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

This document can be downloaded from EPA's website at:
http://www.epa.gov/waterscience/criteria/aqlife.html

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.

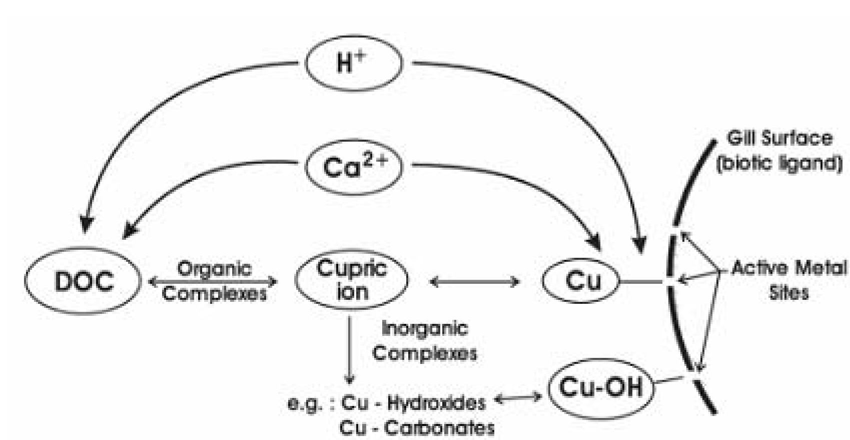


Figure1. Conceptual Diagram of Copper Speciation and Copper-Gill Model (after Pagenkopf, 1983)

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:

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

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

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

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, α_{Cu+2} is the ratio of free copper concentration to total dissolved copper concentration, α_{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 α_{Cu+2} and α_{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.

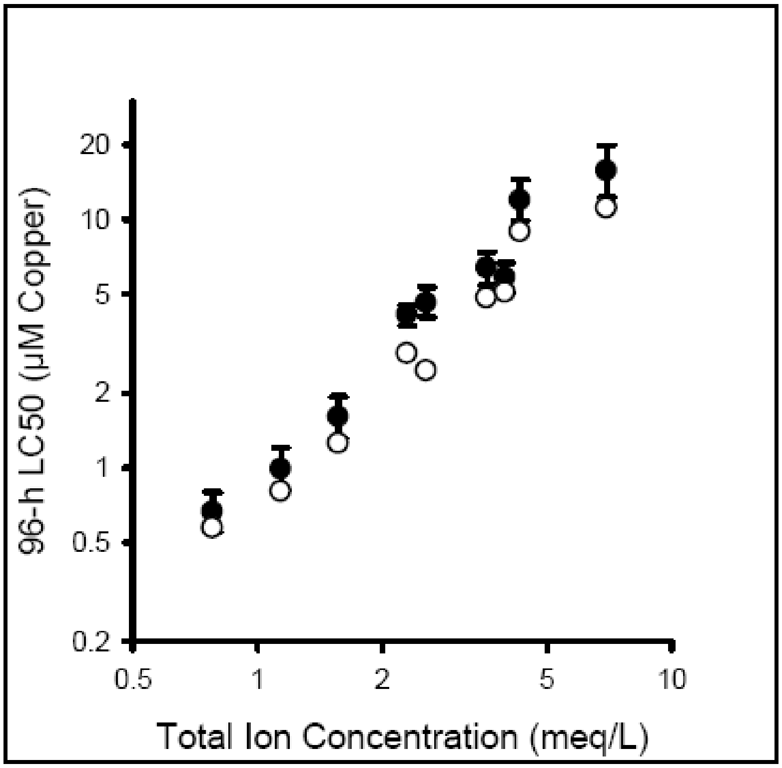


Figure 2. Effects of increasing total ion concentration on the acute lethality of copper to fathead minnows at constant pH=8 and low DOC < 0.5 mg/L. Solid symbols represent observed values, open symbols represent predicted values.

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.

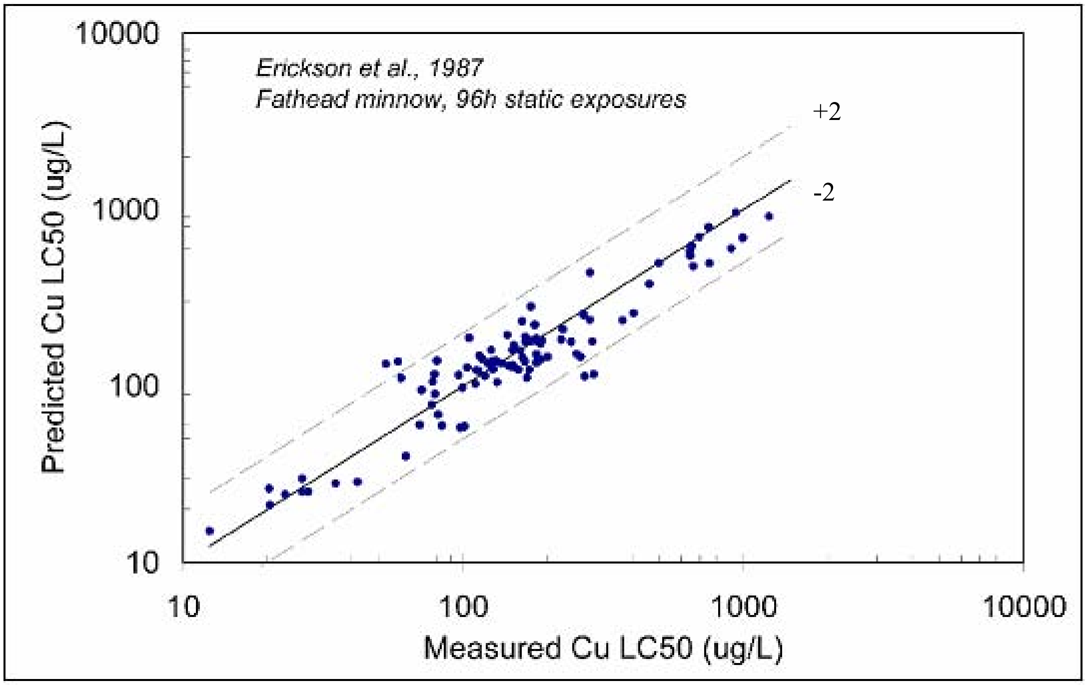


Figure 3. Comparison of Predicted and Measured Acute Copper Toxicity to *P. promelas*.

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 31.39 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

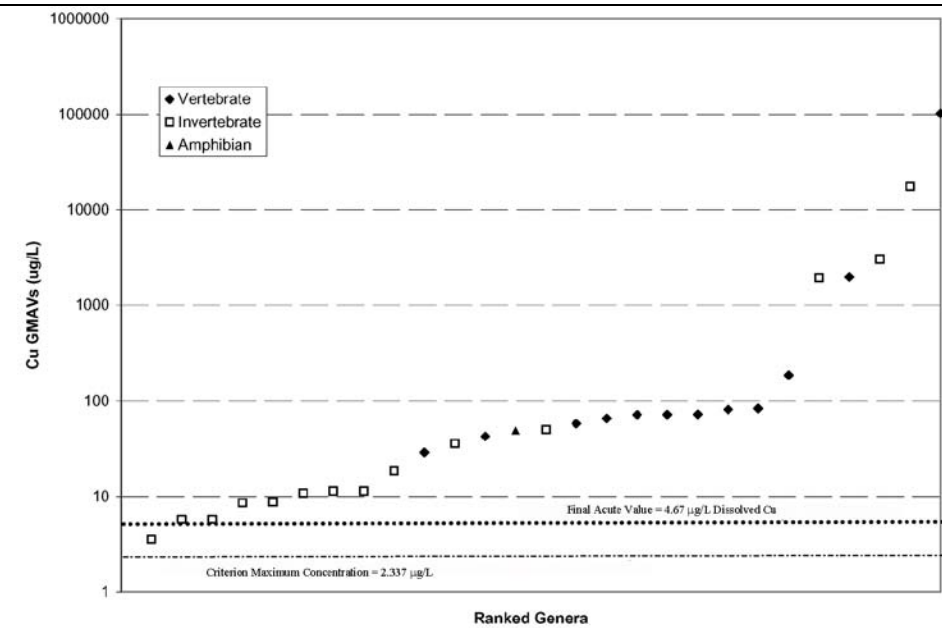


Figure 4. Ranked Freshwater Genus Mean Acute Values (GMAVs)

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.

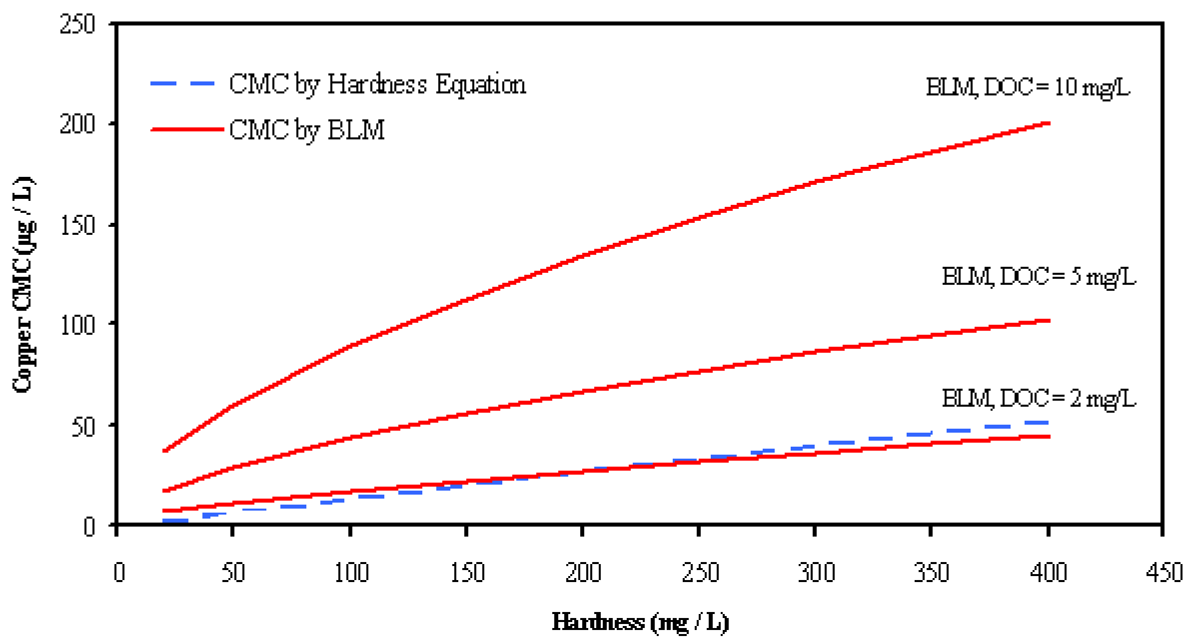


Figure 5. Comparison of CMC calculated by BLM or Hardness Equation Alkalinity (11 - 245 mg CaCO3/L) and pH (7.3 - 8.7) Covary with Hardness

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.

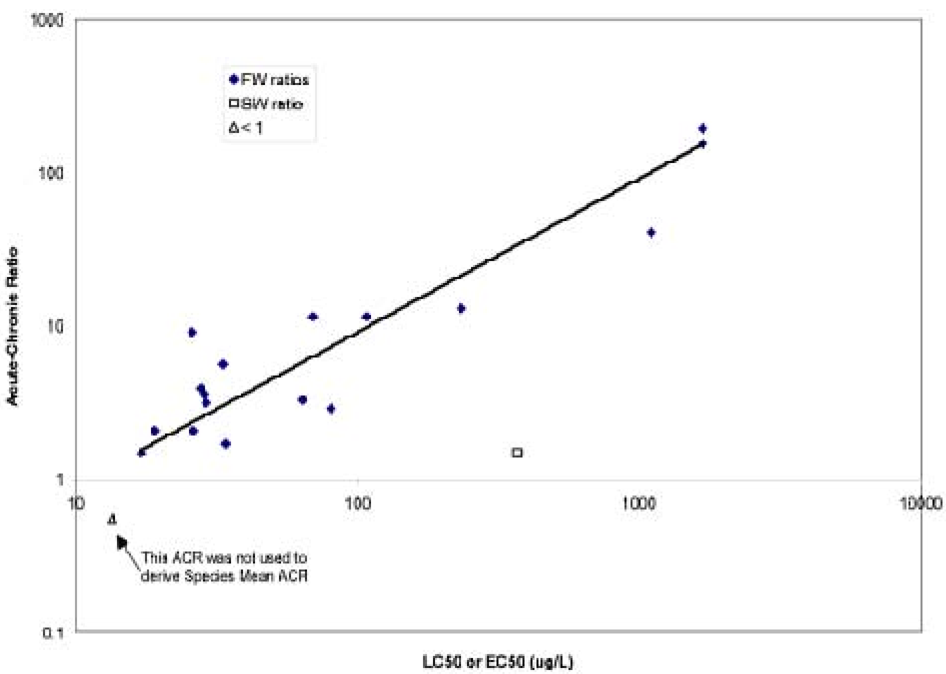


Figure 6. Relationship Between Freshwater Acute Copper Sensitivity (LC50 or EC50) and Acute-Chronic Ratios

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,	1-3 d	F,M,T	S	22	---	GAPS01F	10.39	9.60	Arthur and Leonard 1970
Gammarus	1-3 d	F,M,T	S	19	---	GAPS02F	8.86		Arthur and Leonard 1970
Amphipod,	7-14 d	S,M,T	N	17	---	HYAZ01S	12.19	12.07	Schubauer-Berigan et al. 1993
Hyalella azteca	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	larval, 0.34 g	S,M,T	S	80	---	ONCL01S	34.26	32.97	Dwyer et al. 1995
Oncorhynchus clarki henshawi	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,	alevin (newly hatched	F,M,T	S	190	---	ONNE01F	71.73	54.82	Servizi and Martens 1978
Oncorhynchus nerka	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,	alevin, 0.05 g	F,M,T	C	26	---	ONTS01F	14.48	25.02	Chapman 1975, 1978
Oncorhynchus tshav	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, *Salvelinus confluenti*	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, *Acrocheilus*	4.6 cm, 1.25 g	F,M,T	C	143	---	ACAL01F	216.3	216.3	Andros and Garton 1980
Bonytail chub, *Gila elegans*	larval, 0.29 g	S,M,T	S	200	---	GIEL01S	63.22	63.22	Dwyer et al. 1995
Golden shiner, *Notemigonus crysoleucas*	---	F,M,T	C	84600	---	NOCR01F	107860	107860	Hartwell et al. 1989
Fathead minnow, *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, *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, *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, *Etheostoma rubrum*	2.02 cm, 0.062 g	S,M,T	S	60	---	ETRU01S	22.74	22.74	Dwyer et al. 1999
Boreal toad, *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 by 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] (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] (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: Chronic Value[b] (µg/L)	Chronic Values: EC20[b] (µg/L)	Species Mean Chronic Value (Total µg/L)	Genus Mean Chronic Value (Total µg/L)	ACR	Reference
Caddisfly, *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, *Oncorhynchus mykiss*	ELS,T continuous	Copper chloride	Biomass	120			27.77	23.8	11.9	2.881	Seim et al. 1984
Rainbow trout, *Oncorhynchus mykiss*	ELS,T	Copper sulfate	Biomass	160-180	12-22	16.25	20.32				Besser et al. 2001
Chinook salmon, *Oncorhynchus tshawytscha*	ELS,T	Copper chloride	Biomass	20-45	<7.4	<7.4	5.92	5.92		5.594	Chapman 1975, 1982
Brown trout, *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, *Salvelinus fontinalis*	PLC,T	Copper sulfate	Biomass	35.0	<5 -5	<5	-	12.5	19.7		Sauter et al. 1976
Brook trout, *Salvelinus fontinalis*	ELS,T	Copper sulfate	Biomass	45.4	22.3-43.5	31.15	-				McKim et al. 1978
Lake trout, *Salvelinus namaycush*	ELS, T	Copper sulfate	Biomass	45.4	22.0-43.5	30.94	-	30.9			McKim et al. 1978
Northern pike, *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 *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, *Pimephales promelas*	ELS,T,D	-	Biomass	45			9.38	9.38		11.40	Lind et al. manuscript
White sucker, *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), *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,	[redacted]	28.42[b]	7.90	3.60	[redacted]		
Ceriodaphnia dubia	[redacted]	63.33[b]	19.36	3.27	[redacted]		
	57	13.4	24.5	0.55	Oris et al. 1991		
	--	[redacted]	9.17	1.96	[redacted]	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	[redacted]		
Daphnia pulex	115	27.6	7.07	3.90	[redacted]		
	230	28.79	9.16	3.14	[redacted]	4.82	✓
Rainbow trout, *Oncorhynchus mykiss*	120	80	27.77	2.88	Seim et al. 1984	2.88	✓
Chinook salmon, *Oncorhynchus tshawytscha*	20-45	33.1	5.92	5.59	Chapman 1975, 1982	5.59	✓
Bluntnose minnow, *Pimephales notatus*	172-230	231.9[e]	18	12.88	Horning and Neiheisel 1979	12.88	
Fathead minnow, *Pimephales promelas*	45	106.875[f]	9.38	11.40	Lind et al. 1978	11.40	
Bluegill, *Lepomis macrochirus*	21-40	1100	27.15	40.52	Benoit 1975	40.49	
Sheepshead minnow, *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	107,860	Golden shiner, *Notemigonus crysoleucas*	107,860	
26	20,636	Stonefly, *Acroneuria lycorias*	20,636	
25	3,573	Snail, *Campeloma decisum*	3,573	171.19
24	2,231	Bluegill sunfish, *Lepomis macrochirus*	2,231	40.49
23	1,987	Midge, *Chironomus decorus*	1,987	
22	216.3	Chiselmouth, *Acrocheilus alutaceus*	216.3	
21	80.38	Fantail darter, *Etheostoma flabellare*	124.3	
		Greenthroat darter, *Etheostoma lepidum*	82.80	
		Johnny darter, *Etheostoma nigrum*	178.3	
		Fountain darter, *Etheostoma rubrum*	22.74	
20	78.66	Razorback sucker, *Xyrauchen texanus*	78.66	
19	69.63	Fathead minnow, *Pimephales promelas*	69.63	11.40
18	69.63	Shovelnose sturgeon, *Scaphirhynchus platorynchus*	69.63	
17	68.31	Bull trout, *Salvelinus confluentus*	68.31	
16	63.22	Bonytail chub, *Gila elegans*	63.22	
15	56.15	Gila topminnow, *Poeciliposis occidentalis*	56.15	
14	52.51	Freshwater mussel, *Utterbackia imbecillis*	52.51	
13	48.41	Worm, *Lumbriculus variegatus*	48.41	
12	47.49	Boreal toad, *Bufo boreas*	47.49	
11	43.94	Colorado squawfish, *Ptychocheilus lucius*	132.2	
		Northern squawfish, *Ptychocheilus oregonensis*	14.61	
10	31.39	Apache trout, *Oncorhynchus apache*	32.54	
		Cutthroat trout, *Oncorhynchus clarki*	32.97	
		Pink salmon, *Oncorhynchus gorbuscha*	40.13	
		Coho salmon, *Oncorhynchus kisutch*	22.93	
		Rainbow trout, *Oncorhynchus mykiss*	22.19	2.88
		Sockeye salmon, *Oncorhynchus nerka*	54.82	
		Chinook salmon, *Oncorhynchus tshawytscha*	25.02	5.59
9	20.41	Snail, *Physa integra*	20.41	
8	12.31	Snail, *Juga plicifera*	12.31	
7	12.07	Amphipod, *Hyalella azteca*	12.07	
6	11.33	Freshwater mussel, *Actinonaias pectorosa*	11.33	
5	9.73	Cladoceran, *Scapholeberis sp.*	9.73	
4	9.60	Amphipod, *Gammarus pseudolimnaeus*	9.60	
3	6.67	Snail, *Lithoglyphus virens*	6.67	
2	5.93	Cladoceran, *Ceriodaphnia dubia*	5.93	2.85
1	4.05	Cladoceran, *Daphnia magna*	6.00	3.42
		Cladoceran, *Daphnia pulicaria*	2.73	

* Table updated as of March 2, 2007

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, *Anabaena flos-aqua*	S,U	Copper sulfate	65.2	96 hr	EC75 (cell density)	200	Young and Lisk 1972
Bllue-green alga, *Anabaena variabilis*	S,U	Copper sulfate	65.2	-	EC85 (wet weight)	100	Young and Lisk 1972
Blue-green alga, *Anabaena* strain 7120	-	-	-	-	Lag in growth	64	Laube et al. 1980
Blue-green alga, *Chroococcus paris*	S,U	Copper nitrate	54.7	10 days	Growth reduction	100	Les and Walker 1984
Blue-green alga, *Microcystis aeruginosa*	S,U	Copper sulfate	54.9	8 days	Incipient inhibition	30	Bringmann 1975; Bringmann and Kuhn 1976, 1978a,b
Alga, *Ankistrodesmus braunii*	-	-	-	-	Growth reduction	640	Laube et al. 1980
Green alga, *Chlamydomonas* sp.	S,U	Copper sulfate	68	10 days	Growth inhibition	8,000	Cairns et al. 1978
Green alga, *Chlamydomonas reinhardtii*	S,M,T	-	90 - 133	72 hr	NOEC (deflagellation)	12.2-49.1	Winner and Owen 1991a
Green alga, *Chlamydomonas reinhardtii*	S,M,T	-	90 - 133	72 hr	NOEC (cell density)	12.2-43.0	Winner and Owen 1991a
Green alga, *Chlamydomonas reinhardtii*	F,M,T	-	24	10 days	EC50 (cell density)	31.5	Schafer et al. 1993
Green alga, *Chlorella pyrenoidosa*	S,U	-	-	96 hr	ca. 12 hr lag in growth	1	Steeman-Nielsen and Wium-Andersen 1970
Green alga, *Chlorella pyrenoidosa*	S,U	-	54.7	-	Growth inhibition	100	Steeman-Nielsen and Kamp-Nielsen 1970
Green alga, *Chlorella pyrenoidosa*	S,U	Copper sulfate	365	14 days	EC50 (dry weight)	78-100	Bednarz and Warkowska-Dratnal 1985
Green alga, *Chlorella pyrenoidosa*	S,U	Copper sulfate	36.5	14 days	EC50 (dry weight)	78-100	Bednarz and Warkowska-Dratnal 1985
Green alga, *Chlorella pyrenoidosa*	S,U	Copper sulfate	3.65	14 days	EC50 (dry weight)	78-100	Bednarz and Warkowska-Dratnal 1983/1984
Green alga, *Chlorella saccharophila*	S,U	Copper chloride	-	96 hr	96-h EC50	550	Rachlin et al. 1982
Green alga, *Chlorella vulgaris*	S,U	Copper sulfate	2,000	96 hr	Growth inhibition	200	Young and Lisk 1972
Green alga, *Chlorella vulgaris*	S,U	Copper chloride		33 days	EC20 (growth)	42	Rosko and Rachlin 1977
Green alga, *Chlorella vulgaris*	F,U	Copper sulfate	-	96 hr	EC50 or EC50 (cell numbers)	62	Ferard et al. 1983
Green alga, *Chlorella vulgaris*	S,M,D	Copper sulfate	-	96 hr	IC50	270	Ferard et al. 1983
Green alga, *Chlorella vulgaris*	S,M,T	Copper chloride	-	96 hr	EC50 (cell density)	200	Blaylock et al. 1985
Green alga, *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, *Scenedesmus quadricauda*	S,U	Copper sulfate	68	10 days	Growth reduction	8,000	Cairns et al. 1978
Green alga, *Scenedesmus quadricauda*	S,U	Copper sulfate	181	7 days	LOEC (growth)	1,100	Bringmann and Kuhn 1977a, 1978a,b, 1979, 1980a
Green alga, *Selenastrum capricornutum*	S,U	Copper chloride	14.9	14 days	EC50 (cell volume)	85	Christensen et al. 1979
Green alga, *Selenastrum capricornutum*	S,U	Copper chloride	14.9	7 days	LOEC (growth)	50	Bartlett et al. 1974
Green alga, *Selenastrum capricornutum*	S,M,T	Copper chloride	24.2	96 hr	EC50 (cell count)	400	Blaylock et al. 1985
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	9.3	96 hr	EC50 (cell count)	48.4	Blaise et al. 1986
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	9.3	96 hr	EC50 (cell count)	44.3	Blaise et al. 1986
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	9.3	96 hr	EC50 (cell count)	46.4	Blaise et al. 1986
Green alga, *Selenastrum capricornutum*	S,U	Copper chloride	15	2-3 wk	EC50 (biomass)	53.7	Turbak et al. 1986
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	14.9	5 days	Growth reduction	58	Nyholm 1990
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	9.3	96 hr	EC50 (cell count)	69.9	St. Laurent et al. 1992
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	9.3	96 hr	EC50 (cell count)	65.7	St. Laurent et al. 1992
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	24.2	96 hr	EC50 (cell count)	54.4	Radetski et al. 1995
Green alga, *Selenastrum capricornutum*	R,U	Copper sulfate	24.2	96 hr	EC50 (cell count)	48.2	Radetski et al. 1995
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	16	96 hr	EC50 (cell density)	38	Chen et al. 1997
Algae, mixed culture	S,U	Copper sulfate	-	-	Significant reduction in blue-green algae and nitrogen fixation	5	Elder and Horne 1978
Diatom, *Cyclotella meneghiniana*	S,U	Copper sulfate	68	10 days	Growth inhibition	8,000	Cairns et al. 1978
Diatom, *Navicula incerta*	S,U	Copper chloride	-	96 hr	EC50	10,429	Rachlin et al. 1983
Diatom, *Nitzschia linearis*	-	-	-	5 day	EC50	795-815	Academy of Natural Sciences 1960; Patrick et al. 1968
Diatom, *Nitzschia palea*	-	-	-	-	Complete growth inhibition	5	Steeman-Nielsen and Wium-Andersen 1970
Duckweed, *Lemna minor*	F	-	-	7 day	EC50	119	Walbridge 1977
Duckweed, *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, *Lemna minor*	S,U	-	0	96 hr	EC50 (frond number)	1,100	Wang 1986
Duckweed, *Lemna minor*	S,U	Copper sulfate	78	96 hr	EC50 (chlorophyll a reduction)	250	Eloranta et al. 1988
Duckweed, *Lemna minor*	R,M,T	Copper nitrate	39	96 hr	Reduced chlorophyll production	24	Taraldsen and Norberg-King 1990
Eurasian watermilfoil, *Myriophyllum spicatum*	S,U	-	89	32 days	EC50 (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.

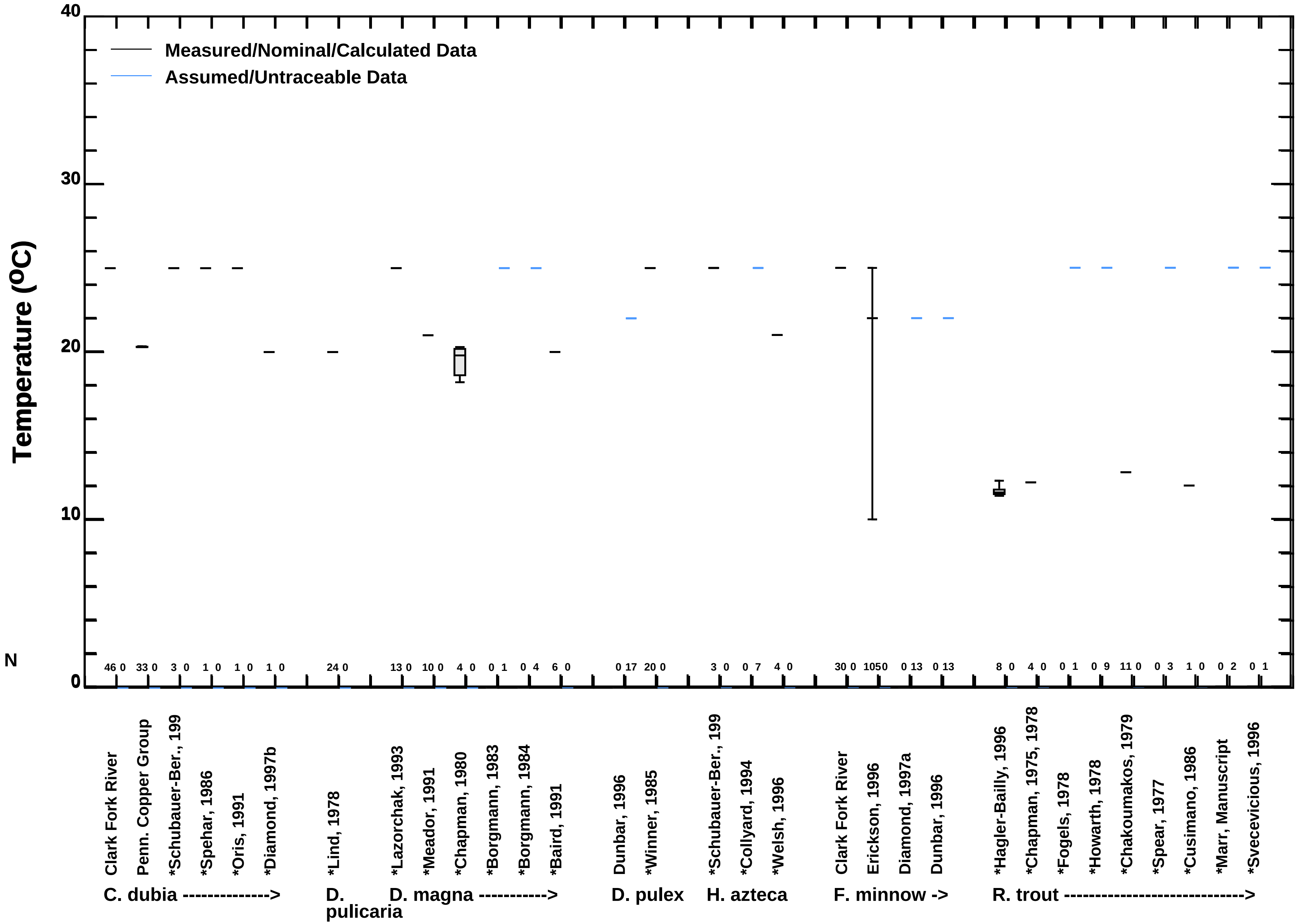
Wood, C. M., Adams, W. J., Ankley, G. T., DiBona, D. R., Luoma, W. N., Playle, R. C., Stubblefield, W. A., Bergman, H. L., Erickson, R. J., Mattice, J. S., and Schlekat, C. E. 1997. Environmental toxicology of metals. In Bergman, H. L., and Dorward-King, E. J. (eds.) Reassessment of Metals Criteria for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

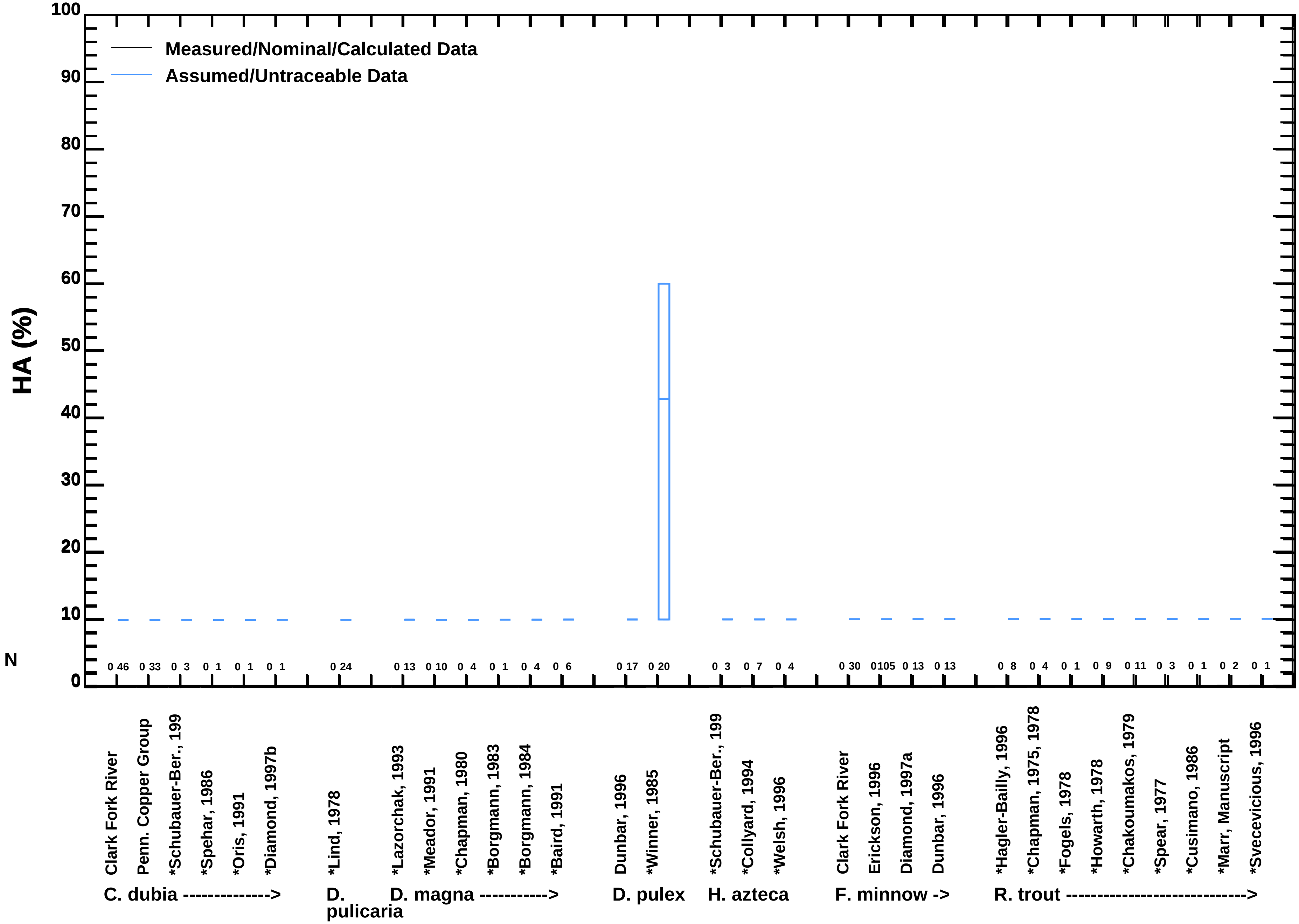
Zitko, V., and Carson, W. G. 1976. A mechanism of the effects of water hardness on the lethality of heavy metals to fish. Chemosphere 5:299-303.

Appendices

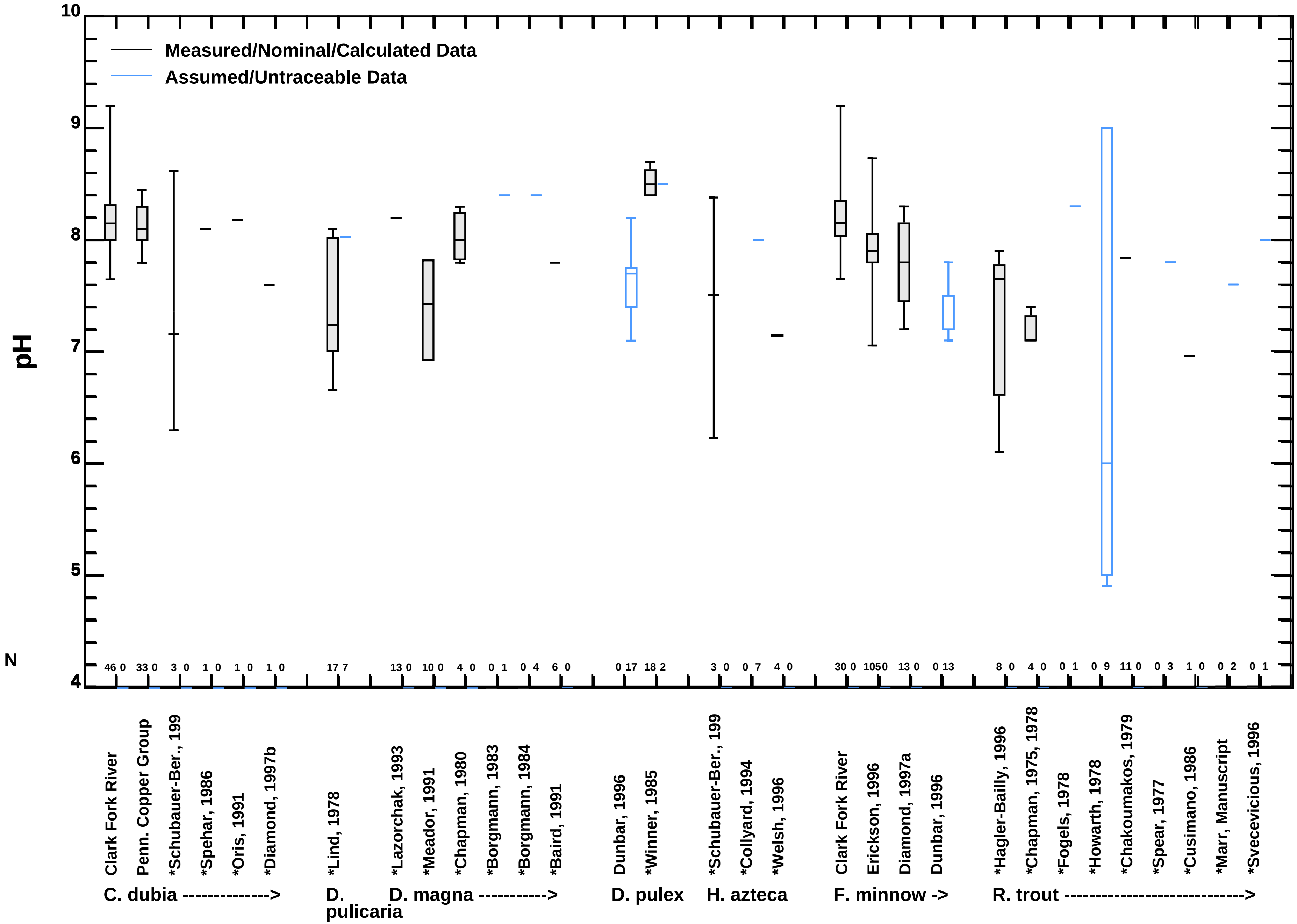
Appendix A. Ranges in Calibration and Application Data Sets



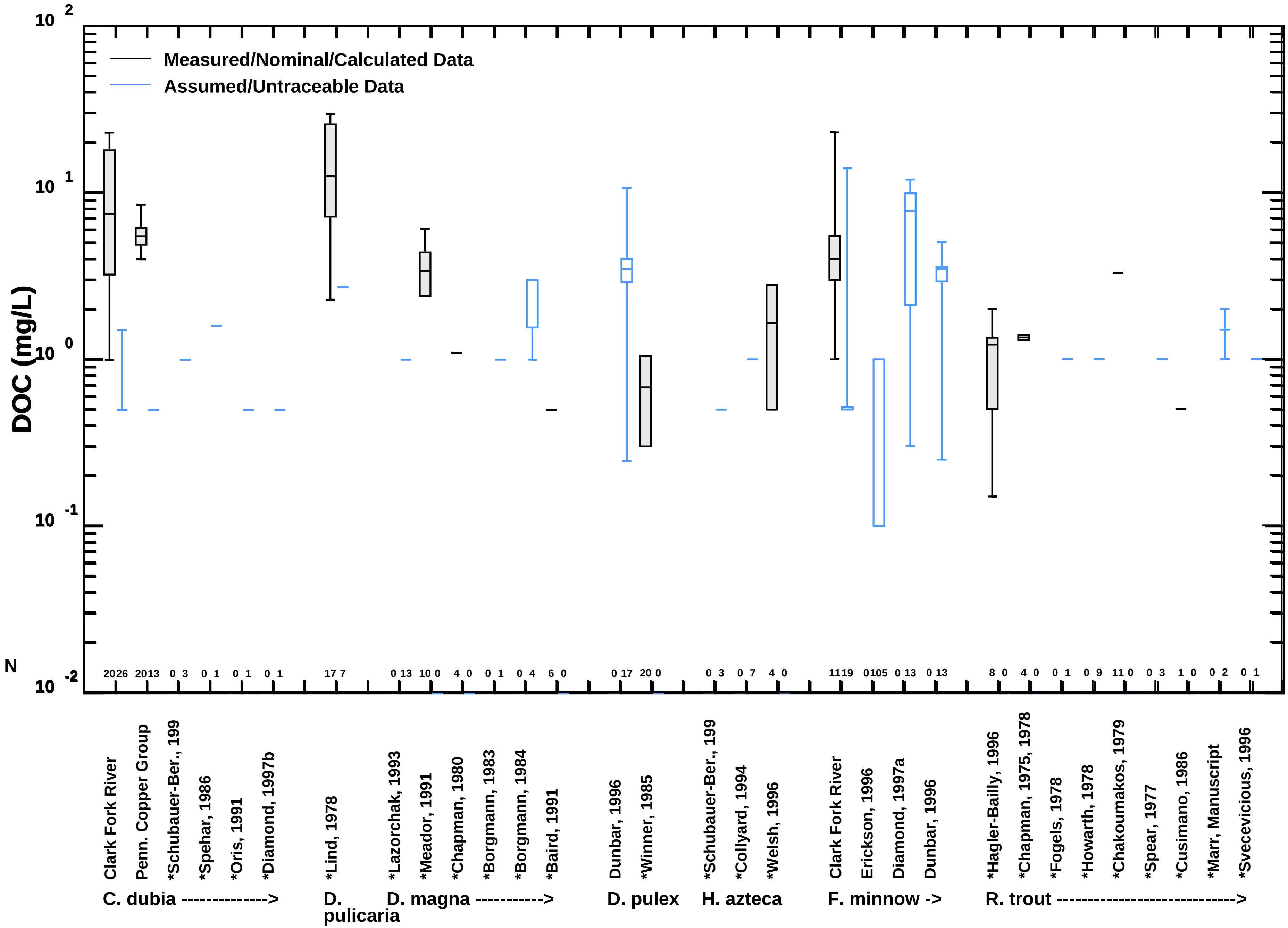
Median, Range and Quartiles of Temperature in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



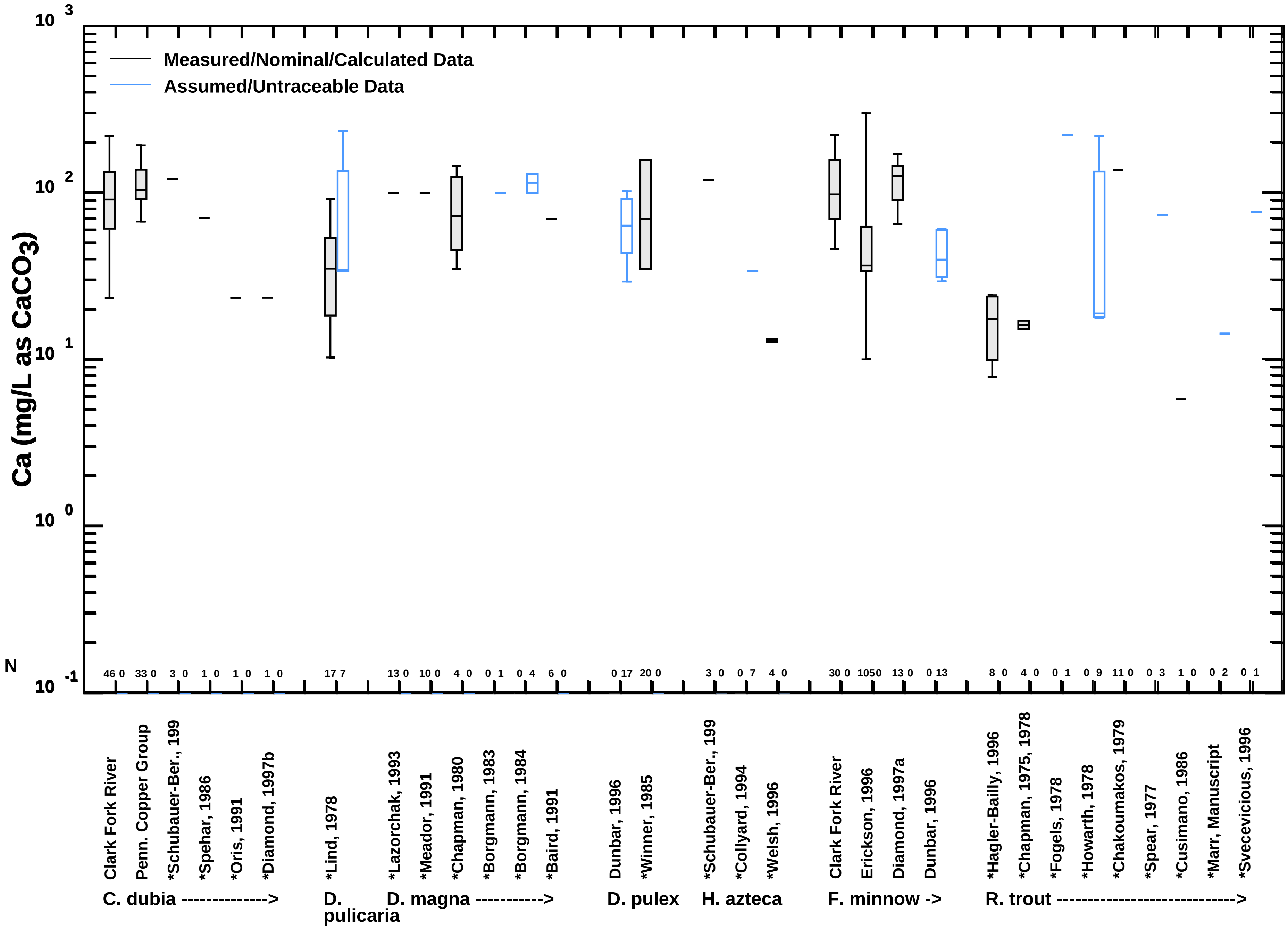
Median, Range and Quartiles of HA in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



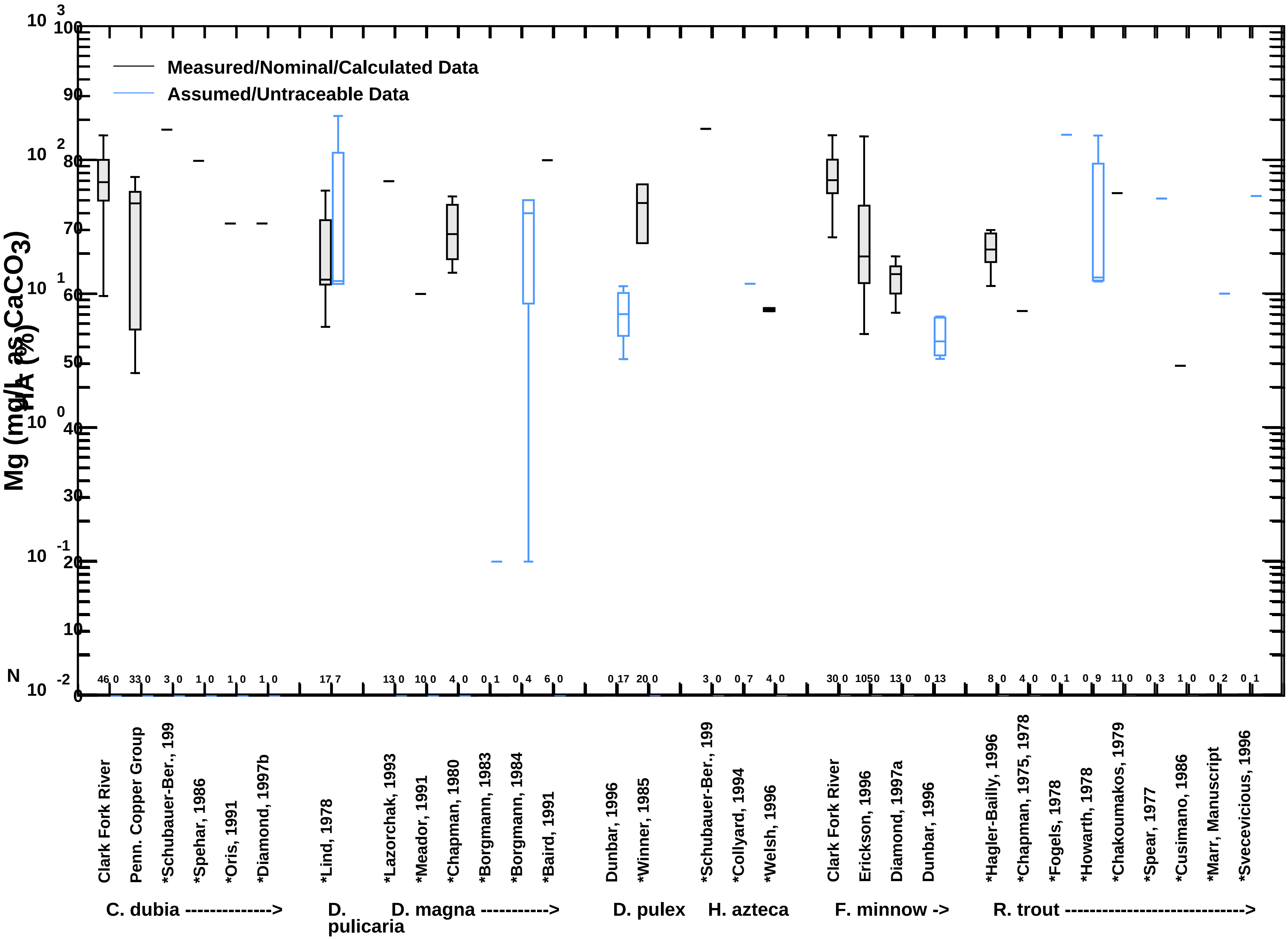
Median, Range and Quartiles of pH in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



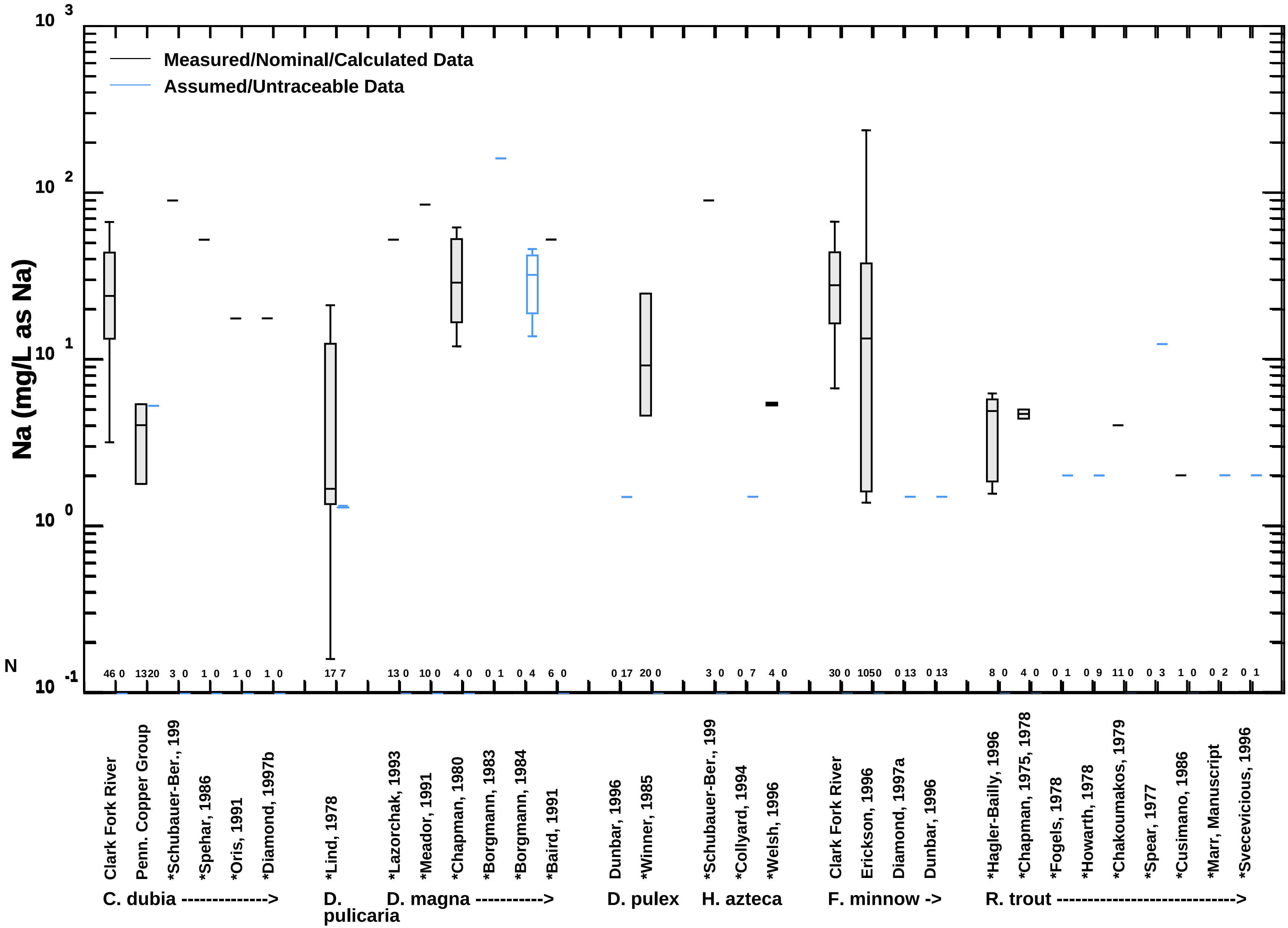
Median, Range and Quartiles of DOC in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



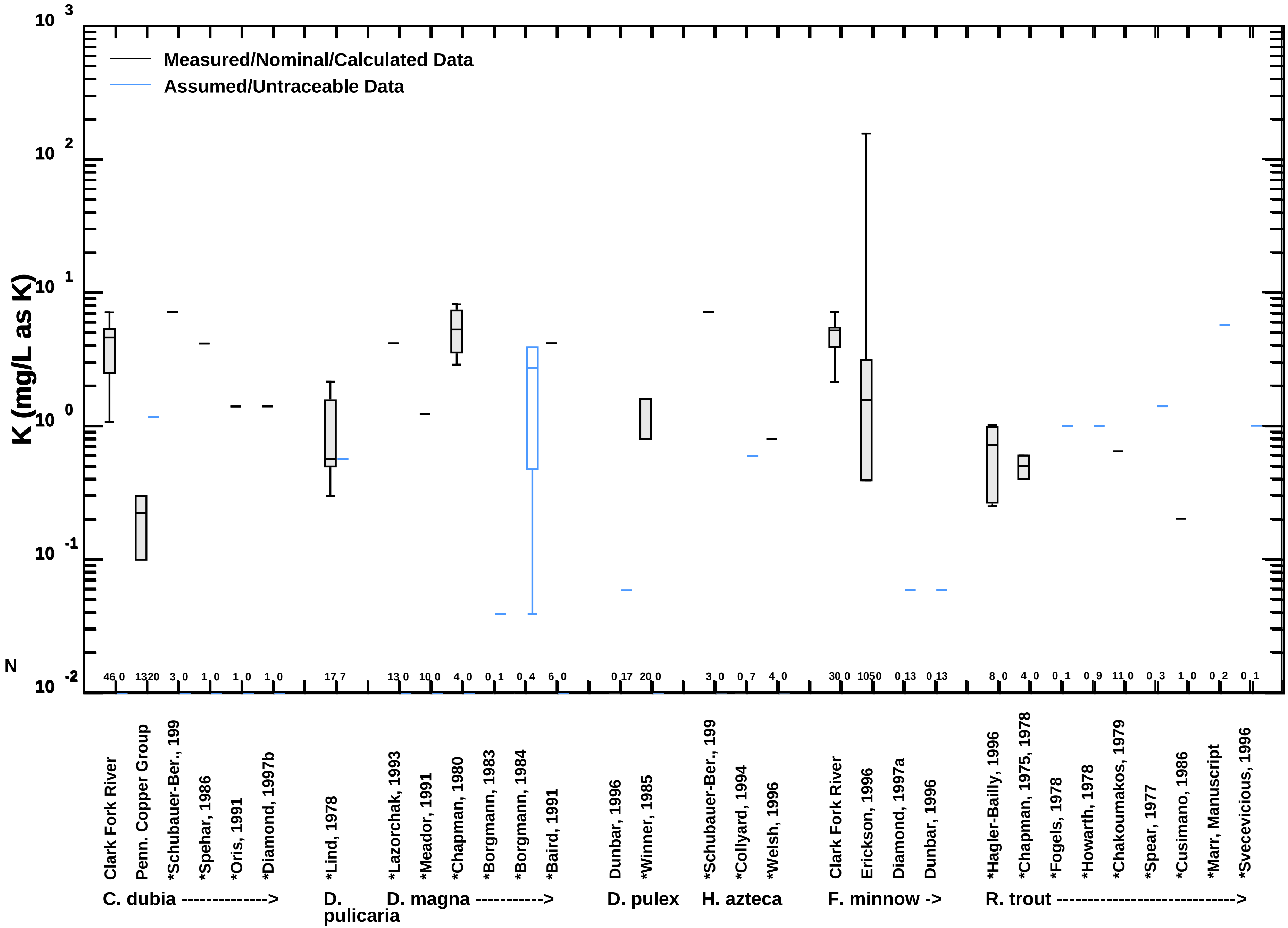
Median, Range and Quartiles of Ca in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



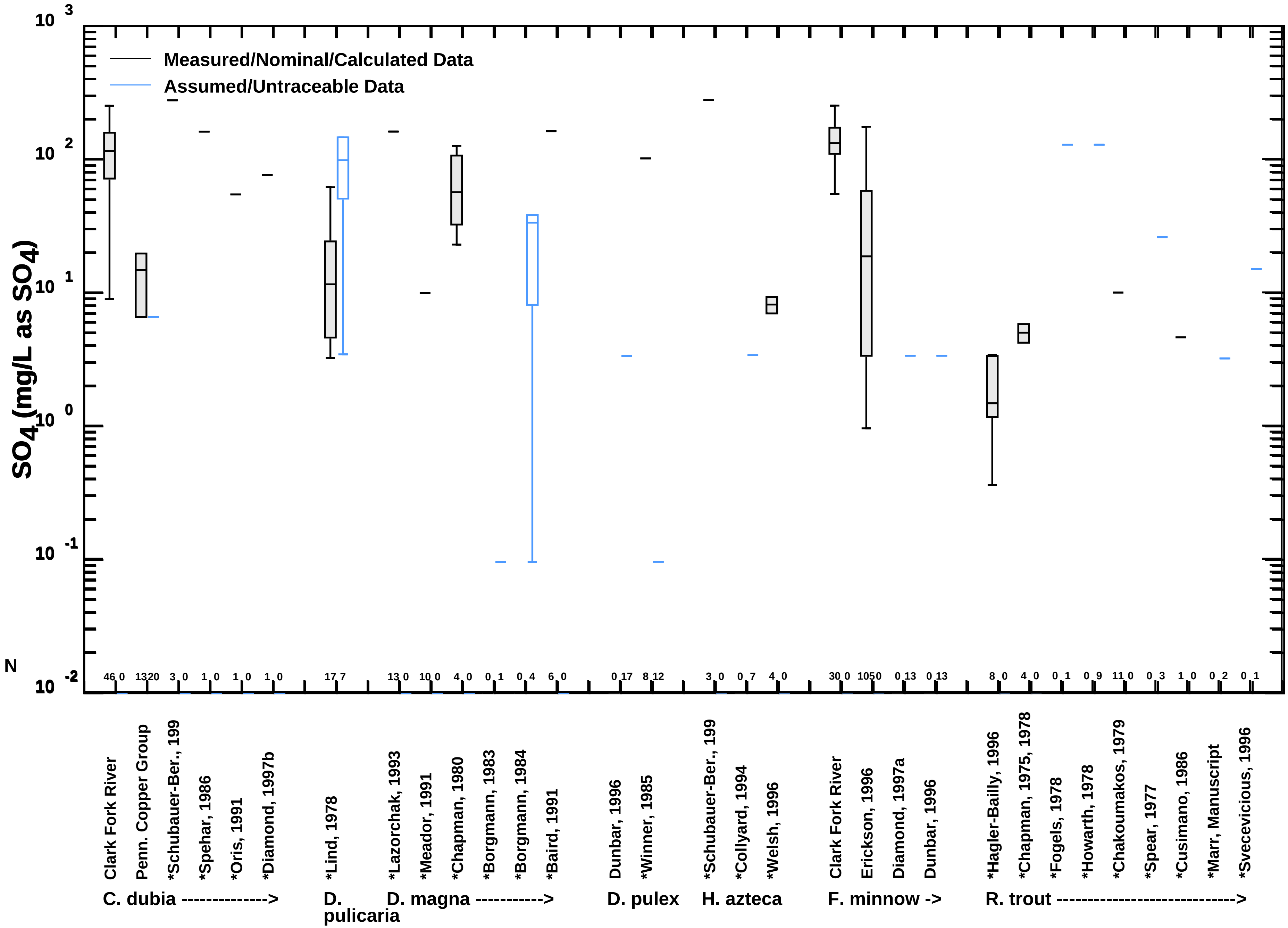
Median, Range and Quartiles of HA in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



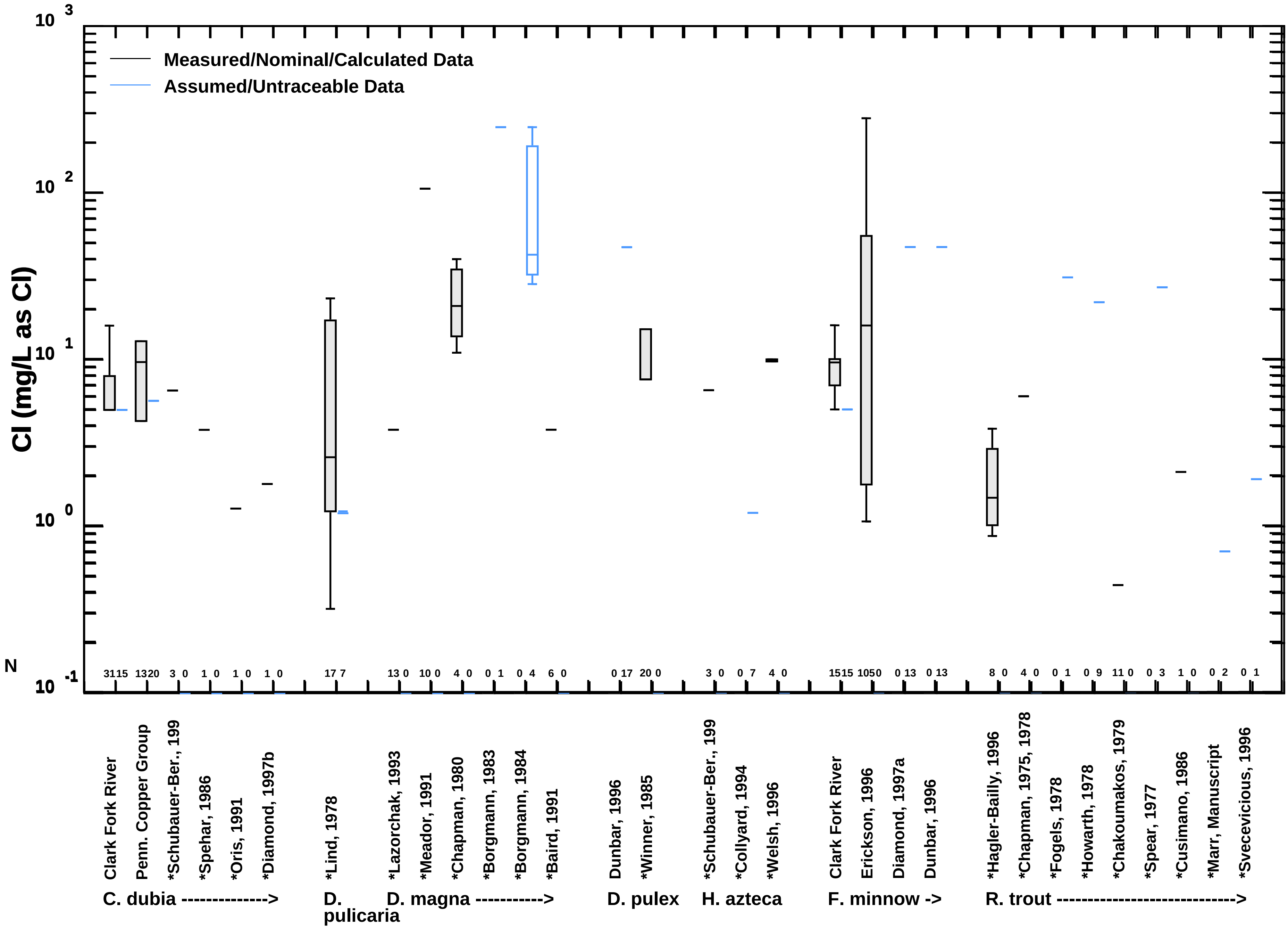
Median, Range and Quartiles of Na in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



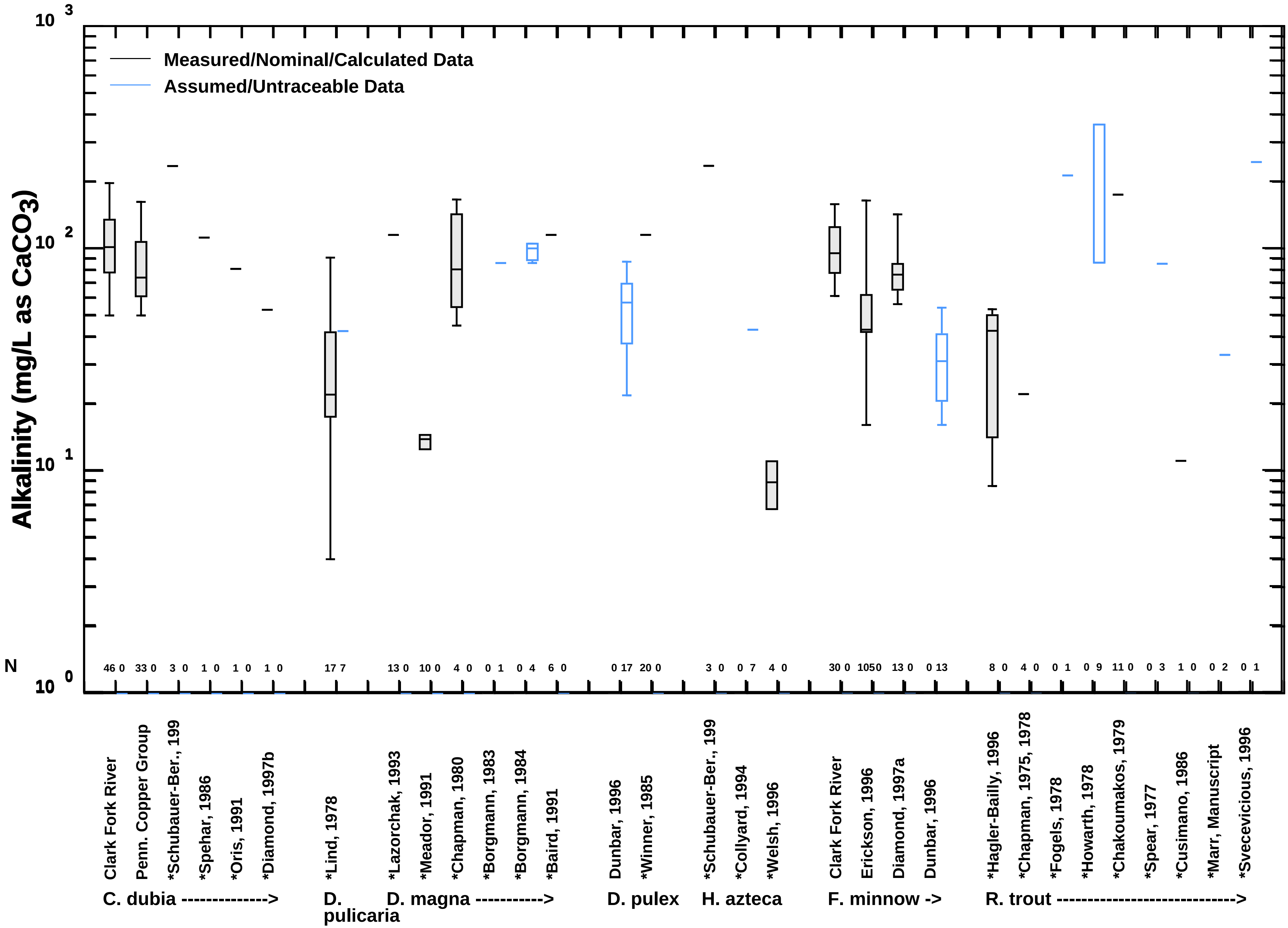
Median, Range and Quartiles of K in BLM Calibration and Application Datasets
(All species, Median and Quartiles calculated directly from data i.e., no distributional assumptions)



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; 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, *Scenedesmus quadricauda*	S,U	Copper sulfate	34.8	24 hr	NOEC (growth)	50	-	Starodub et al. 1987
Green alga, *Scenedesmus quadricauda*	S,U	Copper sulfate	34.8	24 hr	NOEC (growth)	50	-	Starodub et al. 1987
Green alga, *Scenedesmus quadricauda*	S,U	Copper sulfate	34.8	24 hr	NOEC (growth)	>200	-	Starodub et al. 1987
Green alga, *Selenastrum capricornutum*	S,U	Copper chloride	14.9	7 days	Growth reduction	50	-	Bartlett et al.1974
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	29.3	72 hr	EC50 (cell count)	19	-	Vasseur et al. 1988
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	24.2	72 hr	EC50 (cell count)	41	-	Vasseur et al. 1988
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	24.2	72 hr	EC50 (cell count)	28	-	Vasseur et al. 1988
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	14.9	72 hr	EC50 (cell count)	60	-	Vasseur et al. 1988
Green alga, *Selenastrum capricornutum*	S,U	Copper sulfate	24.2	72 hr	EC50 (cell count)	28.5	-	Benhra et al. 1997
Green alga, *Selenastrum capricornutum*	F,U	Copper sulfate	15	24 hr	EC50 (cell density)	21	-	Chen et al. 1997
Diatom, *Cocconeis placentula*	Dosed stream	Copper sulfate	226-310	10 mo	Decreased abundance from 21% dowr to <1%	120	-	Weber and McFarland 1981
Phytoplankton, mixed species	S,U	-	-	124 hr	Averaged 39% reduction in primary production	10	-	Cote 1983
Macrophyte, *Elodea canadensis*	S,U	Copper sulfate	-	24 hr	EC50 (photosynthesis)	150	-	Brown and Rattigan 1979
Microcosm	F,M,T,D	Copper sulfate	200	32 wk	LOEC (primary production)	9.3	-	Hedtke 1984
Microcosm	F,M,T,D	Copper sulfate	200	32 wk	NOEC (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 (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, *Ephydatia fluviatilis*	S,U	Copper sulfate	200	10 days	Reduced growth by 33%	6	-	Francis and Harrison 1988
Sponge, *Ephydatia fluviatilis*	S,U	Copper sulfate	200	10 days	Reduced growth by 100%	19	-	Francis and Harrison 1988
Rotifer, *Philodina acuticornis*	S,U	Copper sulfate	45	48 hr	LC50 (5^0 C)	1,300	-	Cairns et al. 1978
Rotifer, *Philodina acuticornis*	S,U	Copper sulfate	45	48 hr	LC50 (10^0 C)	1,200	-	Cairns et al. 1978
Rotifer, *Philodina acuticornis*	S,U	Copper sulfate	45	48 hr	LC50 (15^0 C)	1,130	-	Cairns et al. 1978
Rotifer, *Philodina acuticornis*	S,U	Copper sulfate	45	48 hr	LC50 (20^0 C)	1,000	-	Cairns et al. 1978
Rotifer, *Philodina acuticornis*	S,U	Copper sulfate	45	48 hr	LC50 (25^0 C)	950	-	Cairns et al. 1978
Rotifer, *Brachionus calyciflorus*	S, U	Copper sulfate	39.8	24 hr	EC50 (mobility)	200	-	Couillard et al. 1989
Rotifer (2 hr), *Brachionus calyciflorus*	S,U	Copper sulfate	-	2 hr	LOEC (swimming activity)	12.5	-	Charoy et al. 1995
Rotifer, *Brachionus calyciflorus*	S,U	Copper sulfate	90	24 hr	EC50 (mobility)	76	-	Ferrando et al. 1992
Rotifer (2 hr), *Brachionus calyciflorus*	S,U	Copper sulfate	90	5 hr	EC50 (filtration rate)	34	-	Ferrando et al. 1993a
Rotifer (2 hr), *Brachionus calyciflorus*	S,U	Copper sulfate	90	6 days	LOEC (reproduction decreased 26%)	5	-	Janssen et al. 1993
Rotifer (2 hr), *Brachionus calyciflorus*	S,U	Copper sulfate	90	5 hr	LOEC (reduced swimming speed)	12	-	Janssen et al. 1993
Rotifer (2 hr), *Brachionus calyciflorus*	S,U	Copper sulfate	85	3 days	LOEC (reproduction decreased 27%)	5	-	Janssen et al. 1994
Rotifer (2 hr), *Brachionus calyciflorus*	S,U	Copper sulfate	85	3 days	LOEC (reproduction decreased 29%)	5	-	Janssen et al. 1994
Rotifer (2 hr), *Brachionus calyciflorus*	S,U	Copper sulfate	85	8 days	LOEC (reproduction decreased 47%)	5	-	Janssen et al. 1994
Rotifer (2 hr), *Brachionus calyciflorus*	S,U	Copper chloride	170	35 min	LOEC (food ingestion rate)	100	-	Juchelka and Snell 1994
Rotifer (2 hr), *Brachionus calyciflorus*	S,U	Copper sulfate	63.2	24 hr	EC50 (mobility)	9.4	-	Porta and Ronco 1993
Rotifer (2 hr), *Brachionus calyciflorus*	S,U	-	90	2 days	LOEC (reproduction decreased 100%)	30	-	Snell and Moffat 1992
Rotifer (<2 hr), *Brachionus calyciflorus*	S, U	-	85	24 hr	EC50 (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), *Brachionus calyciflorus*	S, U	-	85	24 hr	EC50 (mobility; 10^0 C)	18	-	Snell 1991; Snell et al. 1991b
Rotifer (<2 hr), *Brachionus calyciflorus*	S, U	-	85	24 hr	EC50 (mobility; 15^0 C)	31	-	Snell 1991; Snell et al. 1991b
Rotifer (<2 hr), *Brachionus calyciflorus*	S, U	-	85	24 hr	EC50 (mobility; 20^0 C)	31	-	Snell 1991; Snell et al. 1991b
Rotifer (<2 hr), *Brachionus calyciflorus*	S, U	-	85	24 hr	EC50 (mobility; 25^0 C)	26	-	Snell 1991; Snell et al. 1991b
Rotifer (<2 hr), *Brachionus calyciflorus*	S, U	-	85	24 hr	EC50 (mobility; 30^0 C)	25	-	Snell 1991; Snell et al. 1991b
Rotifer (<3 hr), *Brachionus rubens*	S, U	Copper sulfate	90	24 hr	LC50	19	-	Snell and Persoone 1989b
Rotifer, *Keratella cochlearis*	S,U	Copper chloride	-	24 hr	LC50	101	-	Borgman and Ralph 1984
Worm, *Aeolosoma headleyi*	S,U	Copper sulfate	45	48 hr	LC50 (5^0 C)	2,600	-	Cairns et al. 1978
Worm, *Aeolosoma headleyi*	S,U	Copper sulfate	45	48 hr	LC50 (10^0 C)	2,300	-	Cairns et al. 1978
Worm, *Aeolosoma headleyi*	S,U	Copper sulfate	45	48 hr	LC50 (15^0 C)	2,000	-	Cairns et al. 1978
Worm, *Aeolosoma headleyi*	S,U	Copper sulfate	45	48 hr	LC50 (20^0 C)	1,650	-	Cairns et al. 1978
Worm, *Aeolosoma headleyi*	S,U	Copper sulfate	45	48 hr	LC50 (50 C)	1,000	-	Cairns et al. 1978
Worm (adult), *Lumbriculus variegatus*	S,U	Copper sulfate	30		LC50	150		Bailey and Liu, 1980
Worm (7 mg), *Lumbriculus variegatis*	F,M,T	Copper sulfate	45	10 days	LC50	35	-	West et al. 1993
Tubificid worm, *Limnodrilus hoffmeisteri*	S,U	Copper sulfate	100		LC50	102		Wurtz and Bridges 1961
Tubificid worm, *Tubifex tubifex*	R, U	Copper sulfate	245		LC50	158		Khangarot 1991
Snail (11-27 mm), *Campeloma decisum*	F,M,T	Copper sulfate	45	6 wk	LOEC (mortality)	14.8	-	Arthur and Leonard 1970
Snail, *Gyraulus circumstriatus*	S,U	Copper sulfate	100		LC50	108		Wurtz and Bridges 1961
Snail, *Goniobasis livescens*	S,U	Copper sulfate	154	48 hr	LC50	860	-	Cairns et al. 1976
Snail, *Goniobasis livescens*	S,M,D	Copper sulfate	154	96 hr	LC50	-	390	Paulson et al. 1983
Snail, *Nitrocris* sp.	S,U	Copper sulfate	45	48 hr	LC50 (5^0 C)	3,000	-	Cairns et al. 1978
Snail, *Nitrocris* sp.	S,U	Copper sulfate	45	48 hr	LC50 (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), *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), *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), *Coprbicula fluminea*	F,M,T	Copper sulfate	64	96 hr (24 hr LC50 also reported)	LC50	490	-	Rodgers et al. 1980
Asiatic clam (juvenile), *Corbicula fluminea*	F,M,D	Copper sulfate	78	30 days	43.3% mortality	14.48	-	Belanger et al. 1990
Asiatic clam (juvenile), *Corbicula fluminea*	F,M,D	Copper sulfate	78	30 days	Stopped shell growth	8.75	-	Belanger et al. 1990
Asiatic clam (adult), *Corbicula fluminea*	F,M,D	Copper sulfate	78	30 days	13.3% mortality	14.48	-	Belanger et al. 1990
Asiatic clam (adult), *Corbicula fluminea*	F,M,D	Copper sulfate	71	30 days	25% mortality	16.88	-	Belanger et al. 1990
Asiatic clam (adult), *Corbicula fluminea*	F,M,D	Copper sulfate	78	30 days	Inhibited shell growth	8.75	-	Belanger et al. 1990
Asiatic clam (adult), *Corbicula fluminea*	F,M,D	Copper sulfate	-	15-16 days	LC50	-	-	Belanger et al. 1991
Asiatic clam (adult), *Corbicula fluminea*	F,M,D	Copper sulfate	-	19 days	LC100	-	-	Belanger et al. 1991
Asiatic clam (veliger larva), *Corbicula manilensis*	S,M,T	Copper chloride	-	24 hr	34% mortality	10	-	Harrison et al. 1981, 1984
Asiatic clam (juvenile), *Corbicula manilensis*	S,M,T	Copper chloride	17	24 hr	LC50	100	-	Harrison et al. 1984
Asiatic clam (veliger), *Corbicula manilensis*	S,M,T	Copper chloride	17	24 hr	LC50	28	-	Harrison et al. 1984
Asiatic clam (trochophore), *Corbicula manilensis*	S,M,T	Copper chloride	17	8 hr	LC100	7.7	-	Harrison et al. 1984
Asiatic clam (adult), *Corbicula manilensis*	F,M,T	Copper chloride	17	7 days	LC50	3,638	-	Harrison et al. 1981, 1984
Asiatic clam (adult), *Corbicula manilensis*	F,M,T	Copper chloride	17	42 days	LC50	12	-	Harrison et al. 1981, 1984
Asiatic clam (4.3 g adult), *Corbicula manilensis*	F,M,T	Copper chloride	17	30 days	LC50	11	-	Harrison et al. 1984
Cladoceran, *Bosmina longirostrus*	S, U	Copper sulfate	33.8		EC50	1.6		Koivisto et al. 1992
Cladoceran (<24 hr), *Daphnia ambigua*	S,U	Copper sulfate	145	72 hr	LC50	86.5	-	Winner and Farrell 1976
Cladoceran (<24 hr), *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, *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, *Daphnia magna*	-	Copper sulfate	-	72 hr	EC50 (mobility; 15^0 C)	70	-	Braginskij and Shcherben 1978
Cladoceran, *Daphnia magna*	-	Copper sulfate	-	72 hr	EC50 (mobility; 20^0 C)	21	-	Braginskij and Shcherben 1978
Cladoceran, *Daphnia magna*	-	Copper sulfate	-	72 hr	EC50 (mobility; 30^0 C)	9.3	-	Braginskij and Shcherben 1978
Cladoceran, *Daphnia magna*	S,U	Copper sulfate	-	16 hr	EC 50 (mobility)	38	-	Anderson 1944
Cladoceran (<8 hr), *Daphnia magna*	S,U	Copper chloride	-	64 hr	Immobilization threshold	12.7	-	Anderson 1948
Cladoceran (1 mm), *Daphnia magna*	S,U	Copper nitrate	100	24 hr	EC 50 (mobility)	50	-	Bellavere and Gorbi 1981
Cladoceran (1 mm), *Daphnia magna*	S,U	Copper nitrate	200	24 hr	EC 50 (mobility)	70	-	Bellavere and Gorbi 1981
Cladoceran, *Daphnia magna*	S,U	-	100	48 hr	EC50 (mobility)	254	-	Borgmann and Ralph 1983
Cladoceran, *Daphnia magna*	S,U	-	100	49 hr	EC50 (mobility)	1,239	-	Borgmann and Ralph 1983
Cladoceran, *Daphnia magna*	S,U	Copper sulfate	45	48 hr	EC50 (mobility; 5^0 C)	90	-	Cairns et al. 1978
Cladoceran, *Daphnia magna*	S,U	Copper sulfate	45	48 hr	EC50 (mobility; 10^0 C)	70	-	Cairns et al. 1978
Cladoceran, *Daphnia magna*	S,U	Copper sulfate	45	48 hr	EC50 (mobility; 15^0 C)	40	-	Cairns et al. 1978
Cladoceran, *Daphnia magna*	S,U	Copper sulfate	45	48 hr	EC50 (mobility; 25^0 C)	7	-	Cairns et al. 1978
Cladoceran (4 days), *Daphnia magna*	S,U	Copper sulfate	-	24 hr	EC50 (filtration rate)	59	-	Ferrando and Andreu 1993
Cladoceran (24-48 hr), *Daphnia magna*	S,U	Copper sulfate	90	24 hr	EC50 (mobility)	380	-	Ferrando et al. 1992
Cladoceran, *Daphnia magna*	S,U	Copper sulfate	50		EC50	7		Oikari et al. 1992
Cladoceran, *Daphnia magna*	S,U	Copper sulfate	-	48 hr	EC50 (mobility)	45	-	Oikari et al. 1992
Cladoceran (<24 hr), *Daphnia magna*	S,U	Copper sulfate	145	Life span (ca. 18 wk)	Chronic limits (inst. rate of population growth)	70	-	Winner and Farrell 1976
Cladoceran (<24 hrs), *Daphnia magna*	S,M,D	Copper sulfate	72-80	48 hr	LC50	-	11.3	Suedel et al. 1996
Cladoceran (<24 hrs), *Daphnia magna*	S,M,I	-	180	-	LC50	55.3	-	Borgmann and Charlton 1984
Cladoceran (<24 hr), *Daphnia magna*	S,M,I	Copper sulfate	100	48 hr	EC50 (mobility)	46.0	-	Meador 1991
Cladoceran (<24 hr), *Daphnia magna*	S,M,I	Copper sulfate	100	48 hr	EC50 (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), *Chironomus tentans*	F,M,T	Copper chloride	36	20 days	LC50	77.5	-	Nebeker et al. 1984b
Midge (embryo), *Tanytarsus dissimilis*	S,M,T	Copper chloride	46.8	10 days	LC50	16.3	-	Anderson et al. 1980
Midge, Unidentified	F,M,T,D	Copper sulfate	200	32 wk	Emergence	30	-	Hedtke 1984
Bryozoan (2-3 day ancestrula), *Lophopodella carteri*	S,U	-	190-220			510		Pardue and Wood 1980
Bryozoan (2-3 day ancestrula), *Pectinatella magnifica*	S,U	-	190-220			140		Pardue and Wood 1980
Bryozoan (2-3 day ancestrula), *Plumatella emarginata*	S,U	-	190-220			140		Pardue and Wood 1980
American eel (5.5 cm glass eel stage), *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), *Anguilla rostrata*	S,U	Copper sulfate	40-48	96 hr	LC50	3,200		Hinton and Eversole 1979
American eel, *Anguilla rostrata*	S,M,T	Copper nitrate	53	96 hr	LC50	6,400	-	Rehwoldt et al. 1971
American eel, *Anguilla rostrata*	S,M,T	Copper nitrate	55	96 hr	LC50	6,000	-	Rehwoldt et al. 1972
Arctic grayling (larva), *Thymallus arcticus*	S,U	Copper sulfate	41.3	96 hr	LC50	67.5		Buhl and Hamilton 1990
Arctic grayling (larva), *Thymallus arcticus*	S,U	Copper sulfate	41.3	96 hr	LC50	23.9		Buhl and Hamilton 1990
Arctic grayling (larva), *Thymallus arcticus*	S,U	Copper sulfate	41.3	96 hr	LC50	131		Buhl and Hamilton 1990
Arctic grayling (swim-up), *Thymallus arcticus*	S,U	Copper sulfate	41.3	96 hr	LC50	9.6		Buhl and Hamilton 1990
Arctic grayling (0.20 g juvenile), *Thymallus arcticus*	S,U	Copper sulfate	41.3	96 hr	LC50	2.7		Buhl and Hamilton 1990
Arctic grayling (0.34 g juvenile), *Thymallus arcticus*	S,U	Copper sulfate	41.3	96 hr	LC50	2.58		Buhl and Hamilton 1990
Arctic grayling (0.81 g juvenile), *Thymallus arcticus*	S,U	Copper sulfate	41.3	96 hr	LC50	49.3		Buhl and Hamilton 1990
Arctic grayling (0.85 g juvenile), *Thymallus arcticus*	S,U	Copper sulfate	41.3	96 hr	LC50	30		Buhl and Hamilton 1990
Coho salmon (larva), *Oncorhynchus kisutch*	S,U	Copper sulfate	41.3	96 hr	LC50	21		Buhl and Hamilton 1990
Coho salmon (larva), *Oncorhynchus kisutch*	S,U	Copper sulfate	41.3	96 hr	LC50	19.3		Buhl and Hamilton 1990
Coho salmon (0.41 g juvenile), *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), *Oncorhynchus kisutch*	S,U	Copper sulfate	41.3	96 hr	LC50	23.9		Buhl and Hamilton 1990
Coho salmon (0.87 g juvenile), *Oncorhynchus kisutch*	S,U	Copper sulfate	41.3	96 hr	LC50	31.9		Buhl and Hamilton 1990
Coho salmon (10 cm), *Oncorhynchus kisutch*	S,U	Copper sulfate	-	72 hr	LC50	280	-	Holland et al. 1960
Coho salmon (9.7 cm), *Oncorhynchus kisutch*	S,U	Copper sulfate	-	72 hr	LC50	190	-	Holland et al. 1960
Coho salmon (9.7 cm), *Oncorhynchus kisutch*	S,U	Copper sulfate	-	72 hr	LC50	480	-	Holland et al. 1960
Coho salmon (juvenile), *Oncorhynchus kisutch*	R,M,T,I	-	33	96 hr	LC50 (TOC=7.3 mg/L)	164	-	Buckley 1983
Coho salmon (juvenile), *Oncorhynchus kisutch*	R,M,T,I	-	33	96 hr	LC50	286		Buckley 1983
Coho salmon (6.3 cm), *Oncorhynchus kisutch*	F,U	Copper sulfate	-	30 days	LC50	360	-	Holland et al. 1960
Coho salmon (6.3 cm), *Oncorhynchus kisutch*	F,U	Copper sulfate	-	72 hr	LC50	370	-	Holland et al. 1960
Coho salmon (smolts), *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), *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), *Oncorhynchus kisutch*	F,M,T	Copper acetate	276	14 wk	15% reduction in growth	70	-	Buckley et al. 1982
Coho salmon (7.8 cm), *Oncorhynchus kisutch*	-	-	276	7 days	LC50	220	-	Buckley et al. 1982
Coho salmon (3-8 g), *Oncorhynchus kisutch*	F,M,T	Copper acetate	280	7 days	LC50	275	-	McCarter and Roch 1983
Coho salmon (3-8 g), *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), *Oncorhynchus kisutch*	F,M,T,D,I	-	24.4	61 days	NOEC (growth and survival)	22	-	Mudge et al. 1993
Coho salmon, *Oncorhynchus kisutch*	F,M,T,D,I	-	31.1	60 days	NOEC (growth and survival)	18	-	Mudge et al. 1993
Coho salmon (parr), *Oncorhynchus kisutch*	F,M,T,D,I	-	31	61 days	NOEC (growth and survival)	33	-	Mudge et al. 1993
Rainbow trout (15-40g) *Oncorhynchus mykiss*	F,M,	Copper chloride	--	120 hr	LA50 (50% mortality)	~1.4 ug Cu/g gill	-	MacRae et al. 1999
Sockeye salmon (yeasrling), *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), *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, *Oncorhynchus mykiss*	-	-	320	48 hr	LC50	500	-	Brown 1968
Rainbow trout (9-16 cm), *Oncorhynchus mykiss*	In situ	-	21-26	48 hr	LC50	70	-	Calamari and Marchetti 1975
Rainbow trout (0.4 g), *Oncorhynchus mykiss*	S,U	Copper sulfate	-	96 hr	LC50	185	-	Bills et al. 1981
Rainbow trout (larva), *Oncorhynchus mykiss*	S, U	Copper sulfate	41.3	96 hr	LC50	36		Buhl and Hamilton 1990
Rainbow trout (0.60 g juvenile), *Oncorhynchus mykiss*	S, U	Copper sulfate	41.3	96 hr	LC50	13.8		Buhl and Hamilton 1990
Rainbow trout (13-15 cm), *Oncorhynchus mykiss*	S,U	Copper sulfate	250	72 hr	LC50	580	-	Brown et al. 1974
Rainbow trout (13-15 cm), *Oncorhynchus mykiss*	S,U	Copper sulfate	250	72 hr	LC50	960	-	Brown et al. 1974
Rainbow trout (3.2 cm), *Oncorhynchus mykiss*	S,U	Copper sulfate	-	24 hr	LC50	140	-	Shaw and Brown 1974
Rainbow trout (3.2 cm), *Oncorhynchus mykiss*	S,U	Copper sulfate	-	24 hr	LC50	130	-	Shaw and Brown 1974
Rainbow trout (4.0-10.6 cm), *Oncorhynchus mykiss*	S,U	Copper sulfate	45	24 hr	LC50 (5^0 C)	950	-	Cairns et al. 1978
Rainbow trout (4.0-10.6 cm), *Oncorhynchus mykiss*	S,U	Copper sulfate	45	24 hr	LC50 (15^0 C)	430	-	Cairns et al. 1978
Rainbow trout (4.0-10.6 cm), *Oncorhynchus mykiss*	S,U	Copper sulfate	45	24 hr	LC50 (30^0 C)	150	-	Cairns et al. 1978
Rainbow trout (0.52-1.55 g), *Oncorhynchus mykiss*	S,U	Copper sulfate	-	96 hr	LC50 (Silver Cup diet)	23.9	-	Marking et al. 1984
Rainbow trout (0.41-2.03 g), *Oncorhynchus mykiss*	S,U	Copper sulfate	-	96 hr	LC50 (purified H440)	11.3	-	Marking et al. 1984
Rainbow trout (0.0.40-1.68 g), *Oncorhynchus mykiss*	S,U	Copper sulfate	-	96 hr	LC50 (SD-9 diet)	15.9	-	Marking et al. 1984
Rainbow trout (0.0.34-1.52 g), *Oncorhynchus mykiss*	S,U	Copper sulfate	-	96 hr	LC50 (liver diet)	14.3	-	Marking et al. 1984
Rainbow trout (0.0.38-1.30 g), *Oncorhynchus mykiss*	S,U	Copper sulfate	-	96 hr	LC50 (brine shrimp diet)	11.3	-	Marking et al. 1984
Rainbow trout (embryo), *Oncorhynchus mykiss*	S,U	Copper chloride	30	56 hr	LC50	100	-	Rombough 1985
Rainbow trout (6.6 cm), *Oncorhynchus mykiss*	R,U	Copper sulfate	320	72 hr	LC50	1,100	-	Lloyd 1961
Rainbow trout (6.6 cm), *Oncorhynchus mykiss*	R,U	Copper sulfate	17.5	7 days	LC50	44	-	Lloyd 1961
Rainbow trout, *Oncorhynchus mykiss*	R,U	Copper sulfate	320	48 hr	LC50	270	-	Herbert and Vandyke 1964
Rainbow trout (yearling), *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), *Oncorhynchus mykiss*	R,U	Copper sulfate	250	8 days	LC50	500	-	Brown et al. 1974
Rainbow trout (embryo), *Oncorhynchus mykiss*	R,U	Copper sulfate	104	28 days	LC50	90	-	Birge 1978; Birge et al. 1978
Rainbow trout (embryo), *Oncorhynchus mykiss*	R,U	Copper sulfate	101	28 days	EC50 (death or deformity)	110	-	Birge et al. 1980; Birge and Black 1979
Rainbow trout (embryo), *Oncorhynchus mykiss*	R,U	Copper sulfate	101	28 days	EC10 (death or deformity)	16.5	-	Birge et al. 1980
Rainbow trout (eyed embryos), *Oncorhynchus mykiss*	R,U	Copper sulfate	-	96 hr	LC50	1,150	-	Kazlauskiene et al. 1994
Rainbow trout (larva), *Oncorhynchus mykiss*	R,U	Copper sulfate	-	96 hr	LC50	430	-	Kazlauskiene et al. 1994
Rainbow trout (16-18 cm), *Oncorhynchus mykiss*	R,U	Copper sulfate	-	96 hr	LC50	930	-	Kazlauskiene et al. 1994
Rainbow trout (embryo), *Oncorhynchus mykiss*	R,M,T	Copper sulfate	62.9	7-9 mo	Lesions in olfactory rosettes	22	-	Saucier et al. 1991b
Rainbow trout (embryo), *Oncorhynchus mykiss*	R,M,T	Copper sulfate	62.9	7-9 mo	31% mortality	22	-	Saucier et al. 1991b
Rainbow trout (eyed embryos), *Oncorhynchus mykiss*	R,M,T	Copper sulfate	40-48	96 hr	LC50	400	-	Giles and Klaverkamp 1982
Rainbow trout (yearling), *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), *Oncorhynchus mykiss*	R,M,T	Copper sulfate	44	96 hr	15-20% post-hatch mortality	80	-	Giles and Klaverkamp 1982
Rainbow trout (embryo), *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), *Oncorhynchus mykiss*	F,U	Copper nitrate	-	96 hr	LC50	253	-	Hale 1977
Rainbow trout (11 cm), *Oncorhynchus mykiss*	F,U	-	100	96 hr	LC50	250	-	Goettl et al. 1972
Rainbow trout (5 wk post swimup) *Oncorhynchus mykiss*	F,U	Copper sulfate	89.5	1 hr	Avoidance	10	-	Folmar 1976
Rainbow trout (18.5-26.5 cm), *Oncorhynchus mykiss*	F,U	Copper sulfate	90	2 hr	55% depressed olfactory response	50	-	Hara et al. 1976
Rainbow trout (3.2 cm), *Oncorhynchus mykiss*	F,M,I	Copper sulfate	-	8 days	LC50	500	-	Shaw and Brown 1974
Rainbow trout (12-16 cm), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	300	14 days	LC50	870	-	Calamari and Marchetti 1973
Rainbow trout (adult), *Oncorhynchus mykiss*	F,M,T	Copper chloride	42	-	LC50	57	-	Chapman 1975, Chapman and Stevens 1978
Rainbow trout (53.5 g), *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), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	365	15 days	Transient decrease in food consumption	100	-	Lett et al. 1976
Rainbow trout (alevin), *Oncorhynchus mykiss*	F,M,T	Copper chloride	24	200 hr	LC50	20	-	Chapman 1978
Rainbow trout (alevin), *Oncorhynchus mykiss*	F,M,T	Copper chloride	24	200 hr	LC10	19	-	Chapman 1978
Rainbow trout (swimup), *Oncorhynchus mykiss*	F,M,T	Copper chloride	24	200 hr	LC50	17	-	Chapman 1978
Rainbow trout (swimup), *Oncorhynchus mykiss*	F,M,T	Copper chloride	24	200 hr	LC10	9	-	Chapman 1978
Rainbow trout (parr), *Oncorhynchus mykiss*	F,M,T	Copper chloride	25	200 hr	LC50	15	-	Chapman 1978
Rainbow trout (parr), *Oncorhynchus mykiss*	F,M,T	Copper chloride	25	200 hr	LC10	8	-	Chapman 1978
Rainbow trout (smolt), *Oncorhynchus mykiss*	F,M,T	Copper chloride	25	200 hr	LC50	21	-	Chapman 1978
Rainbow trout (smolt), *Oncorhynchus mykiss*	F,M,T	Copper chloride	25	200 hr	LC10	7	-	Chapman 1978
Rainbow trout, *Oncorhynchus mykiss*	F,M,T	Copper sulfate	112.4	80 min	Avoidance threshold	74	-	Black and Birge 1980
Rainbow trout (>8 g), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	49	15-18 days	LC50	48	-	Miller and MacKay 1980
Rainbow trout (>8 g), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	51	15-18 days	LC50	46	-	Miller and MacKay 1980
Rainbow trout (>8 g), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	57	15-18 days	LC50	63	-	Miller and MacKay 1980
Rainbow trout (>8 g), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	12	15-18 days	LC50	19	-	Miller and MacKay 1980
Rainbow trout (>8 g), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	99	15-18 days	LC50	54	-	Miller and MacKay 1980
Rainbow trout (>8 g), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	98	15-18 days	LC50	78	-	Miller and MacKay 1980
Rainbow trout (>8 g), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	12	15-18 days	LC50	18	-	Miller and MacKay 1980
Rainbow trout (>8 g), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	97	15-18 days	LC50	96	-	Miller and MacKay 1980
Rainbow trout (200-250 g), *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), *Oncorhynchus mykiss*	F,M,T	Copper chloride	28.4	20 min	Avoidance	6.4	-	Giattina et al. 1982
Rainbow trout (2.70 g), *Oncorhynchus mykiss*	F,M,T	Copper chloride	9.2	96 hr	LC50	4.2	-	Cusimano et al. 1986
Rainbow trout (2.88 g), *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), *Oncorhynchus mykiss*	F,M,T	Copper chloride	9.2	168 hr	LC50	36.7	-	Cusimano et al. 1986
Rainbow trout (2.70 g), *Oncorhynchus mykiss*	F,M,T	Copper chloride	9.2	168 hr	LC50	3.1	-	Cusimano et al. 1986
Rainbow trout (2.65 g), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	9.2	168 hr	LC50	2.3	-	Cusimano et al. 1986
Rainbow trout (5 day embryo), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	87.7	48 hr	LC50	8,000	-	Shazili and Pascoe 1986
Rainbow trout (10 day embryo), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	87.7	48 hr	LC50	2,000	-	Shazili and Pascoe 1986
Rainbow trout (15 day embryo), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	87.7	48 hr	LC50	400	-	Shazili and Pascoe 1986
Rainbow trout (22 day embryo), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	87.7	48 hr	LC50	600	-	Shazili and Pascoe 1986
Rainbow trout (29 day embryo), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	87.7	48 hr	LC50	400	-	Shazili and Pascoe 1986
Rainbow trout (36 day embryo), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	87.7	48 hr	LC50	100	-	Shazili and Pascoe 1986
Rainbow trout (2 day larva), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	87.7	48 hr	LC50	100	-	Shazili and Pascoe 1986
Rainbow trout (7 day larva), *Oncorhynchus mykiss*	F,M,T	Copper nitrate	87.7	48 hr	LC50	100	-	Shazili and Pascoe 1986
Rainbow trout (yearling), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	63	15 days	Olfactory receptor degeneration	20	-	Julliard et al. 1993
Rainbow trout (swimup), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	60.9	13-40 wk	Inhibited olfactory discrimination	20	-	Saucier and Astic 1995
Rainbow trout (swimup), *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), *Oncorhynchus mykiss*	F,M,T	Copper sulfate	284	96 hr	LC50	650	-	Svecevicius and Vosyliene 1996
Rainbow trout (3.5 cm), *Oncorhynchus mykiss*	F,M,T	Copper chloride	24.2	96 hr	LC50	12.7	-	Marr et al. Manuscript
Rainbow trout (3.5 cm), *Oncorhynchus mykiss*	F,M,T	Copper chloride	24.2	96 hr	LC50	16.6	-	Marr et al. Manuscript
Rainbow trout (3.5 cm), *Oncorhynchus mykiss*	F,M,T	Copper chloride	24.2	96 hr	LC50	21.4	-	Marr et al. Manuscript
Rainbow trout (3.5 cm), *Oncorhynchus mykiss*	F,M,T	Copper chloride	24.2	96 hr	LC50	34.2	-	Marr et al. Manuscript
Rainbow trout (10.0 g), *Oncorhynchus mykiss*	F,M,D	Copper sulfate	362	144 hr	LC50 (extruded diet)	276	-	Dixon and Hilton 1981
Rainbow trout (10.9 g), *Oncorhynchus mykiss*	F,M,D	Copper sulfate	362	144 hr	LC50 (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), *Oncorhynchus mykiss*	F,M,D	Copper sulfate	362	144 hr	LC50 (Low carbohydrate diet)	408	-	Dixon and Hilton 1981
Rainbow trout (11.6 g), *Oncorhynchus mykiss*	F,M,D	Copper sulfate	362	144 hr	LC50 (high carbohydrate diet)	246	-	Dixon and Hilton 1981
Rainbow trout (1.7-3.3 g), *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), *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), *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), *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), *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), *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), *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), *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), *Oncorhynchus mykiss*	F,M,D	Copper sulfate	374	21 days	Incipient lethal level (acclimated to 13 ug/L)	564	-	Dixon and Sprague 1981a
Rainbow trout (1.7-3.3 g), *Oncorhynchus mykiss*	F,M,D	Copper sulfate	374	21 days	Incipient lethal level (acclimated to 19 ug/L)	708	-	Dixon and Sprague 1981a
Rainbow trout (2.9 g), *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), *Oncorhynchus mykiss*	F,M,T,D	Copper sulfate	30	96 hr	LC50	-	19.9	Howarth and Sprague 1978
Rainbow trout (1.4 g), *Oncorhynchus mykiss*	F,M,T,D	Copper sulfate	101	96 hr	LC50	-	176	Howarth and Sprague 1978
Rainbow trout (2.2 g), *Oncorhynchus mykiss*	F,M,T,D	Copper sulfate	370	96 hr	LC50	-	232	Howarth and Sprague 1978
Rainbow trout (smolt), *Oncorhynchus mykiss*	F,M,T,D	Copper sulfate	363	>10 days	LC50	97.92	-	Fogels and Sprague 1977
Rainbow trout (parr), *Oncorhynchus mykiss*	F,M,T,D,I	-	31.0	62 days	NOEC (growth and survival)	90	-	Mudge et al. 1993
Atlantic salmon (2-3 yr parr), *Salmo salar*	S,M,T	-	8-10	96 hr	LC50	125	-	Wilson 1972
Atlantic salmon (6.4-11.7 cm), *Salmo salar*	F,M,T	Copper sulfate	20	7 days	LC50	48	-	Sprague 1964
Atlantic salmon (7.2-10.9 cm), *Salmo salar*	F,M,T	-	14	7 days	LC50	32	-	Sprague and Ramsay 1965
Brown trout (3-6 day larva), *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), *Salmo trutta*	S,M,T	Copper chloride	4	30 days	>90% mortality	20	-	Sayer et al. 1989
Brown trout (larva), *Salmo trutta*	S,M,T	Copper chloride	22	30 days	<10% mortality	80	-	Sayer et al. 1989
Brown trout (larva), *Salmo trutta*	F,M,T	Copper chloride	25	60 days	Inhibited growth	4.6	-	Marr et al. 1996
Brook trout, *Salvelinus fontinalis*	-	-	-	24 hr	Significant change in cough rate	9	-	Drummond et al. 1973
Brook trout (1 g), *Salvelinus fontinalis*	S,M,T	Copper chloride	4	80 hr	75% mortality	25.4	-	Sayer et al. 1991 b, c
Brook trout (8 mo), *Salvelinus fontinalis*	R,M,T	-	20	10 days	IC50 (growth)	187	-	Jop et al. 1995
Brook trout (15-20 cm), *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), *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), *Carassius auratus*	S,U	Copper sulfate	20	96 hr	LC50	36		Pickering and Henderson 1966
Goldfish (10.5 g), *Carassius auratus*	S,M,T	Copper sulfate	34.2	-	LC50	150	-	Hossain et al. 1995
Goldfish (embryo), *Carrassius auratus*	R,U	Copper sulfate	195	7 days	EC50 (death or deformity)	5,200	-	Birge 1978; Birge and Black 1979
Goldfish, *Carassius auratus*	R,U	Copper sulfate	45	24 hr	LC50 (5^0 C)	2,700	-	Cairns et al. 1978
Goldfish, *Carassius auratus*	R,U	Copper sulfate	45	24 hr	LC50 (15^0 C)	2,900	-	Cairns et al. 1978
Goldfish, *Carassius auratus*	R,U	Copper sulfate	45	24 hr	LC50 (30^0 C)	1,510	-	Cairns et al. 1978
Common carp (1.8-2.1 cm), *Cyprinus carpio*	S,U	Copper sulfate	144-188	96 hr	LC50	117.5		Deshmukh and Marathe 1980
Common carp (5.0-6.0 cm), *Cyprinus carpio*	S,U	Copper sulfate	144-188	96 hr	LC50	530		Deshmukh and Marathe 1980
Common carp (embryo), *Cyprinus carpio*	S,U	Copper sulfate	360	-	EC50 (hatch and deformity)	4,775	-	Kapur and Yadav 1982
Common carp (embryo), *Cyprinus carpio*	S,U	Copper acetate	274	96 hr	LC50	140	-	Kaur and Dhawan 1994
Common carp (larva), *Cyprinus carpio*	S,U	Copper acetate	274	96 hr	LC50	4	-	Kaur and Dhawan 1994
Common carp (fry), *Cyprinus carpio*	S,U	Copper acetate	274	96 hr	LC50	63	-	Kaur and Dhawan 1994
Common carp, *Cyprinus carpio*	S,M,T	Copper nitrate	53	-	LC50	110	-	Rehwoldt et al. 1971
Common carp, *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), *Cyprinus carpio*	R,U	Copper sulfate	19	96 hr	LC50	63		Khangarot et al. 1983
Common carp (embryo and larva), *Cyprinus carpio*	R,U	Copper sulfate	50	108 hr	77% deformed	10	-	Wani 1986
Common carp (3.5 cm), *Cyprinus carpio*	R,U	Copper sulfate	-	96 hr	LC50	300	-	Alam and Maughan 1992
Common carp (6.5 cm), *Cyprinus carpio*	R,U	Copper sulfate	-	96 hr	LC50	1,000	-	Alam and Maughan 1992
Common carp (embryo), *Cyprinus carpio*	R,M,T	Copper sulfate	50	72 hr	Prevented hatching	700	-	Hildebrand and Cushman 1978
Common carp (1 mo), *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), *Cyprinus carpio*	F,M,T	Copper chloride	17	48 hr	LC50	170	-	Harrison and Rice 1981
Common carp (embryo and larva), *Cyprinus carpio*	F,M,T	Copper chloride	100	168 hr	55% mortality	19	-	Stouthart et al. 1996
Common carp (embryo and larva), *Cyprinus carpio*	F,M,T	Copper chloride	100	168 hr	18% mortality;	50.8	-	Stouthart et al. 1996
Bonytail (larva), *Gila elegans*	S, U	Copper sulfate	199	96 hr	LC50	364		Buhl and Hamilton 1996
Bonytail (100-110 days), *Gila elegans*	S, U	Copper sulfate	199	96 hr	LC50	231		Buhl and Hamilton 1996
Golden shiner (11-13 cm), *Notemigonus crysoleucas*	S,U	Copper sulfate	221	94 hr	Decreased serum osmolality	2,500	-	Lewis and Lewis 1971
Golden shiner, *Notemigonus crysoleucas*	S,U	Copper sulfate	45	24 hr	LC50 (5^0 C)	330	-	Cairns et al. 1978
Golden shiner, *Notemigonus crysoleucas*	S,U	Copper sulfate	45	24 hr	LC50 (15^0 C)	230	-	Cairns et al. 1978
Golden shiner, *Notemigonus crysoleucas*	S,U	Copper sulfate	45	24 hr	LC50 (30^0 C)	270	-	Cairns et al. 1978
Golden shiner, *Notemigonus crysoleucas*	F,M,T	Copper chloride	72.2	15 min	EC50 (avoidance)	26	-	Hartwell et al. 1989
Striped shiner, *Notropis chrysocephalus*	F,M,T,D	Copper sulfate	318	96 hr	LC50	3,400	-	Geckler et al. 1976
Striped shiner (4.7 cm) *Notropis chrysocephalus*	F,M,T,D	Copper sulfate	316	96 hr	LC50	4,000	-	Geckler et al. 1976
Striped shiner (5.0 cm) *Notropis chrysocephalus*	F,M,T,D	Copper sulfate	274	96 hr	LC50	5,000	-	Geckler et al. 1976
Striped shiner, *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, *Notropis chrysocephalus*	F,M,T,D	Copper sulfate	303	96 hr	LC50	16,000	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	208	48 hr	LC50	290	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	132	48 hr	LC50	150	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	182	48 hr	LC50	200	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	233	48 hr	LC50	180	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	282	48 hr	LC50	260	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	337	48 hr	LC50	260	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	322	48 hr	LC50	6,300	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	322	48 hr	LC50	11,000	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	322	48 hr	LC50	25,000	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	203	48 hr	LC50	160	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	203	48 hr	LC50	1,100	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,U	Copper sulfate	203	48 hr	LC50	2,900	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,M,D	Copper sulfate	320	48 hr	LC50	6,300	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,M,D	Copper sulfate	324	48 hr	LC50	9,000	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,M,D	Copper sulfate	324	48 hr	LC50	4,700	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,M,D	Copper sulfate	320	48 hr	LC50	11,000	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,M,D	Copper sulfate	318	48 hr	LC50	5,700	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,M,D	Copper sulfate	318	48 hr	LC50	10,000	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,M,D	Copper sulfate	314	48 hr	LC50	8,000	-	Geckler et al. 1976
Bluntnose minnow, *Pimephales notatus*	S,M,D	Copper sulfate	318	48 hr	LC50	11,000	-	Geckler et al. 1976
Bluntnose minnow, *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; Benson and Birge 1985
Fathead minnow (adult), *Pimephales promelas*	S,U	Copper sulfate	254-271	96 hr	LC50	390		Birge et al. 1983; 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; 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; 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; 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; 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; 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; 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; 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; 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; 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; 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; 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), *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), *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), *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), *Pimephales promelas*	S,M,T	Copper sulfate	17	96 hr	LC50	15.7	-	Welsh et al. 1993
Fathead minnow (60-90 days), *Pimephales promelas*	S,M,T	-	110	48 hr	LC50	284	-	Dobbs et al. 1994
Fathead minnow (3 wk), *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), *Pimephales promelas*	S,M,T	Copper sulfate	6-10	-	LC50	12.5	-	Suedel et al. 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	S,M,T	Copper sulfate	9.9	96 hr	LC50	10.7	-	Welsh et al. 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	S,M,T	Copper sulfate	7.1	96 hr	LC50	6.3	-	Welsh et al. 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	S,M,T	Copper sulfate	8.3	96 hr	LC50	12.2	-	Welsh et al. 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	S,M,T	Copper sulfate	8.9	96 hr	LC50	9.5	-	Welsh et al. 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	S,M,T	Copper sulfate	16.8	96 hr	LC50	26.8	-	Welsh et al. 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	S,M,T	Copper sulfate	12.2	96 hr	LC50	21.2	-	Welsh et al. 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	S,M,T	Copper sulfate	9.4	96 hr	LC50	19.8	-	Welsh et al. 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	S,M,T	Copper sulfate	11.4	96 hr	LC50	31.9	-	Welsh et al. 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	S,M,T	Copper sulfate	10.9	96 hr	LC50	26.1	-	Welsh et al. 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	S,M,T	Copper sulfate	12.4	96 hr	LC50	26.0	-	Welsh et al. 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	S,M,T	Copper sulfate	17.4	96 hr	LC50	169.5	-	Welsh et al. 1996
Fathead minnow (<24 hrs), *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), *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), *Pimephales promelas*	R,M,T,D	Copper sulfate	80	48 hr	LC50	35.9	-	Diamond et al. 1997a
Fathead minnow (larva), *Pimephales promelas*	R,M,T,D	Copper sulfate	80	48 hr	LC50	28.9	-	Diamond et al. 1997a
Fathead minnow (larva), *Pimephales promelas*	R,M,T,D	Copper sulfate	80	48 hr	LC50	20.7	-	Diamond et al. 1997a
Fathead minnow (larva), *Pimephales promelas*	R,M,T,D	Copper sulfate	80	48 hr	LC50	80.8	-	Diamond et al. 1997a
Fathead minnow (3-7 days), *Pimephales promelas*	R,M,T,D	Copper sulfate	80	48 hr	LC50	297.1	-	Diamond et al. 1997b
Fathead minnow (3-7 days), *Pimephales promelas*	R,M,T,D	Copper sulfate	72	48 hr	LC50	145.8	-	Diamond et al. 1997b
Fathead minnow (32-38 mm), *Pimephales promelas*	F,M,T	Copper sulfate	244	9 mo	LOEC (93% lower fecundity)	120	-	Brungs et al. 1976
Fathead minnow (larva), *Pimephales promelas*	F,M,T	Copper sulfate	202	-	LC50	250	-	Scudder et al. 1988
Fathead minnow (embryo), *Pimephales promelas*	F,M,T	Copper sulfate	202	34 days	Reduced growth; increased abnormality	61	-	Scudder et al. 1988
Fathead minnow (embryo), *Pimephales promelas*	F,M,T	Copper sulfate	202	34 days	LC50	123	-	Scudder et al. 1988
Fathead minnow (24-96 hr), *Pimephales promelas*	F,M,T	Copper sulfate	10.7	21 days	Incipient lethal level	6.2	-	Welsh 1996
Fathead minnow (24-96 hr), *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), *Pimephales promelas*	F,M,T	Copper sulfate	9.3	21 days	Incipient lethal level	17.2	-	Welsh 1996
Fathead minnow (24-96 hr), *Pimephales promelas*	F,M,T	Copper sulfate	9.3	21 days	Growth (length) reduced by 17%	16.2	-	Welsh 1996
Fathead minnow (<24 hrs), *Pimephales promelas*	F,M,T	Copper sulfate	46	96 hr	LC50	305	-	Erickson et al. 1996 a,b
Fathead minnow (<24 hrs), *Pimephales promelas*	F,M,T	Copper sulfate	46	96 hr	LC50	298.6	-	Erickson et al. 1996 a, b
Fathead minnow, *Pimephales promelas*	F,M,T	-	30	96 hr	LC50 (TOC=12 mg/L)	436	-	Lind et al. manuscript
Fathead minnow, *Pimephales promelas*	F,M,T	-	37	96 hr	LC50 (TOC=13 mg/L)	516	-	Lind et al. manuscript
Fathead minnow, *Pimephales promelas*	F,M,T	-	87	96 hr	LC50 (TOC=36 mg/L)	1,586	-	Lind et al. manuscript
Fathead minnow, *Pimephales promelas*	F,M,T	-	73	96 hr	LC50 (TOC=28 mg/L)	1,129	-	Lind et al. manuscript
Fathead minnow, *Pimephales promelas*	F,M,T	-	84	96 hr	LC50 (TOC=15 mg/L)	550	-	Lind et al. manuscript
Fathead minnow, *Pimephales promelas*	F,M,T	-	66	96 hr	LC50 (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, *Pimephales promelas*	F,M,T	-	117	96 hr	LC50 (TOC=30 mg/L)	2,050	-	Lind et al. manuscript
Fathead minnow, *Pimephales promelas*	F,M,T	-	121	96 hr	LC50 (TOC=30 mg/L)	2,336	-	Lind et al. manuscript
Fathead minnow, *Pimephales promelas*	F,M,T	Copper sulfate	117	96 hr	LC50	2,050	-	Lind et al. manuscript
Fathead minnow, *Pimephales promelas*	F,M,T	Copper sulfate	121	96 hr	LC50	2,336	-	Lind et al. manuscript
Fathead minnow (4.4 cm), *Pimephales promelas*	F,M,T,D	Copper sulfate	314	96 hr	LC50	11,000	-	Geckler et al. 1976
Fathead minnow (4.2 cm), *Pimephales promelas*	F,M,T,D	Copper sulfate	303	96 hr	LC50	15,000	-	Geckler et al. 1976
Fathead minnow (<24 hrs), *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), *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), *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), *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), *Pimephales promelas*	F,M,T,D	Copper sulfate	45	96 hr	LC50	65.41	45.78	Erickson et al. 1996a,b
Colorado squawfish (larva), *Ptychocheilus lucius*	S,U	Copper sulfate	199	96 hr	LC50	363		Buhl and Hamilton 1996
Colorado squawfish (155-186 days), *Ptychocheilus lucius*	S,U	Copper sulfate	199	96 hr	LC50	663		Buhl and Hamilton 1996
Colorado squawfish (32-40 days posthatch), *Ptychocheilus lucius*	S,U	Copper sulfate	144	96 hr	LC50	293		Hamilton and Buhl 1997
Colorado squawfish (32-40 days posthatch), *Ptychocheilus lucius*	S,U	Copper sulfate	144	96 hr	LC50	320		Hamilton and Buhl 1997
Creek chub, *Semotilus atromaculatus*	F,M,T	Copper sulfate	316	96 hr	LC50	11,500	-	Geckler et al. 1976
Creek chub, *Semotilus atromaculatus*	F,M,T	Copper sulfate	274	96 hr	LC50	1,100	-	Geckler et al. 1976
Razorback sucker (larva), *Xyrauchen texanus*	S,U	Copper sulfate	199	96 hr	LC50	404		Buhl and Hamilton 1996
Razorback sucker (102-116 days), *Xyrauchen texanus*	S,U	Copper sulfate	199	96 hr	LC50	331		Buhl and Hamilton 1996
Razorback sucker (13-23 days posthatch), *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, *Lepomis macrochirus*	S,U	Copper chloride	43	96 hr	LC50	770		Academy of Natural Sciences 1960
Bluegill, *Lepomis macrochirus*	S,U	Copper sulfate	43	96 hr	LC50	1,250		Academy of Natural Sciences 1960 Cairns and Scheier 1968; Patrick et
Bluegill, *Lepomis macrochirus*	S,U	Copper sulfate	45	24 hr	LC50 (5^0 C)	2,590	-	Cairns et al. 1978
Bluegill, *Lepomis macrochirus*	S,U	Copper sulfate	45	24 hr	LC50 (15^0 C)	2,500	-	Cairns et al. 1978
Bluegill, *Lepomis macrochirus*	S,U	Copper sulfate	45	24 hr	LC50 (30^0 C)	3,820	-	Cairns et al. 1978
Bluegill (3-4 cm), *Lepomis macrochirus*	S,U	-	119	8 days	33% reduction in locomotor activity	40	-	Ellgaard and Guillot 1988
Bluegill (4.2 cm), *Lepomis macrochirus*	S,U	Copper sulfate	52	96 hr	LC50	254		Inglis and Davis 1972
Bluegill (4.2 cm), *Lepomis macrochirus*	S,U	Copper sulfate	209	96 hr	LC50	437		Inglis and Davis 1972
Bluegill (4.2 cm), *Lepomis macrochirus*	S,U	Copper sulfate	365	96 hr	LC50	648		Inglis and Davis 1972
Bluegill (5-15 g), *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), *Lepomis macrochirus*	S,U	Copper sulfate	20	96 hr	LC50	660		Pickering and Henderson 1966
Bluegill (3.8-6.3 cm), *Lepomis macrochirus*	S,U	Copper sulfate	360	96 hr	LC50	10,200		Pickering and Henderson 1966
Bluegill, *Lepomis macrochirus*	S,U	Copper sulfate	20	96 hr	LC50	200		Tarzwell and Henderson 1960
Bluegill, *Lepomis macrochirus*	S,U	Copper sulfate	400	96 hr	LC50	10,000		Tarzwell and Henderson 1960
Bluegill (5-11 cm), *Lepomis macrochirus*	S,U	Copper sulfate	46	48 hr	LC50	3,000	-	Turnbull et al. 1954
Bluegill (5-11 cm), *Lepomis macrochirus*	S,U	Copper sulfate	101.2	48 hr	LC50	7,000	-	Turnbull et al. 1954
Bluegill (0.51g), *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), *Lepomis macrochirus*	S,M,T	Copper chloride	45-47	-	LC50	710	-	Trama 1954
Bluegill (5-9 cm), *Lepomis macrochirus*	S,M,T	Copper sulfate	45-47	-	LC50	770	-	Trama 1954
Bluegill (5-15 g), *Lepomis macrochirus*	F,M	Copper sulfate	35	-	LC50	2400	-	O'Hara 1971
Bluegill (3.5-6.0 cm), *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), *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), *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), *Lepomis macrochirus*	F,M,T	Copper sulfate	273.3	24-96 hr	Various behavioral changes	34	-	Henry and Atchison 1986
Bluegill, *Lepomis macrochirus*	F,M,T	Copper chloride	157	24-96 hr	27% reduction in food consumption	31	-	Sandheinrich and Atchison 1989
Bluegill, *Lepomis macrochirus*	F,M,T,D	Copper sulfate	316	96 hr	LC50 (high BOD)	16,000	-	Geckler et al. 1976
Bluegill, *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), *Lepomis macrochirus*	F,M,T,D	Copper sulfate	246	14 days	LC50	-	2,500	Richey and Roseboom 1978
Bluegill (1.15-2.42 g), *Lepomis macrochirus*	F,M,T,D	Copper sulfate	237	14 days	LC50	-	3,700	Richey and Roseboom 1978
Bluegill (48.3 g), *Lepomis macrochirus*	F,M,T,D	Copper sulfate	40	96 hr	Biochemical changes	2,000	-	Heath 1984
Largemouth bass (embryo), *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, *Micropterus salmoides*	F,U	-	-	24 hr	Affected opercular rhythm	48	-	Morgan 1979
Rainbow darter, *Etheostoma caeruleum*	F,M,T,D	Copper sulfate	318	96 hr	LC50 (high BOD)	4,500	-	Geckler et al. 1976
Rainbow darter, *Etheostoma caeruleum*	F,M,T,D	Copper sulfate	316	96 hr	LC50 (high BOD)	8,000	-	Geckler et al. 1976
Rainbow darter, 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), *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), *Etheostoma caeruleum*	F,M,T,D	Copper sulfate	303	96 hr	LC50 (high BOD)	5,300	-	Geckler et al. 1976
Fantail, *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:

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

$$\text{Mg} = (0.2431 \times \text{measured hardness}) \div (1+\text{Ca:Mg ratio})$$ **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	Na	K	Cl	SO_4	Ca:Mg[b]	Expected Hardness ($mg/L\ CaCO_3$)[c]
Very Soft (10-13 mg/L $CaCO_3$)	1.75	1.51	3.28	0.262	0.238	10.2	0.700	11
Soft (40-48 mg/L $CaCO_3$)	6.99	6.06	13.1	1.05	0.951	40.7	0.700	42
Moderately Hard (80-100 mg/L $CaCO_3$)	14.0	12.1	26.3	2.10	1.90	81.4	0.700	85
Hard (160-180 mg/L $CaCO_3$)	27.9	24.2	52.5	4.20	3.80	163	0.700	170
Very Hard (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

Applied to:	Hardness (mg/L $CaCO_3$)	Alkalinity (mg/L $CaCO_3$)	Specific Ions (mg/L)						
			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

Source	Water Type	pH	Total Hardness (mg/L $CaCO_3$)	Total Alkalinity (mg/L $CaCO_3$)	Specific Ions (mg/L)							Ca:Mg ratio	DOC (mg/L)
					Ca	Mg	Na	K	Cl	SO_4	NO_3		
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) 4.2 (Jun) 3.1 (Sep)	4.0 (May) 3.5 (May-Jul) 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 (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
	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

	Hardness	Alkalinity			Specific Ions (mg/L)						
Applied to:	(mg/L $CaCO_3$)	(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

	Hardness	Alkalinity			Specific Ions (mg/L)						
Applied to:	(mg/L $CaCO_3$)	(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

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	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

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	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

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	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

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	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

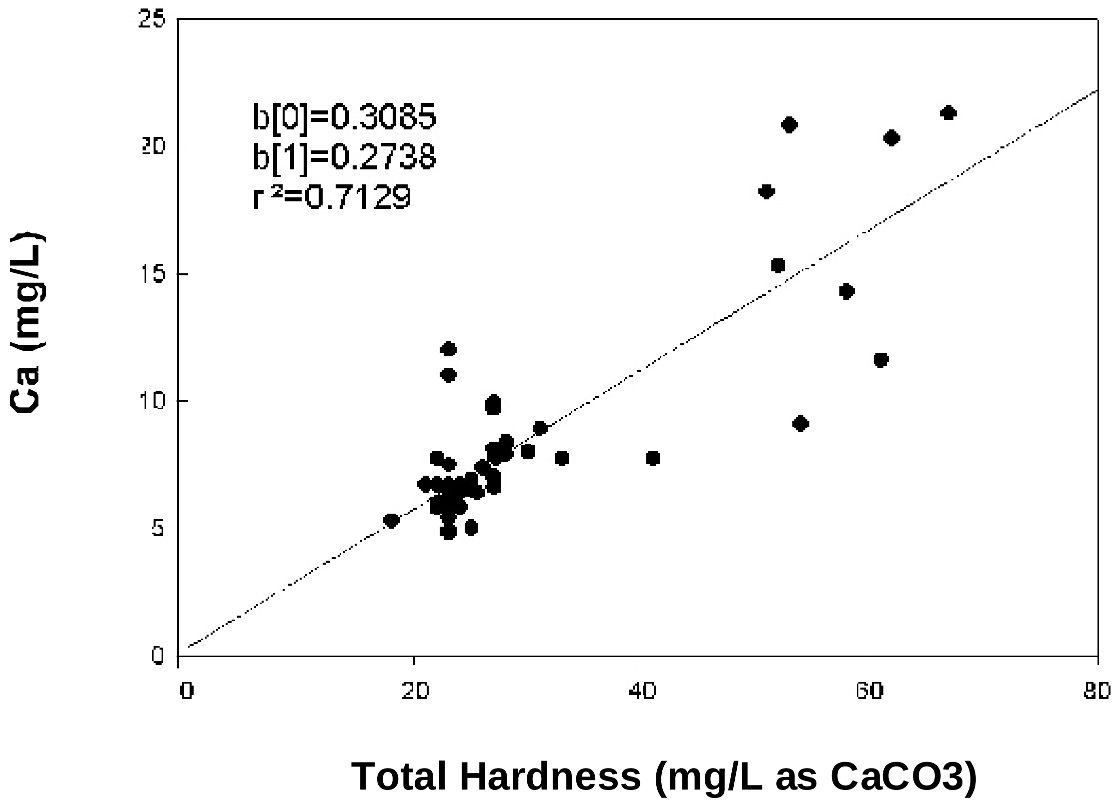


Figure 2. Relationship between Mg and hardness in WFTS well water.

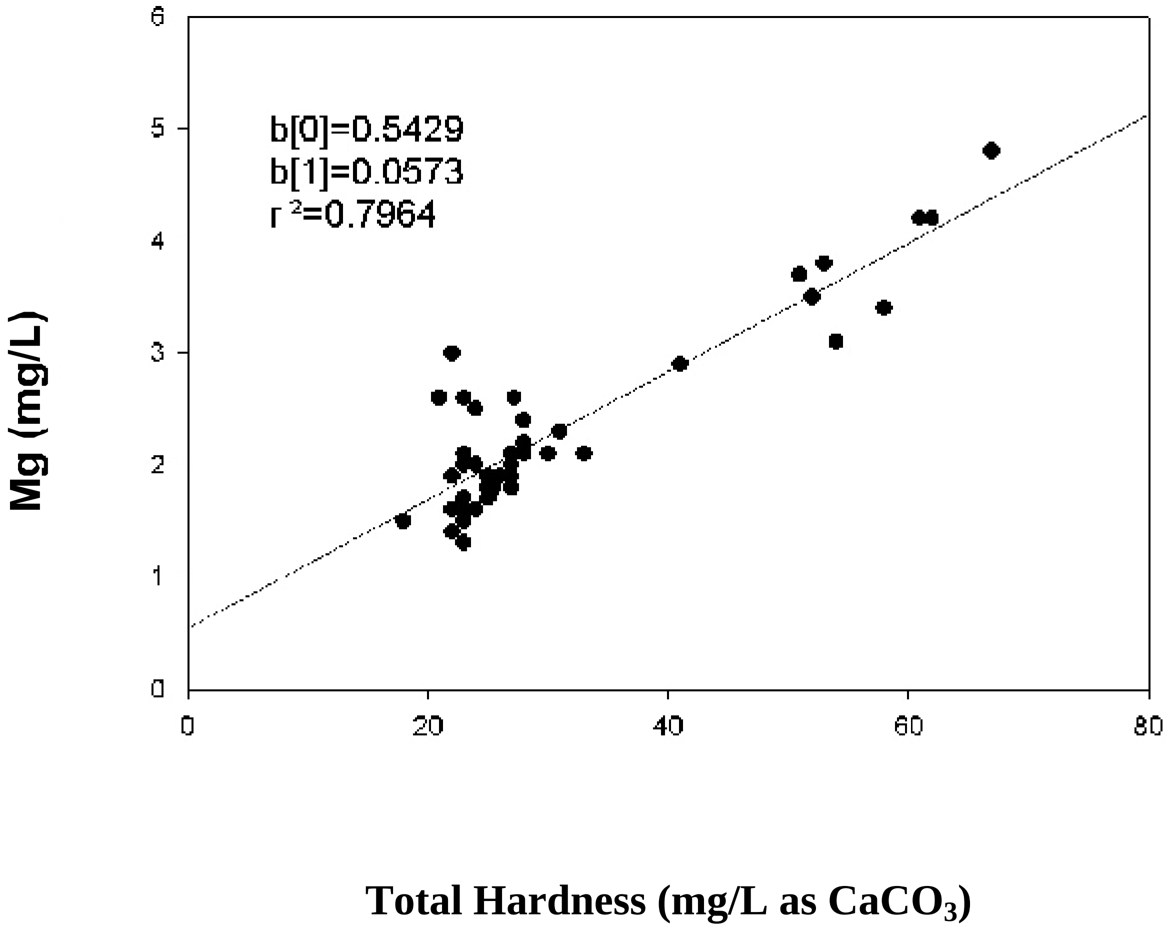


Figure 3. Relationship between Na and hardness in WFTS well water.

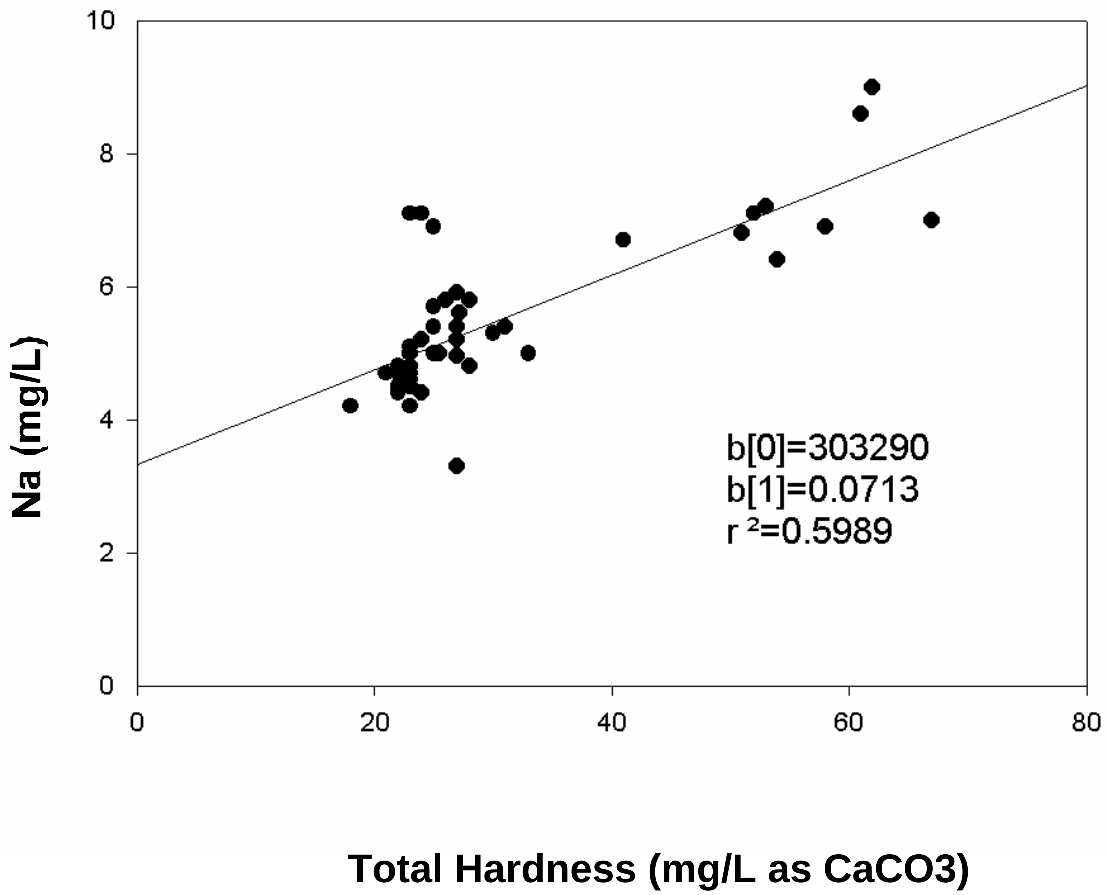


Figure 4. Relationship between K and hardness in WFTS well water

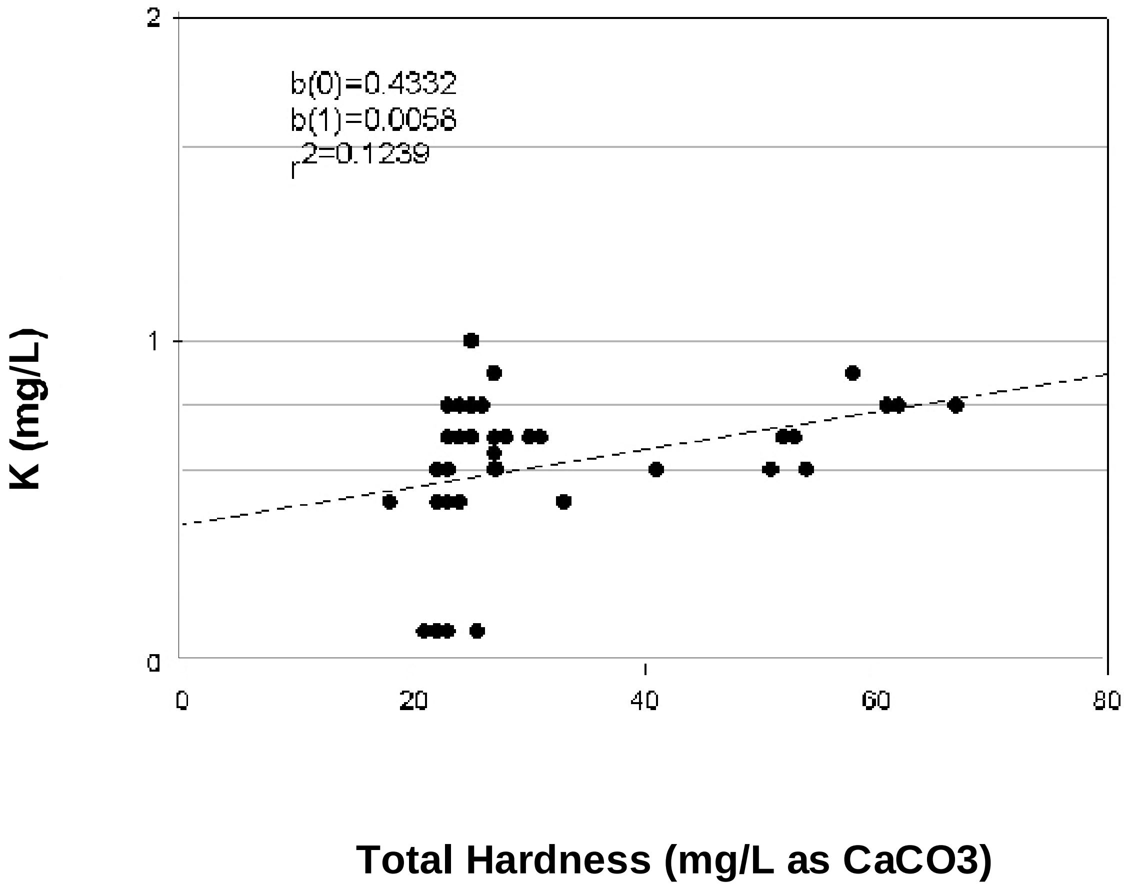


Figure 5. Relationship between Cl and hardness in WFTS well water.

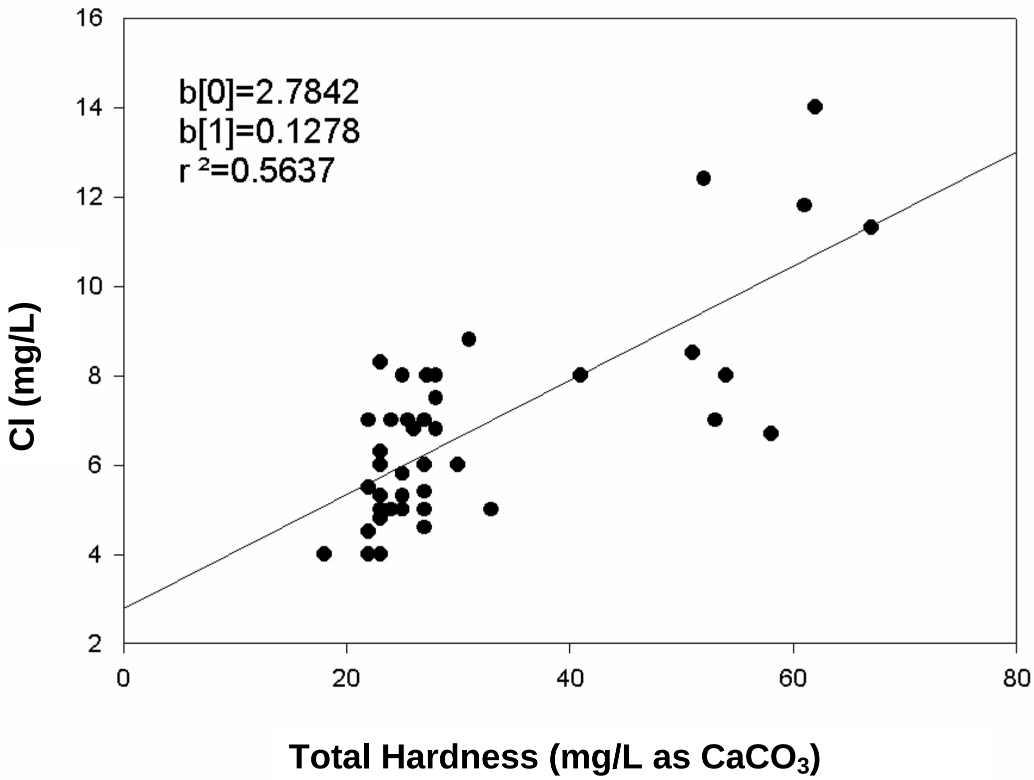


Figure 6. Relationship between SO_4 and hardness in WFTS well water.

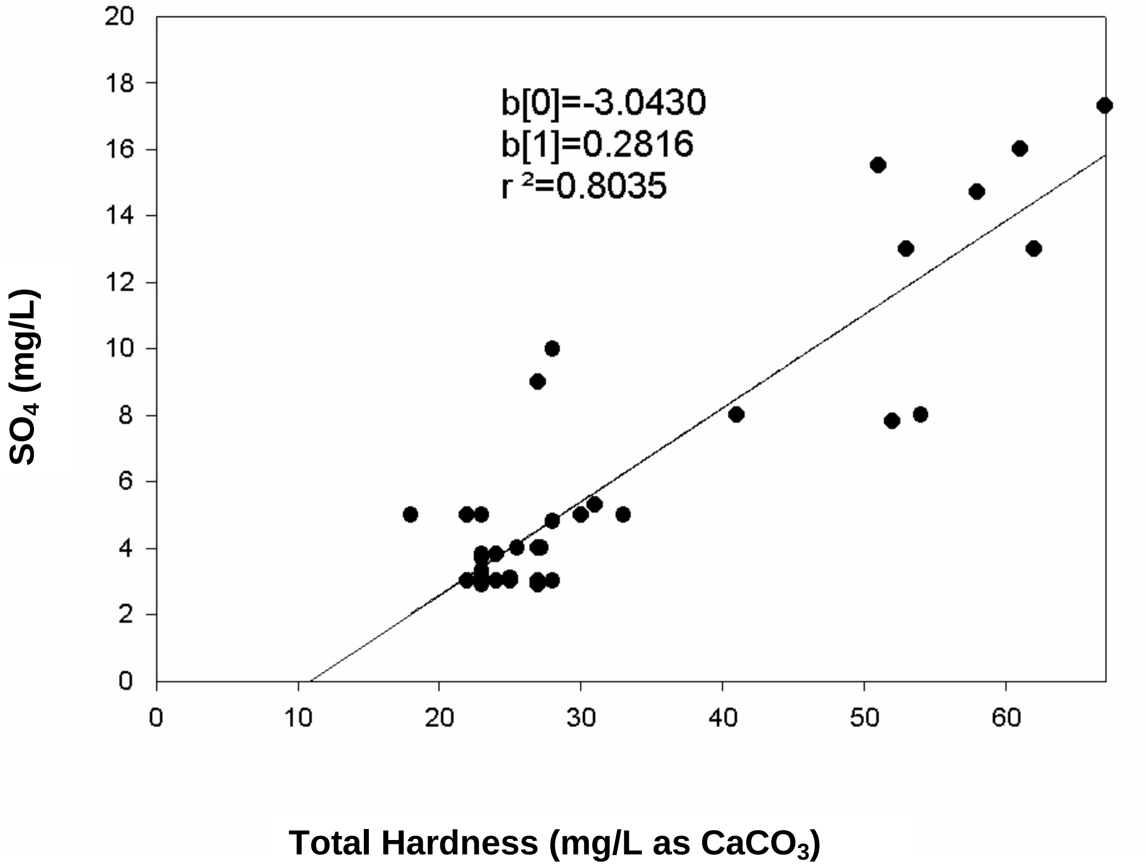


Figure 7. **Slopes of the regression equations derived for Na concentration in St. Louis River, MN, water versus water hardness from 1973 to 1993.**

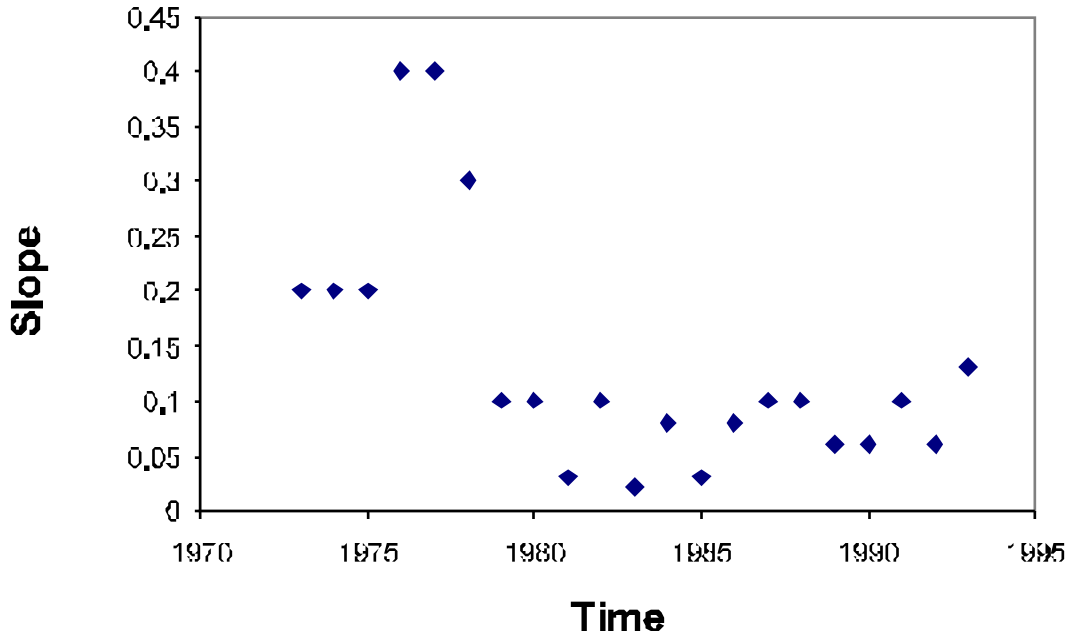
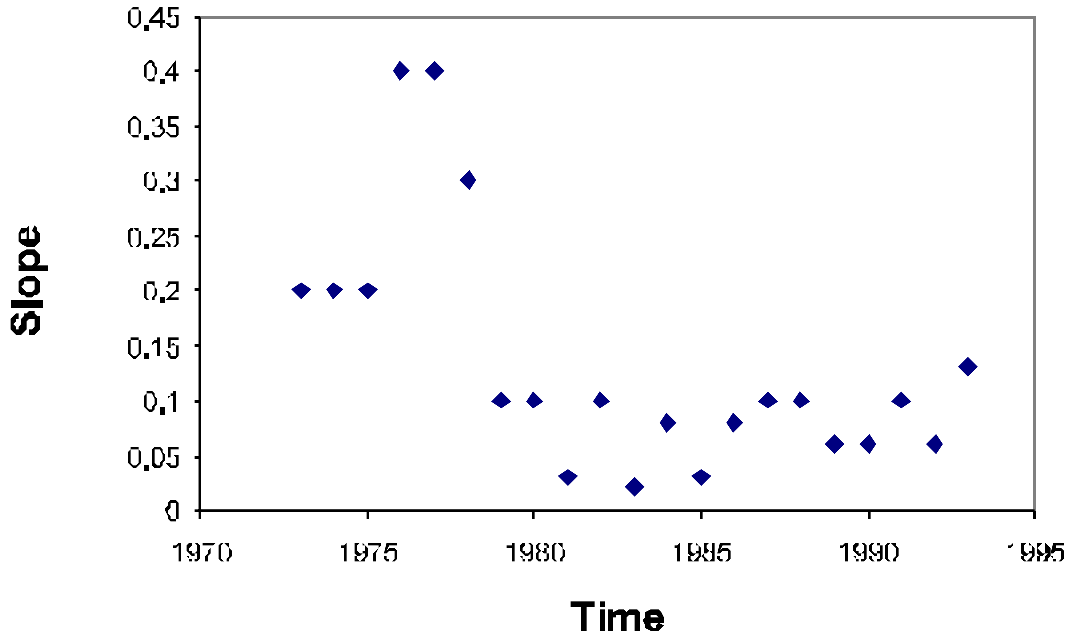


Figure 8. **Intercepts of the regression equations derived for Na concentration in St. Louis River, MN water versus water hardness from 1973 to 1993.**



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
$CaSO_4.2H_2O$ = 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 $CaSO_4.2H_2O$/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 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	---	---	---	---

State	POC	DOC	Streams Est. TOC	Est. DOC:TOC	POC	DOC	Lakes 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	

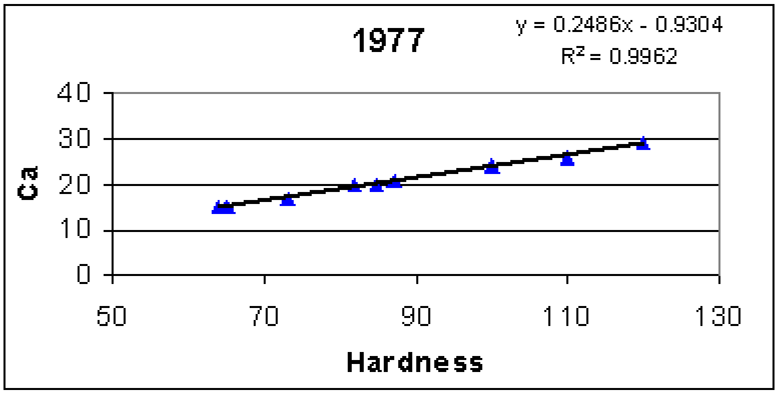
Appendix C-6. Water Composition of St. Louis River, MN, from USGS NASQAN and Select Relationships to Water Hardness

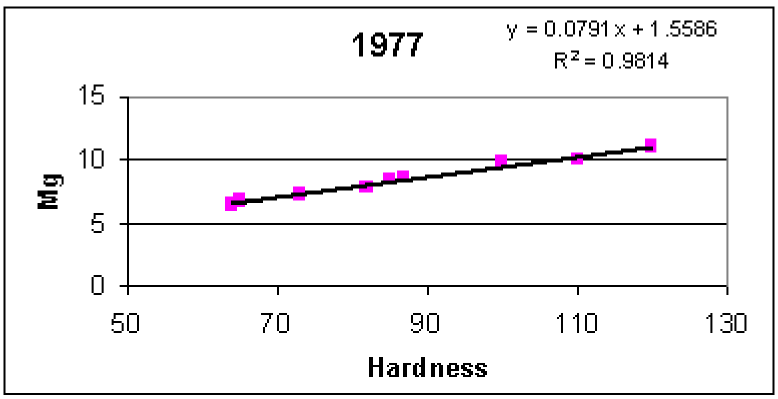
Date	pH	Hardness	Alkalinity	Ca	Mg	Na	K	Cl	SO_4	NO_3	DOC
19730222	6.8	68	53	17	6.3	11	1.6	14	14	0.19	
19730503	7.1	58	46	14	5.5	6.6	1.1	9.5	13	0.17	
19730816	6.9	70	51	17	6.6	7.6	1.2	9	20	0.01	
19731128	7	65	48	16	6.1	7.5	1.3	8.8	14		
19740221	7	64	48	16	5.8	8.9	1.3	12	14		
19740516	6.9	45	32	11	4.3	3.5	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

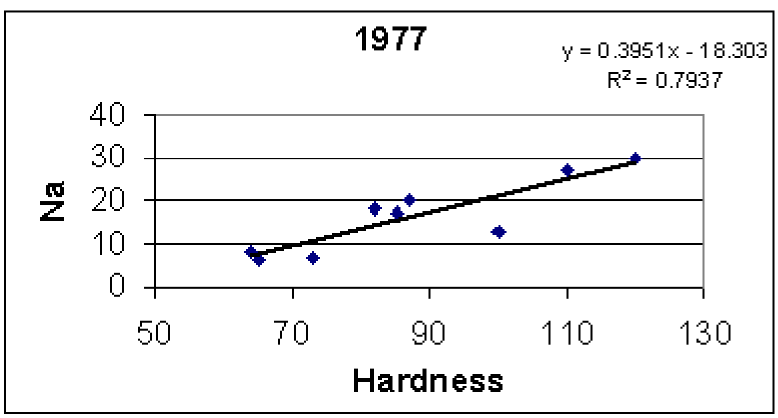
Date	pH	Hardness	Alkalinity	Ca	Mg	Na	K	Cl	SO_4	NO_3	DOCD
19790329	7.6	80	63	19	8	8.4	2.3	7.8	13		
19790430	7.6	37	29	8.7	3.7	2.2	1.3	2.8	8.9		20
19790611	7.2	47	34	11	4.8	3.1	0.8	2.8	9.4		
19790723	7.6	73	55	17	7.3	3.9	0.9	3.7	8.9		30
19790827	7.2										
19791015	8.1	74	54	16	8.2	5	1.1	3.9	13	0.01	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	

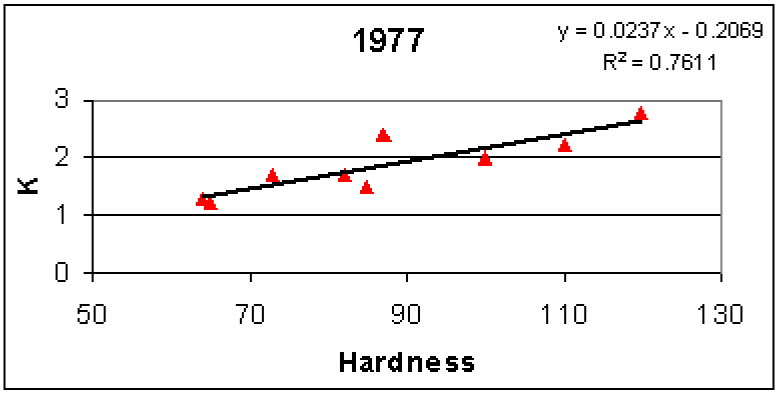
Date	pH	Hardness	Alkalinity	Ca	Mg	Na	K	Cl	SO_4	NO_3	DOCD
19851203	7.4	73		16	8	4	1	4.2	18	0.16	
19860303	7.4	66		15	7	4	1	3.4	10	0.24	
19860407	7.3									0.19	
19860602	7.5	58		13	6.3	3.5	1	2.8	15	0.1	
19860818	7.9	74		15	8.9	4.6	1.2	3.7	24	0.1	
19861112	7.5	55		12	6	3.4	1.4	3.8	19	0.27	
19861210	7.3	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	

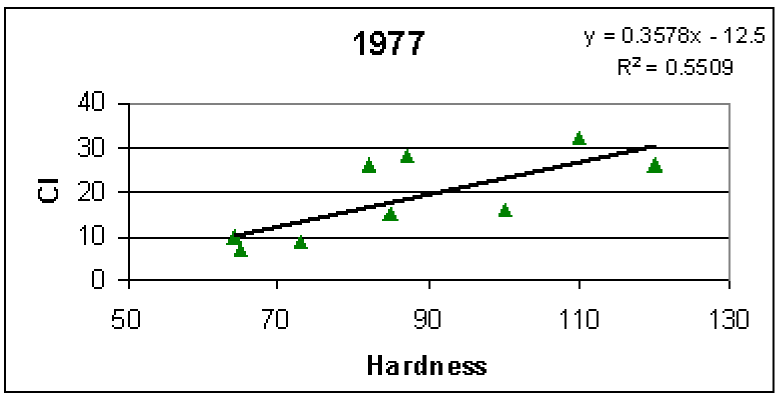
Date	pH	Hardness	Alkalinity	Ca	Mg	Na	K	Cl	SO_4	NO_3	DOCD
19940216	7.3										
19940511	7.7	51		11	5.6	3.7	1.1	3.4	9.4	0.076	
MIN	6.4	30	25	7.5	2.5	2.1	0.2	0.2	3.8	0.01	10
MAX	9.5	130	110	29	15	30	8.5	32	36	0.37	37
MEAN	7.52	71.11	56.94	16.16	7.46	7.09	1.37	7.39	15.04	0.17	22.19

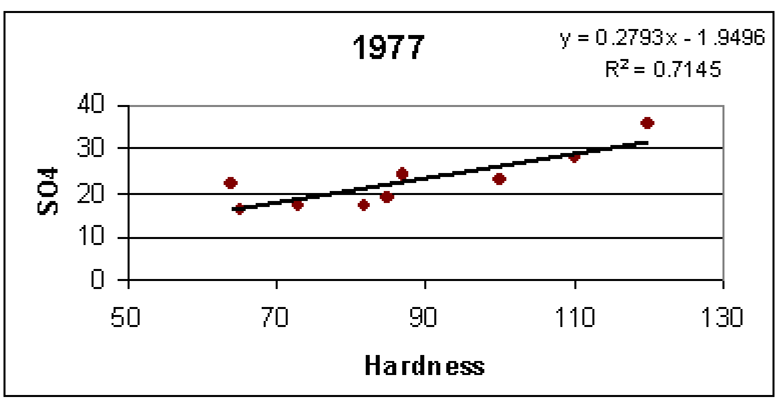

1977
y = 0.2486x - 0.9304
R² = 0.9962
Ca
40
30
20
10
0
50
70
90
110
130
Hardness


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


1977
y = 0.3951x - 18.303
R² = 0.7937
Na
40
30
20
10
0
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 (°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 (°C)	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 (°C)	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

BLM Data Label	Model Output: Critical Accumulation	Hard-ness (mg/L)	Model Input: 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

BLM Data Label	Model Output: Critical Accumulation	Hard-ness (mg/L)	Model Input: 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

BLM Data Label	Model Output: Critical Accumulation	Hard-ness (mg/L)	Model Input: 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

BLM Data Label	Model Output: Critical Accumulation	Hard-ness (mg/L)	Model Input: 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

BLM Data Label	Model Output: Critical Accumulation	Hard-ness (mg/L)	Model Input: 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

BLM Data Label	Model Output: Critical Accumulation	Hard-ness (mg/L)	Model Input: 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: Critical Accumulation	Hard-ness (mg/L)	Model Input: 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
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: Critical Accumulation	Hard-ness (mg/L)	Model Input: 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
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: Critical Accumulation	Hard-ness (mg/L)	Model Input: 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
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).

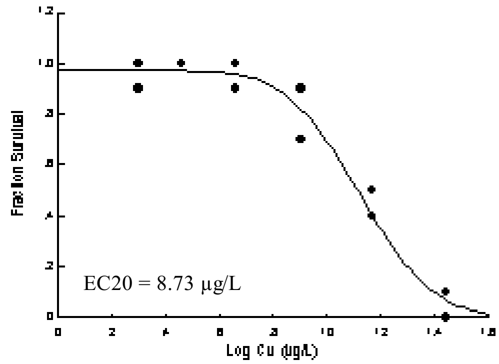
Pimephales notatus. An experimental design similar to that described by Mount and Stephan (1967) and Mount (1968) was used to examine the chronic effect of copper on the bluntnose minnow, *P. notatus* (Horning and Neiheisel 1979). Measured total copper concentrations were 4.3 (control), 18.0, 29.9, 44.1, 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.

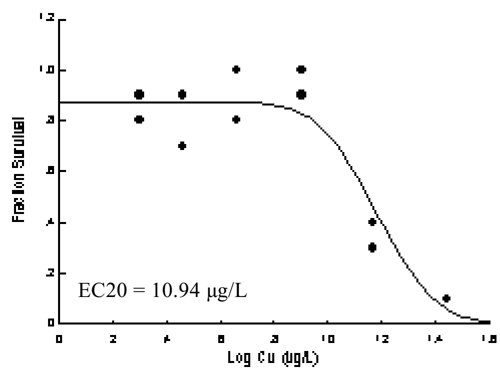
Catastomus commersoni. McKim et al. (1978) examined the survival and growth (expressed as standing crop) of embryo-larval and early juvenile white sucker exposed to copper. The embryo exposure was for 13 days, and the larval-early-juvenile exposure lasted 27 days. The NOAEC and LOAEC were 12.9 and 33.8 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.

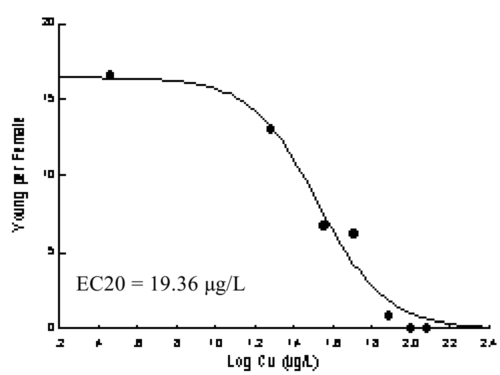
***Campeloma decisum* (Test 1), Life-cycle, Arthur and Leonard 1970**



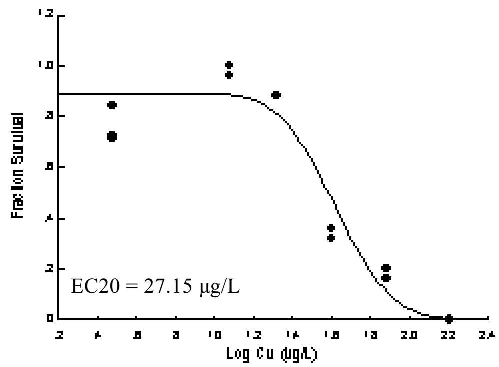
***Campeloma decisum* (Test 2), Life-cycle, Arthur and Leonard 1970**



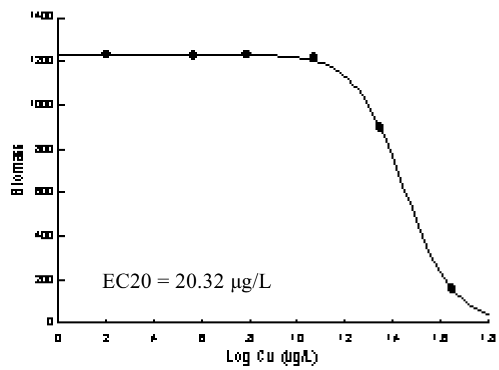
***Ceriodaphnia dubia* (Clinch River), Life-cycle, Belanger et al. 1989**



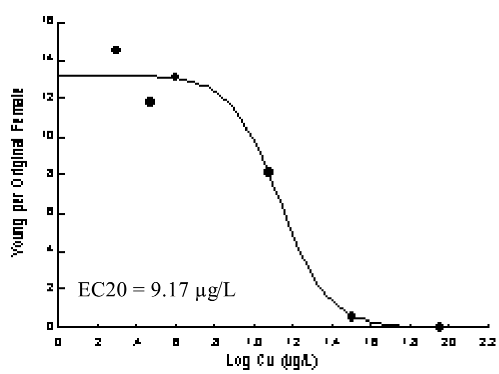
***Lepomis macrochirus*, Early Life-stage, Benoit 1975**



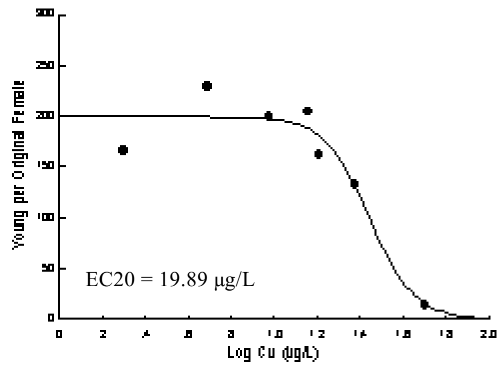
***Oncorhynchus mykiss*, Early Life-Stage, Besser et al. 2001**



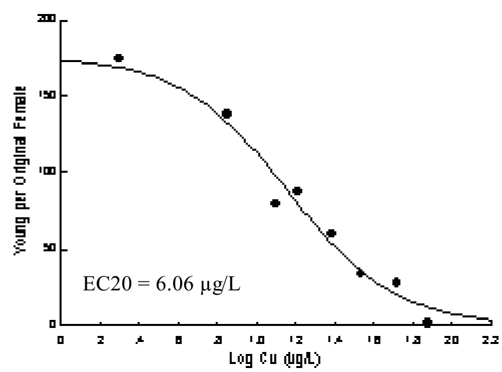
***Ceriodaphnia dubia*, Life-cycle, Carlson et al. 1986**



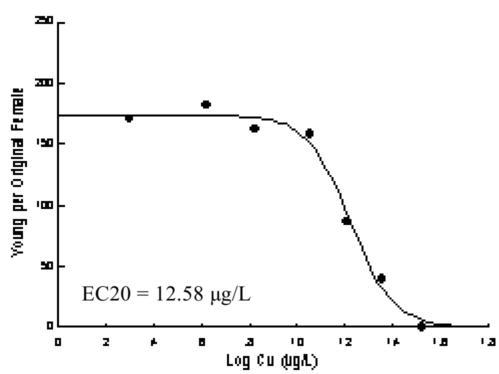
Daphnia magna (Hardness 104), Life-cycle, Chapman et al. Manuscript



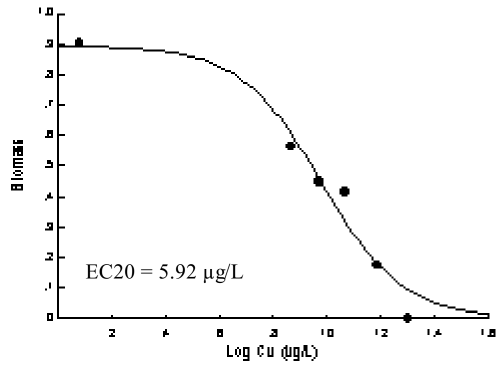
Daphnia magna (Hardness 211), Life-cycle, Chapman et al. Manuscript



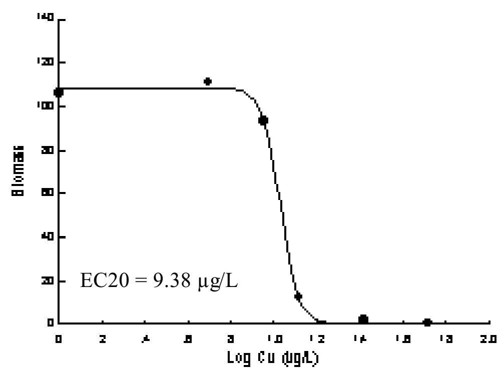
Daphnia magna (Hardness 51), Life-cycle, Chapman et al. Manuscript



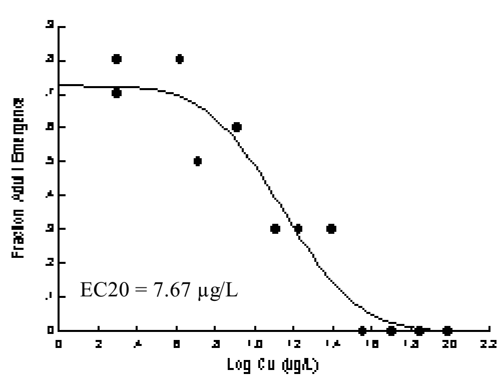
***Oncorhynchus tshawytscha*, Early Life-Stage, Chapman 1975 & 1982**



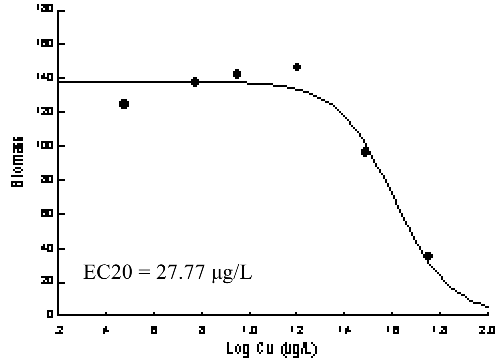
***Pimephales promelas*, Early Life-stage, Lind et al. 1978**



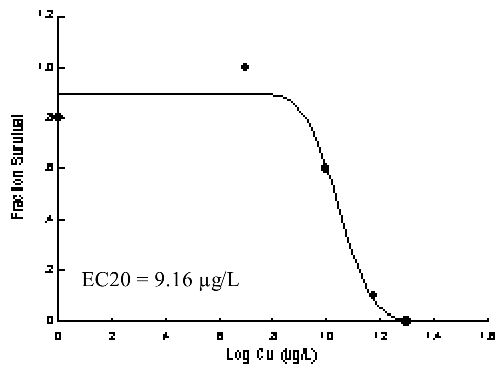
***Clistoronia magnifica*, Life-cycle, Nebeker et al. 1984a**



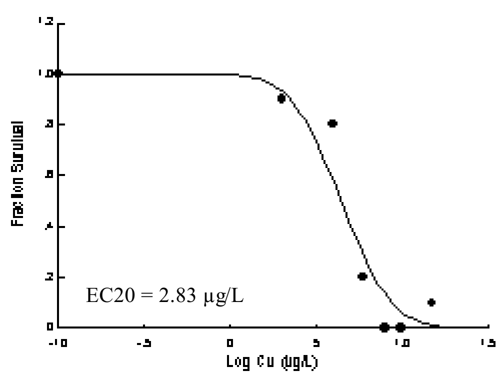
***Oncorhynchus mykiss,* Early Life-stage, Seim et al. 1984**



***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: $\boldsymbol{CMC} = \boldsymbol{e}^{(0.9422\,[\ln(H)]\,-\,1.7)}$

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).