 12.4 |
| | | 8 | 41.5 | 24.9 |
| | | 16 | 41.5 | 50.6 |

| pH | Hardness | DOC | Hardness Equation Based Water Quality Criterion for Cu[1] | BLM Based Instantaneous Water Quality Criterion for Cu |
|---|---|---|---|---|
| | mg/L $CaCO_3$ | mg / L | μg / L | μg / L |
| 7.5 | 40 | 2 | 5.9 | 7.9 |
| | | 4 | 5.9 | 15.8 |
| | | 8 | 5.9 | 32.4 |
| | | 16 | 5.9 | 67.3 |
| | 80 | 2 | 11.3 | 8.7 |
| | | 4 | 11.3 | 17.4 |
| | | 8 | 11.3 | 35.3 |
| | | 16 | 11.3 | 72.5 |
| | 159 | 2 | 21.7 | 10.1 |
| | | 4 | 21.7 | 20.1 |
| | | 8 | 21.7 | 40.5 |
| | | 16 | 21.7 | 82.4 |
| | 317 | 2 | 41.5 | 12.0 |
| | | 4 | 41.5 | 23.9 |
| | | 8 | 41.5 | 47.8 |
| | | 16 | 41.5 | 96.8 |
| 8.0 | 40 | 2 | 5.9 | 13.8 |
| | | 4 | 5.9 | 27.6 |
| | | 8 | 5.9 | 55.8 |
| | | 16 | 5.9 | 115.0 |
| | 80 | 2 | 11.3 | 15.5 |
| | | 4 | 11.3 | 30.6 |
| | | 8 | 11.3 | 61.4 |
| | | 16 | 11.3 | 125.1 |
| | 159 | 2 | 21.7 | 18.0 |
| | | 4 | 21.7 | 35.3 |
| | | 8 | 21.7 | 70.3 |
| | | 16 | 21.7 | 142.0 |
| | 317 | 2 | 41.5 | 21.5 |
| | | 4 | 41.5 | 41.6 |
| | | 8 | 41.5 | 82.3 |
| | | 16 | 41.5 | 165.1 |

| pH | Hardness | DOC | Hardness Equation Based Water Quality Criterion for Cu[1] | BLM Based Instantaneous Water Quality Criterion for Cu |
|---|---|---|---|---|
|  | mg/L $CaCO_3$ | mg / L | μg / L | μg / L |
| 8.5 | 40 | 2 | 5.9 | 22.5 |
|  |  | 4 | 5.9 | 43.3 |
|  |  | 8 | 5.9 | 85.6 |
|  |  | 16 | 5.9 | 172.9 |
|  | 80 | 2 | 11.3 | 26.0 |
|  |  | 4 | 11.3 | 49.1 |
|  |  | 8 | 11.3 | 96.0 |
|  |  | 16 | 11.3 | 191.6 |
|  | 159 | 2 | 21.7 | 31.4 |
|  |  | 4 | 21.7 | 58.0 |
|  |  | 8 | 21.7 | 111.7 |
|  |  | 16 | 21.7 | 220.6 |
|  | 317 | 2 | 41.5 | 39.1 |
|  |  | 4 | 41.5 | 70.3 |
|  |  | 8 | 41.5 | 132.8 |
|  |  | 16 | 41.5 | 259.6 |

Notes:

[1] : Hardness Equation: $CMC = e^{(0.9422\,[\ln(H)] - 1.7)}$

where:
H = water hardness (mg/L $CaCO_3$)

* Appendix updated as of March 2, 2007

# Appendix H. Unused Data

## APPENDIX H. UNUSED DATA

Based on the requirements set forth in the guidelines (Stephan et al. 1985), the following studies are not acceptable for the following reasons and are classified as unused data.

### Studies Were Conducted with Species That Are Not Resident in North America

Abalde et al. (1995)
Abel (1980)
Ahsanullah and Ying (1995)
Ahsanullah et al. (1981)
Aoyama and Okamura (1984)
Austen and McEvoy (1997)
Bougis (1965)
Cid et al. (1995, 1996a,b)
Collvin (1984)
Cosson and Martin (1981)
Daly et al. (1990a,b, 1992)
Denton and Burdon-Jones (1986)
Drbal et al. (1985)
Giudici and Migliore (1988)
Giudici et al. (1987, 1988)
Gopal and Devi (1991)
Gustavson and Wangberg (1995)
Hameed and Raj (1989)
Heslinga (1976)
Hori et al. (1996)
Huebner and Pynnonen (1992)
Ismail et al. (1990)
Jana and Bandyopadhyaya (1987)
Jindal and Verma (1989)
Jones (1997)
Kadioglu and Ozbay (1995)
Karbe (1972)
Knauer et al. (1997)
Kulkarni (1983)
Kumar et al. (1985)
Lan and Chen (1991)
Lee and Xu (1984)
Luderitz and Nicklisch (1989)
Majori and Petronio (1973)
Masuda and Boyd (1993)
Mathew and Fernandez (1992)
Maund et al. (1992)
Migliore and Giudici (1988)
Mishra and Srivastava (1980)
Negilski et al. (1981)
Nell and Chvojka (1992)
Neuhoff (1983)
Nias et al. (1993)
Nonnotte et al. (1993)
Pant et al. (1980)
Paulij et al. (1990)
Peterson et al. (1996)
Pistocchi et al. (1997)
Pynnonen (1995)
Raj and Hameed (1991)
Rajkumar and Das (1991)
Reeve et al. (1977)
Ruiz et al. (1994, 1996)
Saward et al. (1975)
Schafer et al. (1993)
Smith et al. (1993)
Solbe and Cooper (1976)
Steeman-Nielsen and Bruun-Laursen (1976)
Stephenson (1983)
Takamura et al. (1989)
Taylor et al. (1991, 1994)
Timmermans (1992)
Timmermans et al. (1992)
Vardia et al. (1988)
Verriopoulos and Moraitou-Apostolopoulou (1982)
Visviki and Rachlin (1991)
Weeks and Rainbow (1991)
White and Rainbow (1982)
Wong and Chang (1991)
Wong et al. (1993)

### Copper Was a Component of a Drilling Mud, Effluent, Mixture, Sediment, or Sludge

Buckler et al. (1987)
Buckley (1994)
Clements et al. (1988)
de March (1988)
Hollis et al. (1996)
Horne and Dunson (1995)
Hutchinson and Sprague (1987)
Kraak et al. (1993 and 1994a,b)
Lowe (1988)
McNaught (1989)
Munkittrick and Dixon (1987)
Pellegrini et al. (1993)
Roch and McCarter (1984a,b)
Roch et al. (1986)
Sayer et al. (1991b)
Weis and Weis (1993)
Widdows and Johnson (1988)
Wong et al. (1982)

## These Reviews Only Contain Data That Have Been Published Elsewhere

Ankley et al. (1993)
Borgmann and Ralph (1984)
Chapman et al. (1968)
Chen et al. (1997)
Christensen et al. (1983)
Dierickx and Brendael-Rozen (1996)
DiToro et al. (1991)
Eisler (1981)
Eisler et al. (1979)
Enserink et al. (1991)
Felts and Heath (1984)
Gledhill et al. (1997)
Handy (1996)
Hickey et al. (1991)
Janssen et al. (1994)
LeBlanc (1984)
Lilius et al. (1994)
Meyer et al. (1987)
Ozoh (1992c)
Peterson et al. (1996)
Phillips and Russo (1978)
Phipps et al. (1995)
Spear and Pierce (1979b)
Starodub et al. (1987b)
Taylor et al. (1996)
Thompson et al. (1972)
Toussaint et al. (1995)

## No Interpretable Concentration, Time, Response Data, or Examined Only a Single Concentration

Asztalos et al. (1990)
Beaumont et al. (1995a,b)
Beckman and Zaugg (1988)
Bjerselius et al. (1993)
Carballo et al. (1995)
Daoust et al. (1984)
De Boeck et al. (1995b, 1997)
Dick and Dixon (1985)
Felts and Heath (1984)
Ferreira (1978)
Ferreira et al. (1979)
Hansen et al. (1993, 1996)
Heath (1987, 1991)
Hughes and Nemcsok (1988)
Julliard et al. (1996)
Koltes (1985)
Kosalwat and Knight (1987)
Kuwabara (1986)
Lauren and McDonald (1985)
Leland (1983)
Lett et al. (1976)
Miller and McKay (1982)
Mis and Bigaj (1997)
Nalewajko et al. (1997)
Nemcsok et al. (1991)
Ozoh (1990)
Ozoh and Jacobson (1979)
Parrott and Sprague (1993)
Pyatt and Dodd (1986)
Riches et al. (1996)
Sayer (1991)
Sayer et al. (1991a,b)
Schleuter et al. (1995, 1997)
Starcevic and Zielinski (1997)
Steele (1989)
Taylor and Wilson (1994)
Viale and Calamari (1984)
Visviki and Rachlin (1994b)
Waiwood (1980)
Webster and Gadd (1996)
Wilson and Taylor (1993a,b)
Winberg et al. (1992)
Wundram et al. (1996)
Wurts and Perschbacher (1994)

## No Useable Data on Copper Toxicity or Bioconcentration

Cowgill et al. (1986)
de March (1979)
Lehman and Mills (1994)
Lustigman (1986)
Lustigman et al. (1985)
MacFarlane et al. (1986)
van Hoof et al. (1994)
Weeks and Rainbow (1992)
Wong et al. (1977)
Wren and McCarroll (1990)
Zamuda et al. (1985)

## Results Not Interpretable as Total or Dissolved Copper

Brand et al. (1986)
MacFie et al. (1994)
Riedel (1983)
Sanders and Jenkins (1984)
Sanders and Martin (1994)
Sanders et al. (1995)
Stearns and Sharp (1994)
Stoecker et al. (1986)
Sunda et al. (1987)
Winberg et al. (1992)

Some of these studies would be valuable if copper criteria were developed on the basis of cupric ion activity.

## Organisms Were Selected, Adapted or Acclimated for Increased Resistance to Copper

Fisher (1981)
Fisher and Fabris (1982)
Hall (1980)
Hall et al. (1989)
Harrison and Lam (1983)
Harrison et al. (1983)
Lumoa et al. (1983)
Lumsden and Florence (1983)
Munkittrick and Dixon (1989)
Myint and Tyler (1982)
Neuhoff (1983)
Parker (1984)
Phelps et al. (1983)
Ray et al. (1981)
Sander (1982)
Scarfe et al. (1982)
Schmidt (1978a,b)
Sheffrin et al. (1984)
Steele (1983b)
Takamura et al. (1989)
Viarengo et al. (1981a,b)
Wood (1983)

## Either the Materials, Methods, Measurements or Results Were Insufficiently Described

Abbe (1982)
Alam and Maughan (1995)
Balasubrahmanyam et al. (1987)
Baudouin and Scoppa (1974)
Belanager et al. (1991)
Benedeczky et al. (1991)
Benedetti et al. (1989)
Benhra et al. (1997)
Bouquegneau and Martoja (1982)
Burton and Stemmer (1990)
Burton et al. (1992)
Cabejszek and Stasiak (1960)
Cain and Luoma (1990)
Chapman (1975, 1982)
Cochrane et al. (1991)
Devi et al. (1991)
Dirilgen and Inel (1994)
Dodge and Theis (1979)
Doucet and Maly (1990)
Dunbar et al. (1993)
Durkina and Evtushenko (1991)
Enesco et al. (1989)
Erickson et al. (1997)
Evans (1980)
Ferrando and Andreu (1993)
Finlayson and Ashuckian (1979)
Furmanska (1979)
Gibbs et al. (1981)
Gordon et al. (1980)
Gould et al. (1986)
Govindarajan et al. (1993)
Hayes et al. (1996)
Howard and Brown (1983)
Janssen et al. (1993)
Janssen and Persoone (1993)
Kean et al. (1985)
Kentouri et al. (1993)
Kessler (1986)
Khangarot et al. (1987)
Kobayashi (1996)
Kulkarni (1983)
Labat et al. (1977)
Lakatos et al. (1993)
LeBlanc (1985)
Leland et al. (1988)
Mackey (1983)
Magni (1994)
Martin et al. (1984)
Martincic et al. (1984)
McIntosh and Kevern (1974)
McKnight (1980)
Moore and Winner (1989)
Muramoto (1980, 1982)
Nyholm and Damgaard (1990)
Peterson et al. (1996)
Pophan and D'Auria (1981)
Reed-Judkins et al. (1997)
Rehwoldt et al. (1973)
Riches et al. (1996)
Sakaguchi et al. (1977)
Sanders et al. (1995)
Sayer (1991)
Schultheis et al. (1997)
See et al. (1974)
Shcherban (1977)
Smith et al. (1981)
Sorvari and Sillanpaa (1996)
Stearns and Sharp (1994)
Strong and Luoma (1981)
Sullivan and Ritacco (1988)
Taylor (1978)
Taylor et al. (1994)
Thompson (1997)
Trucco et al. (1991)
Verma et al. (1980)
Visviki and Rachlin (1994a)
Watling (1983)
Winner et al. (1990)
Young and Harvey (1988, 1989)
Zhokhov (1986)

### Questionable Effect Levels Due to Graphical Presentation of Results

Alliot and Frenet-Piron (1990)
Andrew (1976)
Arsenault et al. (1993)
Balasubrahmanyam et al. (1987)
Bjerselius et al. (1993)
Bodar et al. (1989)
Chen (1994)
Cowgill and Milazzo (1991b)
Cvetkovic et al. (1991)
Dodoo et al. (1992)
Francisco et al. (1996)
Gupta et al. (1985)
Hansen et al. (1996)
Hoare and Davenport (1994)
Lauren and McDonald (1985)
Llanten and Greppin (1993)
Metaxas and Lewis (1991)
Michnowicz and Weeks (1984)
Miersch et al. (1997)
Nasu et al. (1988)
Pearlmutter and Lembi (1986)
Pekkala and Koopman (1987)
Peterson et al. (1984)
Romanenko and Yevtushenko (1985)
Sanders et al. (1994)
Smith and Heath (1979)
Stokes and Hutchinson (1976)
Winner and Gauss (1986)
Wong (1989)
Young and Lisk (1972)

### Studies of Copper Complexation With No Useable Toxicology Data for Surface Waters

Borgmann (1981)
Filbin and Hough (1979)
Frey et al. (1978)
Gillespie and Vaccaro (1978)
Guy and Kean (1980)
Jennett et al. (1982)
Maloney and Palmer (1956)
Nakajima et al. (1979)
Stauber and Florence (1987)
Sunda and Lewis (1978)
Swallow et al. (1978)
van den Berg et al. (1979)
Wagemann and Barica (1979)

### Questionable Treatment of Test Organisms or Inappropriate Test Conditions or Methodology

Arambasic et al. (1995)
Benhra et al. (1997)
Billard and Roubaud (1985)
Bitton et al. (1995)
Brand et al. (1986)
Bringmann and Kuhn (1982)
Brkovic-Popovic and Popovic (1977a,b)
Dirilgen and Inel (1994)
Folsom et al. (1986)
Foster et al. (1994)
Gavis et al. (1981)
Guanzon et al. (1994)
Hawkins and Griffith (1982)
Ho and Zubkoff (1982)
Hockett and Mount (1996)
Huebert et al. (1993)
Huilsom (1983)
Jezierska and Slominska (1997)
Kapu and Schaeffer (1991)
Kessler (1986)
Khangarot and Ray (1987a)
Khangarot et al. (1987)
Lee and Xu (1984)
Marek et al. (1991)
McLeese (1974)
Mis et al. (1995)
Moore and Winner (1989)
Nasu et al. (1988)
Ozoh and Jones (1990b)
Reed and Moffat (1983)
Rueter et al. (1981)
Sayer et al. (1989)
Schenck (1984)
Shaner and Knight (1985)
Sullivan et al. (1983)
Tomasik et al. (1995)
Watling (1981, 1982, 1983)
Wikfors and Ukeles (1982)
Wilson (1972)
Wong and Chang (1991)
Wong (1992)

High control mortalities occurred in all except one test reported by Sauter et al. (1976). Control mortality exceeded 10% in one test by Mount and Norberg (1984). Pilgaard et al. (1994) studied interactions of copper and hypoxia, but failed to run a hypoxic control. Beaumont et al. (1995a,b) studied interactions of temperature, acid pH and copper, but never separated pH and copper effects. The 96-hour values reported by Buikema et al. (1974a,b) were subject to error because of possible reproductive interactions (Buikema et al. 1977).

### Bioconcentration Studies Not Conducted Long Enough, Not Steady-State, Not Flow-through, or Water Concentrations Not Adequately Characterized or Measured

Anderson and Spear (1980a)
Felton et al. (1994)
Griffin et al. (1997)
Harrison et al. (1988)
Krantzberg (1989)
Martincic et al. (1992)
McConnell and Harrel (1995)
Miller et al. (1992)
Ozoh (1994)
Wright and Zamuda (1987)
Xiaorong et al. (1997)
Yan et al. (1989)
Young and Harvey (1988, 1989)
Zia and Alikhan (1989)

Anderson (1994), Anderson et al. (1994), Viarengo et al. (1993), and Zaroogian et al. (1992) reported on *in vitro* exposure effects. Benedeczky et al. (1991) studied only effects of injected copper. Ferrando et al. (1993b) studied population effects of copper and cladoceran predator on the rotifer prey, but the data are difficult to interpret. A similar problem complicated use of the cladoceran competition study of LeBlanc (1985).