United States
Environmental Protection
Agency

Office of Water
4304T

EPA-822-R-18-001
December 2018

FINAL
AQUATIC LIFE AMBIENT WATER QUALITY CRITERIA FOR ALUMINUM
2018

EPA-822-R-18-001

FINAL

AQUATIC LIFE

AMBIENT WATER QUALITY CRITERIA FOR ALUMINUM - 2018

(CAS Registry Number 7429-90-05)

December 2018

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF WATER
OFFICE OF SCIENCE AND TECHNOLOGY
HEALTH AND ECOLOGICAL CRITERIA DIVISION
WASHINGTON, D.C.

NOTICES

This document provides information to states and tribes authorized to establish water quality standards under the Clean Water Act (CWA), to protect aquatic life from toxic effects of aluminum. Under the CWA, states and tribes are to establish water quality criteria to protect designated uses. State and tribal decision makers retain the discretion to adopt approaches that are scientifically defensible that differ from these criteria to reflect site-specific conditions. While this document contains the Environmental Protection Agency's (EPA) scientific recommendations regarding ambient concentrations of aluminum that protect aquatic life, the Aluminum Criteria Document does not substitute for the CWA or the EPA's regulations; nor is it a regulation itself. Thus, the document does not impose legally binding requirements on the EPA, states, tribes, or the regulated community, and might not apply to a particular situation based upon the circumstances. The EPA may update this document in the future. This document has been approved for publication by the Office of Science and Technology, Office of Water, U.S. Environmental Protection Agency.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use. This document can be downloaded from: https://www.epa.gov/wqc/aquatic-life-criteria-and-methods-toxics.

FOREWORD

The Clean Water Act (CWA) Section 304(a)(l) (P.L. 95-217) directs the Administrator of the Environmental Protection Agency (EPA) 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 groundwater. This document is a final ambient water quality criteria (AWQC) document for the protection of aquatic life based upon consideration of all available information relating to effects of aluminum on aquatic organisms.

The term Water Quality Criteria is used in two sections of the CWA, Section 304(a)(l) and Section 303(c)(2). The term has different meanings in each section. In Section 304, the term represents a non-regulatory, scientific assessment of ecological and human health effects. Criteria presented in this document are such a scientific assessment of ecological effects. In section 303, if water quality criteria associated with specific surface water uses are adopted by a state or the EPA as water quality standards, they become the CWA water quality standards applicable in ambient waters within that state or authorized tribe. Water quality criteria adopted in state water quality standards could have the same numerical values as recommended criteria developed under section 304. However, in some situations states might want to adjust water quality criteria developed under section 304 to reflect local water chemistry or ecological conditions. Alternatively, states and authorized tribes may develop numeric criteria based on other scientifically defensible methods, but the criteria must be protective of designated uses. It is not until their adoption as part of state water quality standards, and subsequent approval by the EPA under section 303(c), that criteria become CWA applicable water quality standards. Guidelines to assist the states and authorized tribes in modifying the criteria presented in this document are contained in the Water Quality Standards Handbook (U.S. EPA 2014).

This document presents recommendations only. It does not establish or affect legal rights or obligations. It does not establish a binding requirement and cannot be finally determinative of the issues addressed. The EPA will make decisions in any particular situation by applying the CWA and the EPA regulations on the basis of specific facts presented and scientific information then available.

Deborah G. Nagle
Director
Office of Science and Technology

ACKNOWLEDGEMENTS

Technical Analysis Lead
Diana Eignor, Office of Water, Office of Science and Technology, Health and Ecological Criteria Division, Washington, DC

Reviewers (2018)
Kathryn Gallagher and Elizabeth Behl, Office of Water, Office of Science and Technology, Health and Ecological Criteria Division, Washington, DC

EPA Peer Reviewers (2017, 2018)
Nicole Shao and Robert Cantilli, U.S. EPA, Office of Research and Development, Office of Science Policy, Washington, DC

Russ Hockett, U.S. EPA, Office of Research and Development, Mid-Continent Ecology Division, Duluth, MN

Jan Gilbreath and Joseph Adamson, U.S. EPA, Office of Policy, Office of Regulatory Policy and Management, Washington, DC

Lee Schroer and Alexis Wade, U.S. EPA, Office of General Counsel, Washington, DC

Steve Ells and Matthew Lambert, U.S. EPA, Office of Land and Emergency Management, Washington, DC

Lars Wilcut and Heather Goss, U.S. EPA, Office of Water, Office of Science and Technology, Washington, DC

David Hair and Janita Aguirre, U.S. EPA, Office of Water, Office of Wastewater Management, Washington, DC

Jennifer Phillips, U.S. EPA Region 5, Chicago, IL

Mark Jankowski, U.S. EPA Region 10, Seattle, WA

We would like to thank Russ Erickson, U.S. EPA, Office of Research and Development, Mid-Continent Ecology Division, Duluth, MN and Bill Stubblefield, Oregon State University, for their technical support and contributions to this document.

TABLE OF CONTENTS

Page

Notices iii
Foreword iv
Acknowledgements v
Table of Contents vi
List of Tables viii
List of Figures viii
List of Appendices ix
Acronyms x
Executive Summary xi
1 Introduction and Background 1
2 Problem Formulation 2
  2.1 Overview of Aluminum Sources and Occurrence 2
  2.2 Environmental Fate and Transport of Aluminum in the Aquatic Environment 7
  2.3 Mode of Action and Toxicity 10
    2.3.1 Water Quality Parameters Affecting Toxicity 14
  2.4 Conceptual Model 16
    2.4.1 Conceptual Diagram 16
  2.5 Assessment Endpoints 18
  2.6 Measurement Endpoints 19
    2.6.1 Overview of Toxicity Data Requirements 20
    2.6.2 Measures of Effect 21
  2.7 Analysis Plan 27
    2.7.1 pH, Total Hardness and DOC Normalization 30
    2.7.2 Acute Criterion 40
    2.7.3 Chronic Criterion 41
3 Effects Analyses 41
  3.1 Acute Toxicity to Aquatic Animals 42
    3.1.1 Freshwater 42
    3.1.2 Estuarine/Marine 49
  3.2 Chronic Toxicity to Aquatic Animals 50
    3.2.1 Freshwater 50
    3.2.2 Estuarine/Marine 59
  3.3 Bioaccumulation 59
  3.4 Toxicity to Aquatic Plants 60
4 Summary of National Criteria 60
  4.1 Freshwater 60
  4.2 Estuarine/Marine 65

5 Effects Characterization 66
  5.1 Effects on Aquatic Animals 66
    5.1.1 Freshwater Acute Toxicity 66
    5.1.2 Freshwater Chronic Toxicity 70
    5.1.3 Freshwater Field Studies 71
    5.1.4 Estuarine/Marine Acute Toxicity 73
    5.1.5 Estuarine/Marine Chronic Toxicity 74
    5.1.6 Bioaccumulation 74
  5.2 Effects on Aquatic Plants 76
  5.3 Identification of Data Gaps and Uncertainties for Aquatic Organisms 77
    5.3.1 Acute Criteria 77
    5.3.2 Chronic Criteria 78
    5.3.3 Laboratory to Field Exposures 78
    5.3.4 Lack of Toxicity Data for Estuarine/Marine Species and Plants 79
    5.3.5 Bioavailability Models 79
    5.3.6 pH, Total Hardness and DOC MLR Models 80
  5.4 Protection of Endangered Species 82
    5.4.1 Key Acute Toxicity Data for Listed Fish Species 82
    5.4.2 Key Chronic Toxicity Data for Listed Fish Species 82
    5.4.3 Concerns about Federally Listed Endangered Mussels 82
  5.5 Comparison of 1988 and 2018 Criteria Values 84
6 Unused Data 84
7 References 86

LIST OF TABLES

Page

Table 1. Summary of Assessment Endpoints and Measures of Effect Used in Criteria Derivation. 19
Table 2. Summary of Acceptable Toxicity Data Used to Fulfill the Minimum Data Requirements in the 1985 Guidelines for Aluminum. 29
Table 3. Ranked Freshwater Genus Mean Acute Values at pH 7, Total Hardness of 100 mg/L, and DOC of 1.0 mg/L. 47
Table 4. Freshwater Final Acute Value and Criterion Maximum Concentration (normalized to pH 7, total hardness of 100 mg/L and DOC of 1.0 mg/L). 48
Table 5. Ranked Genus Mean Chronic Values at pH 7, Total Hardness of 100 mg/L, and DOC of 1.0 mg/L........ 57
Table 6. Freshwater Final Chronic Value and Criterion Continuous Concentration (normalized to pH 7, total hardness of 100 mg/L and DOC of 1.0 mg/L). 58
Table 7. Freshwater Acute and Chronic Criteria at Example Conditions of DOC of 1.0 mg/L and Various Water Total Hardness Levels and pH. 65
Table 8. Ranked Estuarine/Marine Genus Mean Acute Values. 73
Table 9. Comparison of the 2018 Recommended Aluminum Aquatic Life AWQC and the 1988 Criteria. 84

LIST OF FIGURES

Page

Figure 1. Geographic Distribution of Dissolved Aluminum Concentrations in Groundwater Collected from Wells as Part of the National Water-Quality Assessment Program, 1992–2003........ 5
Figure 2. Results of Al Speciation Calculations at a Total of 65 µM Al in the Absence of Ligands (panel A) and in the Presence of Citrate (65 µM) (panel B), Maltolate (195 µM) (panel C), and Fluoride (260 µM) (panel D) in the pH Range 2 to 8. 10
Figure 3. Conceptual Model for Aluminum Effects on Aquatic Organisms. 17
Figure 4. Observed and Individual MLR-Predicted Aluminum EC_{20}s (±95% CLs) for *C. dubia* where DOC or pH was Varied. 34
Figure 5. Observed and Individual MLR-Predicted Aluminum EC_{20}s (±95% CLs) for *C. dubia* where Total Hardness was Varied........ 35
Figure 6. Observed and Individual MLR-Predicted Aluminum EC_{20}s (±95% CLs) for *P. promelas* where DOC or pH was Varied........ 37
Figure 7. Observed and Individual MLR-Predicted Aluminum EC_{20}s (±95% CLs) for *P. promelas* where Total Hardness was Varied. 38

Figure 8. Ranked Summary of Total Aluminum Genus Mean Acute Values (GMAVs) - Freshwater at pH 7, Total Hardness of 100 mg/L, and DOC of 1.0 mg/L. 49
Figure 9. Ranked Summary of Total Aluminum Genus Mean Acute Values (GMAVs) - Estuarine/Marine. 50
Figure 10. Ranked Summary of Total Aluminum Genus Mean Chronic Values (GMCVs) – Freshwater Supplemented with Other Data to Fulfill Missing MDRs at pH 7, Total Hardness of 100 mg/L, and DOC of 1.0 mg/L. 59

LIST OF APPENDICES

Page

Appendix A Acceptable Acute Toxicity Data of Aluminum to Freshwater Aquatic Animals A-1
Appendix B Acceptable Acute Toxicity Data of Aluminum to Estuarine/Marine Aquatic Animals B-1
Appendix C Acceptable Chronic Toxicity Data of Aluminum to Freshwater Aquatic Animals C-1
Appendix D Acceptable Chronic Toxicity Data of Aluminum to Estuarine/Marine Aquatic Animals D-1
Appendix E Acceptable Toxicity Data of Aluminum to Freshwater Aquatic Plants E-1
Appendix F Acceptable Toxicity Data of Aluminum to Estuarine/Marine Aquatic Plants F-1
Appendix G Acceptable Bioaccumulation Data of Aluminum by Aquatic Organisms G-1
Appendix H Other Data on Effects of Aluminum to Freshwater Aquatic Organisms H-1
Appendix I Other Data on Effects of Aluminum to Estuarine/Marine Aquatic Organisms I-1
Appendix J List of Aluminum Studies Not Used in Document Along with Reasons J-1
Appendix K Recommended Criteria for Various Water Chemistry Conditions K-1
Appendix L EPA’s MLR Model Comparison of DeForest et al. (2018b) Pooled and Individual-Species Model Options L-1

ACRONYMS

ACR	Acute to Chronic Ratio
AIC	Akaike Information Criterion
AVS	Acid Volatile Sulfide
AWQC	Ambient Water Quality Criteria
BAF	Bioaccumulation Factor
BCF	Bioconcentration Factor
BIC	Bayesian Information Criterion
CCC	Criterion Continuous Concentration
CMC	Criterion Maximum Concentration
CV	Chronic Value (expressed in this document as an EC_{20})
CWA	Clean Water Act
DOC	Dissolved Organic Carbon
ECOTOX	Ecotoxicology Database
EC_x	Effect Concentration at X Percent Effect Level
ELS	Early-Life Stage
EPA	Environmental Protection Agency
EU	European Union
FACR	Final Acute-to-Chronic Ratio
FAV	Final Acute Value
FCV	Final Chronic Value
FDA	US Food and Drug Administration
GMAV	Genus Mean Acute Value
GMCV	Genus Mean Chronic Value
IC_x	Inhibitory Concentration at X Percent Level
LC_x	Lethal Concentration at X Percent Survival Level
LOEC	Lowest Observed Effect Concentration
MATC	Maximum Acceptable Toxicant Concentration (expressed mathematically as the geometric mean of the NOEC and LOEC)
MDR	Minimum Data Requirement
MLR	Multiple Linear Regression
NAWQA	USGS National Water Quality Assessment Program
NOAA	National Oceanic and Atmospheric Administration
NOEC	No Observed Effect Concentration
NPDES	National Pollutant Discharge Elimination System
QA/QC	Quality Assurance and Quality Control
SMAV	Species Mean Acute Value
SMCV	Species Mean Chronic Value
TMDL	Total Maximum Daily Load
TRAP	Toxicity Relationship Analysis Program
US	United States
USGS	United States Geological Survey
WQC	Water Quality Criteria
WQS	Water Quality Standards

EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA) is updating its aquatic life ambient water quality criteria (AWQC) recommendation for aluminum, in accordance with the provisions of section 304(a) directing the EPA to revise AWQC from time to time to reflect the latest scientific knowledge. The recommended aluminum aquatic life AWQC were developed using peer reviewed methods and data that are acceptable for the derivation of criteria, as described in the EPA's 1985 "*Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses*" (Stephan et al. 1985, referred to herein as "1985 Guidelines"). The previous aquatic life AWQC for aluminum were developed in 1988 (EPA 440/5-86-008). These 2018 final recommended aquatic life AWQC for aluminum supersedes the 1988 recommended criteria.

The 2017 draft aquatic life AWQC for aluminum were posted to the Federal Register (Docket ID: EPA-HQ-OW-2017-0260) in late July 2017 for public comment. The public comment period was open for 90 days and closed in late October 2017. Public comments received were incorporated and addressed in these final AWQC, where applicable. The EPA responses to all of the public comments can be found on the website for the aluminum criteria (https://www.epa.gov/wqc/aquatic-life-criteria-aluminum).

Literature searches for laboratory tests published from 1988 to 2017 identified new studies describing the toxicity of aluminum to aquatic life. The EPA supplemented these studies with additional data made available by researchers in late-2017 and 2018. The EPA conducted a full evaluation of available data to determine test acceptability for criteria development. Appendix A of "*Quality Criteria for Water 1986*" (U.S. EPA 1986) provides an in-depth discussion of the minimum requirements for data quality needed to develop AWQC for aquatic life.

This update to the recommended aluminum aquatic life AWQC establishes freshwater criteria magnitude values resulting from the interactions of aluminum and three water chemistry parameters: pH, total hardness, and dissolved organic carbon (DOC). It also expands the toxicity database to include those studies conducted in waters with pH values below 6.5. There were insufficient data to establish an estuarine/marine aluminum criteria.

Multiple linear regression (MLR) models were developed to characterize the bioavailability of aluminum in aquatic systems, based on the effects of pH, total hardness and

DOC on aluminum toxicity (DeForest et al. 2018a,b). These authors used a dataset comprised of 22 chronic tests with the fathead minnow (*Pimephales promelas*), and 23 chronic tests with an invertebrate (*Ceriodaphnia dubia*) to evaluate the ability of MLR models to predict chronic toxicity of aluminum as a function of pH, total hardness and DOC water chemistry conditions. These three parameters are considered to be the most influential for aluminum bioavailability and can be used to explain the range of differences in the observed toxicity values. These datasets were supplemented in 2018 with an additional nine *C. dubia* toxicity tests and nine *P. promelas* toxicity tests to expand the range of water chemistry conditions for model development (OSU 2018a,b,d). All of the toxicity test data used in the model were subjected to independent external expert peer review.

Two models, one for invertebrates and one for vertebrates, were used to normalize freshwater aluminum toxicity values. These separate models correspond to effects on invertebrates and vertebrates due to differing effects of pH, total hardness and DOC on aluminum bioavailability and toxicity, and therefore enable the criteria magnitudes to be calculated as a function of the unique chemistry conditions at a given site. The EPA conducted both independent external expert peer review and internal reviews of these models, published by DeForest et al. (2018a,b), to verify the results. The updated aluminum criteria were derived using these MLR models to normalize the freshwater acute and chronic toxicity data. The MLR equations applied to the acute toxicity data were those developed using chronic tests, with the expectation that the effect of water chemistry on bioavailability remains consistent across exposure duration.

Freshwater Criteria Update

The 1988 aluminum freshwater criteria (U.S. EPA 1988) are expressed as total recoverable aluminum. Acid soluble aluminum was considered but not used because the methods were not developed. These updated 2018 criteria are also based on total recoverable aluminum concentrations.

The 1988 criteria did not consider the variable effects of water chemistry on aluminum toxicity, but simply specified that the recommended criteria only applied to a pH range of 6.5 to 9.0. The 2018 final aluminum recommended AWQC take into account the effects of pH, total hardness and DOC on aluminum toxicity.

The 1988 freshwater acute criterion was based on data from eight species of invertebrates and seven species of fish for a total of 15 species grouped into 14 genera. This 2018 freshwater acute criterion update is based on data from 13 species of invertebrates, eight species of fish, and one species of frog for a total of 22 species grouped into 20 genera.

The freshwater acute criterion represents the concentration of aluminum at which approximately 95% of genera in a freshwater aquatic ecosystem should be protected if the one-hour average (duration) concentration of total aluminum is not exceeded more than once in three years (frequency). The magnitude of the criterion depends on the water chemistry conditions in the waterbody, using the MLR models to normalize the freshwater acute toxicity data. As a result, the acute criterion will vary with water chemistry conditions. Example acute criteria values for various water chemistry conditions are presented in **Appendix K** (*Recommended Criteria for Various Water Chemistry Conditions*) and can also be calculated with the Aluminum Criteria Calculator V.2.0[1].

The 1988 aluminum freshwater chronic dataset included two species of invertebrates and one fish species grouped into three genera. This 2018 criteria update includes new chronic data for an additional nine species, and consists of eight invertebrate and four fish species grouped into 12 genera. With the addition of one study from **Appendix H** (*Other Data on Effects of Aluminum to Freshwater Aquatic Organisms*), the Minimum Data Requirements (MDRs) for direct calculation (using a sensitivity distribution, as described in the 1985 Guidelines) of the Final Chronic Value (FCV) were fulfilled. This method does not require the use of an acute to chronic ratio (ACR).

Like the acute criterion, the freshwater chronic criterion is also dependent on the water chemistry of the waterbody. Therefore, it is also a function of the MLR models used to normalize the chronic toxicity data. Example chronic criteria (CCC) for various water chemistry conditions are presented in **Appendix K** (*Recommended Criteria for Various Water Chemistry Conditions*) and can also be calculated with the Aluminum Criteria Calculator V.2.0.

The empirical toxicity test data used to develop the MLR models were developed under a range of water chemistry conditions (for more detail, see **Section 4** of this document). The MLRs were then used to normalize all of the toxicity data used in the criteria calculations. MLR models

---

[1] https://www.epa.gov/wqc/aquatic-life-criteria-aluminum

are useful for characterizing trends in data, but should be used with caution when extrapolating beyond the range of data used for model development.

The bounds for pH of the models ranged from 6.0-8.7. The EPA criteria calculator is designed to allow the user to extrapolate beyond the pH values used to generate the MLR models. The criteria calculator can be used to address all waters within a pH range of 5.0 to 10.5. This is reflected in the criteria lookup tables in **Appendix K**. The EPA took this approach so that the recommended criteria can be calculated for, and will be protective of, a broader range of natural waters found in the U.S. Extrapolated criteria values outside of the empirical pH data tend to be more conservative (i.e., lower values) and will be more protective of the aquatic environment in situations where pH plays a critical role in aluminum toxicity. Criteria values generated outside of the range of the pH conditions of the toxicity tests underlying the MLR models are more uncertain than values within the pH conditions of the MLR toxicity tests, and thus should be considered carefully and used with caution.

The bounds for total hardness of the models ranged from 9.8 to 428 mg/L. Since a decrease in total hardness tends to increase aluminum toxicity, the EPA concludes that it is reasonable to extrapolate below the lower bound of the empirical hardness data of 9.8 mg/L to enable generation of more stringent criteria at low hardnesses. This is consistent with existing EPA approaches to address low end hardness values (U.S. EPA 2002). Therefore, hardness input values in the criteria calculator can be entered that are less than 9.8 mg/L down to a limit of 0.01 mg/L. However, hardness input values into the criteria calculator will be bounded at the approximate upper limit of the empirical MLR models' underlying hardness data, at a maximum of 430 mg/L total hardness (as $CaCO_3$). The user can input hardness values greater than 430 mg/L for total hardness into the criteria calculator, but the criteria magnitude will reach its maximum value at 430 mg/L total hardness (as $CaCO_3$), and criteria magnitudes will not increase or decrease by increasing the hardness above 430 mg/L total hardness (as $CaCO_3$). This is also consistent with existing EPA guidance on high end hardness caps (U.S. EPA 2002). This recommendation is reflected in the criteria lookup tables provided in **Appendix K**. The EPA took this approach to ensure that the recommended criteria are protective of a broader range of natural waters found in the U.S. Criteria values generated beyond the lower bound of the hardness conditions of the toxicity tests underlying the MLR models are more uncertain than values within the hardness bounds of the MLR toxicity test data.

The bounds for DOC of the models ranged from 0.08 to 12.3 mg/L. Since most natural waters contain some DOC, the lower bound of the empirical toxicity test data (0.08 mg/L) is the lowest value that can be entered into the criteria calculator; thus no extrapolation below the lowest empirical DOC of 0.08 mg/L is provided. Similar to hardness, the criteria values generated will be bounded at the upper limit of the empirical MLR models' underlying DOC data, at a maximum 12.0 mg/L DOC in the criteria calculator. The user can input DOC values greater than 12.0 mg/L into the calculator, but the criteria magnitude will reach its maximum value at 12.0 mg/L DOC, and criteria magnitudes will not increase or decrease by increasing the DOC above 12.0 mg/L. This limitation on the maximum DOC value is also reflected in the criteria lookup tables provided in **Appendix K**. This is consistent with the existing approach for hardness (U.S. EPA 2002) to provide for protection of aquatic organisms through the use of protective, conservative values under water chemistry conditions beyond the upper limits of the empirical toxicity test data.

In addition to **Appendix K** look-up tables, the EPA created a user-friendly **Aluminum Criteria Calculator V.2.0** (Aluminum Criteria Calculator V.2.0.xlsm) that allows users to enter site-specific values for pH, total hardness and DOC to calculate the appropriate recommended freshwater acute and chronic criteria magnitudes for site-specific parameters and will generate criteria magnitude values based on the bounds described above.

2018 Recommended Aluminum Aquatic Life AWQC and the 1988 Criteria[a]

Version	**Freshwater Acute** (1-hour, total aluminum)	**Freshwater Chronic** (4-day, total aluminum)
2018 AWQC (vary as a function of a site's pH, DOC and total hardness)	1-4,800 µg/L[b]	0.63-3,200 µg/L[b]
1988 AWQC (pH 6.5 – 9.0, across all total hardness and DOC ranges)	750 µg/L	87 µg/L

[a] Values are recommended not to be exceeded more than once every three years on average.

[b] Criteria values will be different under differing water chemistry conditions as identified in this document, as described in Appendix K and applied in the Aluminum Criteria Calculator.

Estuarine/Marine Criteria Update

As with the 1988 AWQC for aluminum, there are still insufficient data on estuarine and marine species to fulfill the MDRs as specified in the 1985 Guidelines. As a result, the EPA cannot recommend criteria for estuarine/marine waters at this time. The 1985 Guidelines require that data from a minimum of eight families are needed to calculate an estuarine/marine Final Acute Value (FAV). New acute toxicity data for five families representing five species of estuarine/marine organisms are available for aluminum; no data were previously available. The most sensitive species was the polychaete worm (*Ctenodrilus serratus*) with a Species Mean Acute Value (SMAV) of 97.15 µg/L total aluminum, and the most tolerant species was a copepod (*Nitokra spinipes*) with a SMAV of 10,000 µg/L. No acceptable acute tests on estuarine/marine fish species were available. There are no estuarine/marine chronic toxicity data for fish or other genera that meet the test acceptability and quality assurance and quality control (QA/QC) principles as outlined in the 1985 Guidelines. Thus acute and chronic aluminum toxicity data for estuarine and marine species remain a data gap.

1 INTRODUCTION AND BACKGROUND

The United States Environmental Protection Agency (EPA) establishes national recommended Ambient Water Quality Criteria (AWQC) as authorized under section 304(a)(1) of the Clean Water Act (CWA). Section 304(a)(1) aquatic life criteria serve as recommendations to states and authorized tribes by defining ambient water concentrations that will protect against unacceptable adverse ecological effects to aquatic life resulting from exposure to pollutants found in water, consistent with the 1985 Guidelines. Section 304(a) recommended aquatic life criteria are developed to provide for the protection and propagation of fish and shellfish. Once the EPA publishes final section 304(a) recommended water quality criteria, states and authorized tribes may adopt these criteria into their water quality standards to protect designated uses of water bodies. States and authorized tribes may adopt water quality criteria that reflect adjustments to the EPA's recommended section 304(a) criteria to reflect local environmental conditions and human exposure patterns. Alternatively, states and authorized tribes may derive numeric criteria based on other scientifically defensible methods that protect the designated use. After adoption, states and authorized tribes submit new and revised water quality standards (WQS) to the EPA for review and approval or disapproval under CWA section 303(c). When approved by the EPA, the state or authorized tribe's WQS become the applicable WQS for CWA purposes. Such purposes include identification of impaired waters and establishment of Total Maximum Daily Loads (TMDLs) under CWA section 303(d) and derivation of water quality-based effluent limitations in permits issued under the CWA Section 402 National Pollutant Discharge Elimination System (NPDES) permit program.

As required by the CWA, the EPA periodically reviews and revises section 304(a) AWQC to ensure the criteria accurately reflect the latest scientific knowledge. The EPA previously published AWQC recommendations for aluminum in 1988 (EPA-440/5-86-008[2]), and is updating these criteria through its authority under CWA section 304(a). Water quality criteria are developed following the guidance outlined in the EPA's "*Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses*" (Stephan et al. 1985) (herein referred to as the "1985 Guidelines"). This document describes

---

[2] https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table

scientifically defensible water quality criteria values for aluminum pursuant to CWA section 304(a), derived utilizing best available data in a manner consistent with the 1985 Guidelines.

2 PROBLEM FORMULATION

Problem formulation provides a strategic framework to develop water quality criteria by providing an overview of a chemical's sources and occurrence, fate and transport in the environment, and toxicological characteristics and factors affecting toxicity. A problem formulation uses this information to develop a conceptual model and identify the most relevant chemical properties and endpoints for evaluation. The structure of this effects assessment for aluminum is consistent with the EPA's *Guidelines for Ecological Risk Assessment* (U.S. EPA 1998a). This ecological effects assessment describes scientifically defensible water quality criteria values for aluminum under CWA section 304(a)(1).

2.1 Overview of Aluminum Sources and Occurrence

This section provides an overview of available reliable information from the peer-reviewed literature that characterizes sources and occurrence of aluminum in the environment. Aluminum is the third most abundant element and the most common metal in the Earth's crust, comprising about eight percent of the lithosphere (CRC 2000). It is typically found in complexation with oxygen (as oxides) and silica (as silicates), but rarely in the elemental state (Greenwood and Earnshaw 1997). Aluminum is found in most rocks, particularly igneous rocks, containing aluminosilicate minerals (Staley and Haupin 1992), and associated with clays and soil/sediments. Different water column forms include monomeric, polymeric, particulate (suspended) and colloidal forms of aluminum. Ions such as chloride, fluoride, nitrate, phosphate and sulfate form soluble complexes with aluminum, as do fulvic and humic acids (U.S. EPA 1988).

Aluminum enters the aquatic environment from both natural and anthropogenic sources, with natural sources typically dominating occurrence (Lantzy and MacKenzie 1979). This is due to the abundance of aluminum in rocks and minerals released by weathering (Lee and Von Lehmden 1973; Sorenson et al. 1974). Other natural aluminum sources include volcanic activity and acidic spring waters (USGS 1993; Varrica et al. 2000).

Anthropogenic releases are primarily associated with industrial processes and include air emissions, wastewater effluent and solid waste (ATSDR 2008). Anthropogenic sources include fossil fuel combustion, aluminum production (mining and smelting) and aluminum present in fertilizers used in agriculture (Lantzy and MacKenzie 1979; Lee and Von Lehmden 1973; Ondov et al. 1982; Que Hee et al. 1982). Alum (potassium aluminum sulfate), used as a coagulant to clarify drinking water and wastewater, can also be a source of aluminum if this water is discharged to aquatic systems (Gidde et al. 2012).

A common source of aluminum in freshwater systems is from the mobilization of aluminum from rocks and soils by acid precipitation, heavy rains, or snow melt (Bjerknes et al. 2003). For estuaries and oceans, the primary source of aluminum is from riverine discharges, with the majority of the introduced aluminum sorbed to the surface of clay particles in estuarine sediments (Hydes and Liss 1977). However, aluminum that is either bound to clays or complexed to dissolved organic carbon can be converted to the reactive species upon mixing with high pH and high salinity ocean waters (Bjerknes et al. 2003; Rosseland et al. 1998; Teien et al. 2006a). The mechanism of this conversion is not well understood.

Aluminum is still actively mined in the U.S. from bauxite, the primary aluminum ore (mainly in Arkansas), with approximately 2 million metric tons produced in 2014. This raw domestic feedstock, plus imported bauxite and recycled aluminum, are currently processed at nine U.S. smelters into refined products (Bray 2015; USGS 2013). Because of aluminum's properties (light weight, resistance to corrosion, electrical conductivity, and durability), it has many diverse uses including: the transportation industry (automobiles, airplanes, trucks, railcars, marine vessels, etc.); packaging (cans, foil, etc.); construction (windows, doors, siding, etc.); consumer durables (appliances, cooking utensils, etc.); electrical transmission lines; and machinery (USGS 2013). Aluminum is also used in wastewater treatment to reduce effluent phosphorus levels (Tchobanoglous et al. 2003) and in the pharmaceutical industry in antacids and as a food additive (Government of Canada 1998).

The Water Quality Data Portal (https://www.waterqualitydata.us/) is an extensive database of environmental measurements available to identify concentrations of chemical contaminants, including aluminum, in surface waters such as rivers and streams. The results are reported in filtered and unfiltered categories. The terms filtered, dissolved, unfiltered, and total and their relationships, as defined by the U.S. Geological Survey (USGS), are presented below. "Dissolved" refers to constituents that exist in chemical solution in a water sample. "Filtered" pertains to constituents in a water sample passed through a filter membrane of specified pore diameter, most commonly 0.45 micrometer or less for inorganic analytes. Therefore, for interpretation, the filtered samples (prior to acidification) will be assumed to be dissolved aluminum. “Total” pertains to the constituents in an unfiltered, representative water-suspended-sediment sample. This term is used only when the analytical procedure includes an acid digestion procedure that ensures measurement of at least 95 percent of the constituent present in both the dissolved and suspended phases of the sample. Therefore, for interpretation, the unfiltered samples are assumed to be total recoverable aluminum.

Aluminum data for freshwater systems were obtained from the Water Quality Data Portal (accessed 2/16/17) for data representing years 1991 to 2017. A total of 7,483 surface water samples were collected (4,991 filtered samples and 2,492 unfiltered samples) in that timeframe and analyzed for dissolved and total aluminum, respectively. The range of concentrations reported for dissolved aluminum was 0.8 µg/L to a maximum concentration reported of 20,600 µg/L. The range of total aluminum concentrations across all sites was a minimum of 0.9 µg/L, with a maximum reported total concentration of 210,000 µg/L. Groundwater concentrations of dissolved aluminum (filtered using a 0.45 micrometer filter) from the USGS National Water Quality Assessment Program (NAWQA) database collected during 1992-2003 are presented in **Figure 1**, and had a 90th percentile concentration of dissolved aluminum concentrations of 11 µg/L.

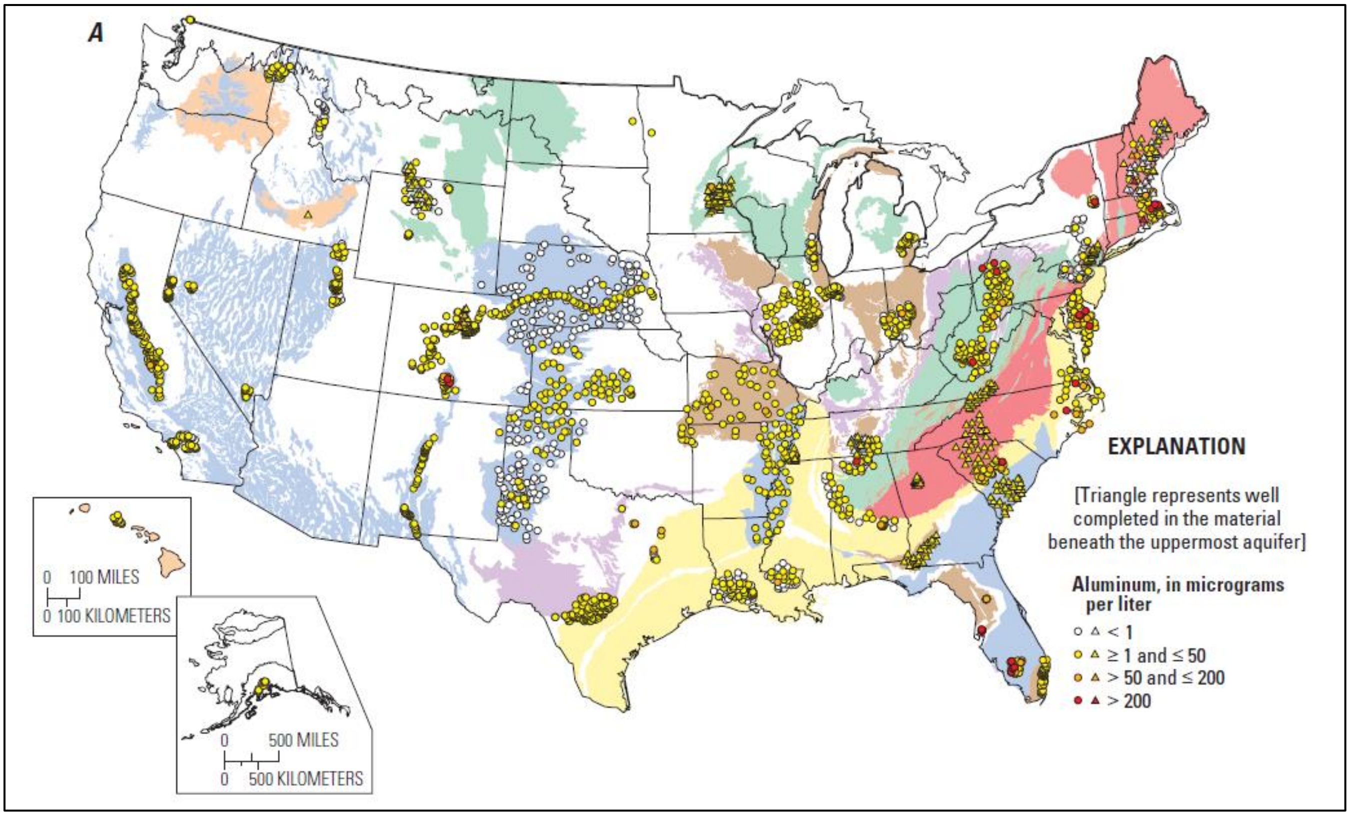

Figure 1. Geographic Distribution of Dissolved Aluminum Concentrations in Groundwater Collected from Wells as Part of the National Water-Quality Assessment Program, 1992–2003.
(Ayotte et al. 2011, used with permission.)

Aluminum concentrations in marine and estuarine waters are generally lower than levels found in freshwater systems, especially compared to acid-impacted areas (Gensemer and Playle 1999). Data for dissolved aluminum in coastal and marine waters were compiled from the scientific literature by Angel et al. (2016) and indicate that concentrations range from 0.5 to 2 µg/L in coastal waters, and from 0.008 to 0.68 µg/L in the open ocean. Other researchers have also reported that values are generally ≤1 µg/L in ocean waters (Brown et al. 2010; Hydes and Liss 1977; Tria et al. 2007). At the typical ocean pH of 8.0-8.3, aluminum forms complexes with hydroxide ion, primarily as $Al(OH)_4$, which precipitates out of solution. This largely explains the low concentrations in marine waters.

Much of the early to mid-1970s metals data in samples from natural waters are considered erroneously high due to contamination from sampling methods or containers. These flaws were corrected with the implementation of clean sampling techniques and guidance provided by U.S. EPA's Method 1669: Sampling Ambient Water for Trace Metals at EPA Water

Quality Criteria Levels (U.S. EPA. 2004). This method was designed to support water quality monitoring programs authorized under the Clean Water Act, specifically created for measuring toxic metals at the low part-per-trillion to low part-per-billion range (U.S. EPA 1996).

Average concentrations of total aluminum in the atmosphere were observed to range from 0.005 to 0.18 μg/m^3 (Hoffman et al. 1969; Potzl 1970; Sorenson et al. 1974). These concentrations are dependent on the location, weather conditions and industrial activity in the area with most of the airborne aluminum present in the form of small suspended particles of soil (dust) (ATSDR 2008). It should be noted that aluminum concentrations in air samples are often dependent upon the aluminum levels of the entrained soil particles, especially if measured as total aluminum. Goncharuk et al. (2012) sampled sea aerosols from the lower portion of the troposphere in the Black Sea (2002-2008), the Caspian Sea (2002-2006), the Baltic Sea (2001-2008), the White, Barents and Kara Seas (2005-2007) and high-altitude arctic regions in the Arctic and South Atlantic Oceans. Air samples were collected by aerosol filters for 3 to 5 hours during headwind conditions in the direction of atmospheric phenomenon. Most reported atmospheric total aluminum concentrations were less than 1 μg/m^3. The authors noted that the lowest concentrations were found at the high-altitude northern arctic regions, with increasing levels observed for the Western Arctic seas, and the highest concentrations reported for the most southerly located Black and Caspian Seas. They suggested that this northern to southern increasing concentration trend could be due to differential anthropogenic loading to the respective water bodies, and also with the increasing emissions of domestic and industrial wastes, wastewater, and emergency discharges of toxicants. Urban and industrial areas can have higher atmospheric total aluminum concentrations with levels reported from 0.4 to 8.0 μg/m^3 (Cooper et al. 1979; Dzubay 1980; Kowalczyk et al. 1982; Lewis and Macias 1980; Moyers et al. 1977; Ondov et al. 1982; Pillay and Thomas 1971; Sorenson et al. 1974; Stevens et al. 1978).

Total aluminum concentrations in North Atlantic precipitation collected in 1988 ranged from 6.1 to 827 μg/L (Lim and Jickells 1990). This is similar to a recent study that collected rainfall from two Mexico locations: a rural forested region 80 km south and downwind of Mexico City and Mexico City itself (Garcia et al. 2009). Average total aluminum precipitation concentrations reported in the rural area (107.2 μg/L, range of 28.8-222.7 μg/L) were higher than observed in the urban area (83.9 μg/L, range 35.8-125.4 μg/L). Samples of wet deposition collected in semi-rural Dexter, Michigan, had an average total aluminum concentration of 57 µg/L (Landis and Keeler 1997). Much lower levels of total aluminum were found in rainfall samples collected in Japan during 2000 and 2002 where average concentrations ranged from 2.71 to 6.06 µg/L (Takeda et al. 2000; Vuai and Tokuyama 2011). Atmospheric precipitation (i.e., rain and snow) samples collected in the U.S. have contained up to 1,200 µg/L total aluminum (Dantzman and Breland 1970; DOI 1971; Fisher et al. 1968; USGS 1964). No available information was found reporting concentrations of aluminum in fog.

Due to the abundance of aluminum in the earth's crust, soil concentrations can range widely from approximately 700 mg/kg to over 100,000 mg/kg (Shacklette and Boerngen 1984; Sorenson et al. 1974), averaging 71,000 mg/kg (Frink 1996). These concentrations are generally dependent on local geology and associated vegetation types and can vary within the same area, often strongly correlated with its clay content (Ma et al. 1997). Total aluminum concentrations in 1,903 soil samples collected from the continental U.S., Hawaii, Virgin Islands, Guam and Puerto Rico ranged from 500 to 142,000 mg/kg (Burt et al. 2003). In streambed sediment samples collected from locations in the conterminous U.S. from 1992 to 1996, aluminum concentrations ranged from 1.4 to 14% (by weight) (Rice 1999). Marsh/estuarine sediment samples collected from nine sampling sites within or along Georgia's Cockspur Island and McQueen's Island at Fort Pulaski's National Monument, a salt marsh ecosystem, had aluminum concentrations ranging from 17 to 820 mg/kg dry weight (Kumar et al. 2008).

Aluminum may form a precipitate when aluminum-rich water meets less acidic water. This precipitate mix, referred to as a floc, may include other co-precipitated ions, as well as nutrients, suspended materials and microorganisms. Removal of phosphorus from water has been observed in laboratory studies (Auvraya et al. 2006; Gilmore 2009; Matheson 1975; Minzoni 1984; Peterson et al. 1974; Westholm 2006) and in lake field studies (Knapp and Soltero 1983; Pilgrim and Brezonik 2005; Reitzel et al. 2005). Turbidity due to clay has been removed from pond waters using aluminum sulfate (Boyd 1979). Unz and Davis (1975) hypothesized that aluminum floc might coalesce bacteria and concentrate organic matter in effluents, thus assisting the biological sorption of nutrients. Aluminum sulfate (or alum) has been used to flocculate algae from water (McGarry 1970; Minzoni 1984; Zarini et al. 1983).

2.2 Environmental Fate and Transport of Aluminum in the Aquatic Environment

Aluminum (CAS Number 7429-90-05) is a silver white, malleable, and ductile metal that is odorless, and has a molecular weight of 26.98 g/mole (HSDB 2008). It has a density of 2.70

g/cm^3, a melting point of 660°C, a boiling point of 2,327°C, a vapor pressure of 1 mm Hg at 1,284°C, and is insoluble in water (CRC 2000; HSDB 2008). The n-octanol/water partitioning coefficient (K_{ow}), organic-carbon normalized partition coefficient (K_{oc}), and Henry's law constant for aluminum are unknown.

The chemistry of aluminum in surface water is complex because of the following properties: 1) it is amphoteric, meaning it is more soluble in acidic solutions and in basic solutions than in circumneutral solutions; 2) specific ions such as chloride, fluoride, nitrate, phosphate and sulfate form soluble complexes with aluminum; 3) it can form strong complexes with fulvic and humic acids; 4) hydroxide ions can connect aluminum ions to form soluble and insoluble polymers (e.g. gibbsite, corundum); and 5) under at least some conditions, solutions of aluminum in water approach chemical equilibrium rather slowly, with monomeric species of aluminum transforming into insoluble polymers which precipitate out of solution over time (Angel et al. 2016; Campbell et al. 1983; Hem 1968a,b; Hem and Roberson 1967; Hsu 1968; Roberson and Hem 1969; Smith and Hem 1972).

Aluminum exists as inorganic, monomeric species (Al^{3+}, $Al(OH)^{2+}$, $Al(OH)_2^+$, $Al(OH)_3$, and $Al(OH)_4^-$), as amorphous $Al(OH)_3$ leading to gibbsite formation and precipitation, and as polynuclear species such as the tridecameric Al_{13} polynuclear species (Gensemer and Playle 1999). The chemistry of aluminum in aquatic environments is complex, and several comprehensive reviews on its biological effects have been published (e.g., Driscoll and Schecher 1988; Gensemer and Playle 1999; Gostomski 1990; Havas 1986a,b; Havas and Jaworski 1986; Howells et al. 1990; Lewis 1989; Lydersen and Lofgren 2002; Rosseland et al. 1990; Scheuhammer 1991; Sigel and Sigel 1988; Sparling and Lowe 1996a; Sposito 1989, 1996; Wilson 2012; Yokel and Golub 1997). Effects on the aquatic community and considerations for criteria development are addressed below.

Aluminum from both natural and anthropogenic sources is transported by several means. Natural aluminum transport mechanisms include rock and mineral weathering, volcanic activity and acidic spring waters (USGS 1993; Varrica et al. 2000). Anthropogenic releases include air emissions, effluent dischargers and solid waste leaching. Aluminum is transported through the atmosphere as windblown particulate matter and is deposited onto land and water by wet and dry deposition. Atmospheric loading rates of aluminum to Lake Michigan have been estimated at 5 million kg/year (Eisenreich 1980), and at 0.1 g/m^2-year on Massachusetts Bay (Golomb et al. 1997).

Factors such as pH, temperature, and presence of complexing ions influence the fate and transport of aluminum in the environment. Of primary importance to understanding aluminum fate and behavior are its interactions with pH (see **Figure 2**). At neutral pH, aluminum is nearly insoluble, but its solubility increases exponentially as the pH reaches either acidic ($pH<6$) or basic ($pH>8$) conditions (Gensemer and Playle 1999). At pH values between 6.5 and 9.0 in fresh water, aluminum occurs predominantly in solution as monomeric, dimeric, and polymeric hydroxides and as complexes with fulvic and humic acids, chloride, phosphate, sulfate, and less common anions. The K_{sp} (solubility product) of aluminum hydroxide (gibbsite) ranges from 1.06×10^{-33} (Gayer et al. 1958) to 3.7×10^{-15} at 25°C (CRC 2000). Thus, aluminum hydroxide is insoluble compared to the more soluble salts used to determine aluminum toxic effect levels to aquatic species (aluminum chloride $K_{sp} = 2.04 \times 10^4$, aluminum nitrate $K_{sp} = 2.16 \times 10^3$, and aluminum sulfate $K_{sp} = 6.92 \times 10^1$) (CRC 2000).

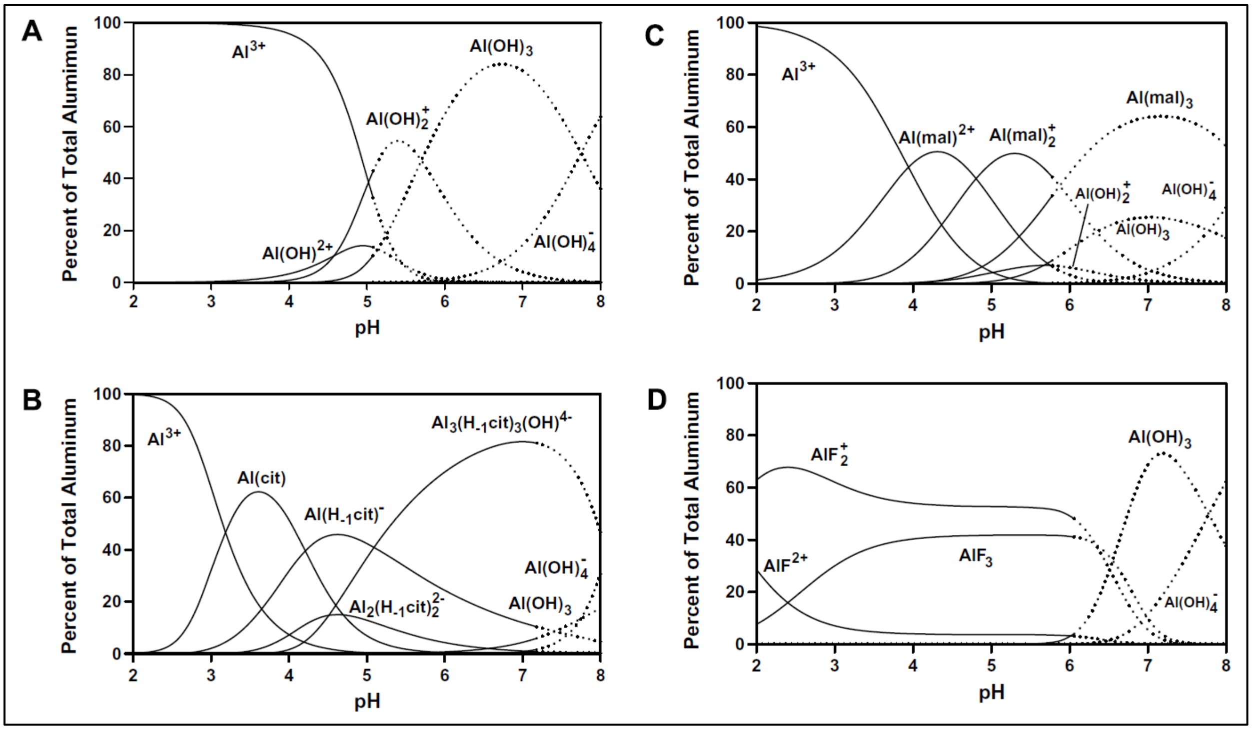

Figure 2. Results of Al Speciation Calculations at a Total of 65 µM Al in the Absence of Ligands (panel A) and in the Presence of Citrate (65 µM) (panel B), Maltolate (195 µM) (panel C), and Fluoride (260 µM) (panel D) in the pH Range 2 to 8.
The dotted lines indicate solutions that would be supersaturated with respect to freshly prepared $Al(OH)_3$. (Zhou et al. 2008, Figure 1, used with permission.)

Aluminum solubility increases at lower temperatures and in the presence of complexing ligands (both inorganic and organic) (ATSDR 2008; Lydersen, 1990; Wilson 2012). These two characteristics are significant because episodic acidic pulses in streams, for example during winter snowmelt, maximize the solubility of aluminum if pH drops to 5.5 or lower (Schofield 1977; Wilson 2012), and therefore may mobilize aluminum.

In the early 1980s the impacts of acid rain and aluminum toxicity were observed in aquatic and terrestrial environments in specific regions of the U.S., most notably in the northeastern part of the country where aquatic systems had limited buffering capacity to prevent pH changes. Researchers observed that aluminum can be a major factor responsible for the demise of biotic communities since the toxicant becomes more soluble and potentially more toxic to aquatic biota at acidic pH (Gensemer and Playle 1999).

2.3 Mode of Action and Toxicity

Aluminum has no biologically important functions or beneficial properties to aquatic life, and is therefore considered a non-essential metal (Eichenberger 1986; Exley 2003; Tchounwou et al. 2012; Williams 1999; Wood 1984, 1985). It has been identified as the cause of harmful effects on fish and wildlife, but is not a known teratogen, carcinogen or mutagen (Leonard and Gerber 1988). The specific mechanisms of aluminum toxicity to aquatic organisms have been investigated extensively for fish and to a lesser extent for aquatic invertebrates.

For invertebrates, it is postulated that aluminum disrupts concentrations of specific ions, primarily resulting in a loss of sodium (Hornstrom et al. 1984). Elevated levels of aluminum affect ion regulation and the respiratory efficiency of sensitive species (Sparling and Lowe 1996a). Havas (1985) found that aluminum interfered with salt regulation in *Daphnia magna*, which caused a reduction in whole body sodium and chloride concentrations, resulting in death. In addition, aluminum has been shown to increase respiration, and thereby energy demands among mayfly species (Herrmann and Andersson 1986).

For fish, the gill is the primary site of aluminum toxic action, resulting in ionoregulatory, osmoregulatory and respiratory dysfunction. The gill is the primary site of aluminum toxicity under either acidic or alkaline conditions (Wilson 2012). Under acidic conditions, aluminum disrupts the barrier properties of the gill epithelium by binding with functional groups at both the apical gill surface and intracellularly within the lamellar epithelial cells (Exley et al. 1991). At reduced pH (<6.5), aluminum will accumulate on the gill surface resulting in physical damage to the epithelial cells that subsequently causes a loss of plasma ions (Na^+, Cl^-), reduced ion uptake and gas exchange. At alkaline pH (>8), the negatively charged aluminate anion dominates which also disrupts gill function, but to a lesser degree due to the lack of binding of the aluminate anion to the negatively charged gill surface. The subsequent necrosis of the epithelial cells causes a loss of plasma ions (Na^+, Cl^-), reduced osmolality and gas exchange, and if severe enough, the death of the fish (Dietrich 1988; Dietrich and Schlatter 1989a,b; Leivestad et al. 1980; Mallatt 1985; Muniz and Leivestad 1980a,b; Rosseland and Skogheim 1984, 1987). Mitigation of these toxic effects was observed with moderate concentrations of calcium (Brown 1981b), high concentrations of humic acids (Baker and Schofield 1982; Driscoll et al. 1980), and high concentrations of silica (Birchall et al. 1989). Fish in low pH waters with high aluminum concentrations will accumulate aluminum on the gill surface (Rosseland et al. 1990). Bjerknes et al. (2003) observed elevated aluminum concentrations in the gills of dead and “sluggish” Atlantic salmon (*Salmo salar*) associated with ruptured atria, which the authors suggested may have resulted from hypercapnia (abnormally elevated carbon dioxide levels in the blood) caused by circulatory distress from the clogging of gills with aluminum. The specific mechanisms of aluminum toxicity at alkaline pH are not well understood.

In laboratory toxicity tests, organisms are exposed to a mixture of dissolved and particulate aluminum depending on how long the acidic aluminum stock solution has been allowed to equilibrate prior to dosing the organisms (Angel et al. 2016). Over time (minutes) as the aluminum from the stock solution equilibrates with the test water and the pH increases, the monomeric species of aluminum transform to the newly-formed insoluble polymeric hydroxide species, which are more toxic (Cardwell et al. 2018). Thus, soon after test initiation, there is a transformation period of rapid speciation changes from short-lived transient amorphous and colloidal forms of aluminum (from minutes to a few hours) to more stable crystalline forms that can take days to form (Gensemer et al. 2018). Aged stock solutions (aluminum solutions that have been given sufficient time (i.e., hours to days) to form more stable forms of aluminum) have been shown to be less toxic than those that are not aged (Exley et al. 1996; Witters et al. 1996). Unfortunately, many studies included for criteria derivation did not describe stock solution age prior to test initiation, and this variable therefore cannot be factored into the toxicity assessment.

Several investigators have found different trends in the toxicity of aluminum under different pH conditions, and toxicity of aluminum appears to be lowest at neutral pH (approximately 7), with toxicity tending to increase with either increasing or decreasing pH (above and below neutral pH). Freeman and Everhart (1971) found that the lethal time to 50% of the rainbow trout decreased (i.e., was more toxic) as the pH increased from 6.8 to 8.99 when rainbow trout were exposed in flow-through tests to the same nominal (unmeasured) aluminum concentration. They concluded that soluble aluminum was the toxic form. Hunter et al. (1980) observed the same relationship of increasing toxicity with rainbow trout over a pH range of 7.0 to 9.0 in chronic static renewal toxicity studies (also nominal aluminum exposures). Call (1984) conducted measured static acute toxicity studies with fathead minnows at pH of 7.61 and 8.05 and showed a slight increase in toxicity at increased pH. However, in another measured static acute toxicity study with a different species, rainbow trout, Call (1984) found a decrease in toxicity as pH increased for the studies conducted at pH 7.31 and 8.17. Thus, generally, most studies show that aluminum toxicity increases as pH increases in the range of approximately 7.0 to 9.0.

Regarding toxicity at low pH, Freeman and Everhart (1971) also observed the greater toxicity at acidic pH 6.52 in static renewal tests with rainbow trout. In a measured static acute toxicity study with rainbow trout by Call (1984), tests were conducted with pH measurements of 6.59, 7.31 and 8.17. The greatest toxicity was observed at the acidic pH of 6.59. The tests conducted by Freeman and Everhart (1971) and Hunter et al. (1980) were static renewal or flow-through and showed the lowest acute values. The flow-through and renewal tests are considered to be a more reliable way to conduct toxicity tests for aluminum because the dosed chemical is more likely to remain in solution at the desired concentration, and less likely to drop below nominal levels due to precipitation and/or adherence to test vessel surfaces. In addition, because the polymerization of aluminum hydroxide is a relatively slow process, the chemical form of aluminum might have differed from test to test due to the amount of time the aluminum was in stock and test solutions.

The influence of pH on aluminum speciation and associated toxicity to aquatic organisms is readily apparent and highlights the importance of pH control during toxicity tests. Depending on the pH at test initiation, the greatest potential for pH drift would be static exposures, followed by static-renewal and finally flow-through studies. All of the studies evaluated for criteria derivation reported pH, and most included the standard deviation of the measurements, thus providing a rough estimate of pH drift during the exposure. Only selected studies, however, described pH drift for individual tests (e.g., ENSR 1992c,d; European Aluminum Association 2009).

Driscoll et al. (1980) tested postlarvae of brook trout and white suckers under slightly acidic conditions and concluded that only inorganic forms of aluminum were toxic to fish. Hunter et al. (1980) reported that the toxicity of test solutions was directly related to the concentration of dissolved aluminum that passed through a 0.45 μm membrane filter.

In dilute aluminum solutions, formation of particles and the large insoluble polynuclear complexes known as floc is primarily a function of the concentration of organic acids and the hydroxide ion. Time for particle formation varies from less than one minute to several days depending upon the source of aluminum (i.e., aluminum chloride, aluminum nitrate), the pH and the presence of electrolytes and organic acids (Snodgrass et al. 1984). When particles form an aggregate large enough to become visible, the floc is white in color, and tends to settle. Mats of aluminum floc have been reported blanketing a stream bed (Hunter et al. 1980). Laboratory studies conducted at alkaline pH levels have reported floc in the exposure chambers (Brooke 1985; Call 1984; Lamb and Bailey 1981; Zarini et al. 1983). The floc did not appear to affect most aquatic species. However, the swimming ability of *Daphnia magna* was impeded by "fibers" of flocculated aluminum trailing from the carapaces. Additionally, the mobility and feeding of midges also was affected, ultimately resulting in death (Lamb and Bailey 1981). Bottom-dwelling organisms may be impacted more by aluminum floc in the field than in the laboratory due to the greater floc layer thickness observed in the field relative to laboratory exposures (U.S. EPA 1988), but this will also depend on the water velocity and mixing in both the field and the laboratory.

Aquatic plant toxicity to aluminum can be dependent on the speciation of aluminum which is controlled by pH. In a study of cell growth rate of the green alga, *Chlorella pyrenoidosa*, to aluminum, Helliwell et al. (1983) found that decreased cell growth occurred in the pH range of 5.8 to 6.2. This is near the pH of minimum solubility of aluminum and maximum concentration of $Al(OH)_2^+$. They found that the toxicity of aluminum decreased as pH increased from 6.2 to 7 or as pH decreased from 5.8 to 4.7, and they hypothesized that the monovalent hydroxide is the most toxic form. Seip et al. (1984) stated that "the simple hydroxides ($Al(OH)^{+2}$ and $Al(OH)_2^+$) are regarded as the most dangerous forms, while organically bound aluminum and polymeric forms are less toxic or essentially harmless." However, one study found algae productivity and biomass were seldom affected if the pH is above 3.0 (Sparling and Lowe 1996a). Aluminum and acid toxicity tend to be additive to some algae when the pH is less than 4.5. Because aluminum binds with inorganic phosphorus, it may reduce the availability of this nutrient thereby reducing productivity (Sparling and Lowe 1996a). As shown in **Appendix E** and **Appendix H**, the effects of aluminum on algae productivity and biomass are dependent on the pH, total hardness and DOC of the exposure solutions.

2.3.1 Water Quality Parameters Affecting Toxicity

Bioavailability of aluminum is affected by water chemistry parameters such as pH, total hardness and DOC, and to a lesser extent fluoride. The pH of waters affects aluminum speciation and solubility. Aluminum can sorb to dissolved organic carbon (DOC), such as humic and fulvic acids, and form organic aluminum complexes. An increase in DOC in waters reduces the bioavailability of aluminum to aquatic organisms as a result of this binding (Wilson 2012). Hardness also has an effect on the toxicity of aluminum, as the cation Al^{+3} competes with other cations present in water such as calcium (Ca^{+2}) for uptake (Gensemer and Playle 1999). The observed effect of total hardness may be due to one or more of a number of usually interrelated ions, such as hydroxide, carbonate, calcium, and magnesium. Acute tests were conducted at four different levels of water total hardness with *Ceriodaphnia dubia* (ENSR 1992d), demonstrating that daphnids were more than 138 times more sensitive to aluminum in soft water than in hard water (**Appendix A** *Acceptable Acute Toxicity Data of Aluminum to Freshwater Aquatic Animals*). Data in **Appendix A** also indicate that aluminum was more toxic to *Daphnia magna*, brook trout, and fathead minnows in soft water than in hard water. In contrast, no apparent total hardness-toxicity relationship was observed for rainbow trout exposed to three different total hardness levels at a controlled pH of 8.3 (Gundersen et al. 1994). This is consistent with data recently published by DeForest et al. (2018a) and Gensemer et al. (2018) demonstrating that there is a reduced effect of total hardness at elevated pH levels.

Development of the Biotic Ligand Model (BLM - formerly the “gill model”) and multi-parameter linear regression models in recent years were intended to better account for the water chemistry parameters that most strongly affect the bioavailability, and hence toxicity, of metals to aquatic life. The BLM, a mechanistic model that uses a series of submodels to quantify the capacity of metals to accumulate or bind to active sites on the gills of aquatic organisms, estimates the bioavailable portion of dissolved metals in the water column based on site-specific water quality parameters such as pH, hardness, and DOC (McGeer et al. 2000; Meyer et al. 1999; Pagenkopf 1983; Paquin et al. 1999; U.S. EPA 1999a, 2000). Multiple linear regression (MLR) models are statistical in nature and can also take into account pH, total hardness and DOC. While MLR models are less complex than BLM models, they also estimate the bioavailability of aluminum to aquatic species. The EPA evaluated the use of empirical, non-mechanistic MLR models for aluminum (DeForest et al. 2018a) as a bioavailability-based approach for deriving water quality criteria as well as a BLM model for aluminum (Santore et al. 2018). Note that the aluminum BLM developed by Santore et al. (2018) differs from earlier BLMs for other metals, because the aluminum BLM accounts for the dissolved and precipitated fraction of aluminum. Previous BLMs for other metals only account for the dissolved fraction of the metal.

The EPA decided to use an empirical MLR approach in this aluminum criteria update rather than a BLM model due to: 1) the relative simplicity and transparency of the model, 2) the relative similarity to the available BLM model outputs, and 3) the decreased number of input data on water chemistry needed to derive criteria at different sites. An external peer review of an approach using a pH and total hardness equation-based criteria, an MLR approach, and a BLM approach for aluminum criteria development was conducted in 2015 and peer-reviewers' comments were considered in the selection of the MLR-based criteria approach. The EPA independently examined and verified the quality and fit of the DeForest et al. (2018a,b) MLR models before applying them in this criteria document.

2.4 Conceptual Model

Conceptual models consist of a written description and diagram (U.S. EPA 1998a) that illustrate the relationships between human activities, stressors, and ecological effects on assessment endpoints. The conceptual model links exposure characteristics with the ecological endpoints important for management goals.

2.4.1 Conceptual Diagram

Aluminum can originate from both natural and anthropogenic sources (Lantzy and MacKenzie 1979). The environmental fate properties of aluminum indicate that weathering/erosion, volcanic activity, runoff/leaching, groundwater recharge, spray drift from aluminum-containing pesticides, and atmospheric deposition represent potential transport mechanisms of aluminum to surface water habitats for aquatic organisms (ATSDR 2008). These transport mechanisms are depicted in the conceptual model below for natural (i.e., weathering and erosion, volcanic activity) and anthropogenic sources of aluminum to the environment (i.e., wastewater treatment, resource extraction, smelting/manufacturing operations, agricultural uses and fossil fuel combustion) (**Figure 3**). The model also depicts exposure pathways for biological receptors of concern (e.g., aquatic animals) and the potential attribute changes (i.e., effects such as reduced survival, growth and reproduction) in the receptors due to aluminum exposure. A solid line indicates a major pathway and a dashed line indicates a minor pathway. Aquatic assessments address exposure primarily through anthropogenic releases, runoff and atmospheric deposition.

The conceptual model provides a broad overview of how aquatic organisms can potentially be exposed to aluminum. Derivation of criteria focuses on effects on survival, growth and reproduction of aquatic organisms. However, the pathways, receptors, and attribute changes depicted in **Figure 3** may be helpful for states and authorized tribes as they adopt criteria into standards and need to evaluate potential exposure pathways affecting designated uses.

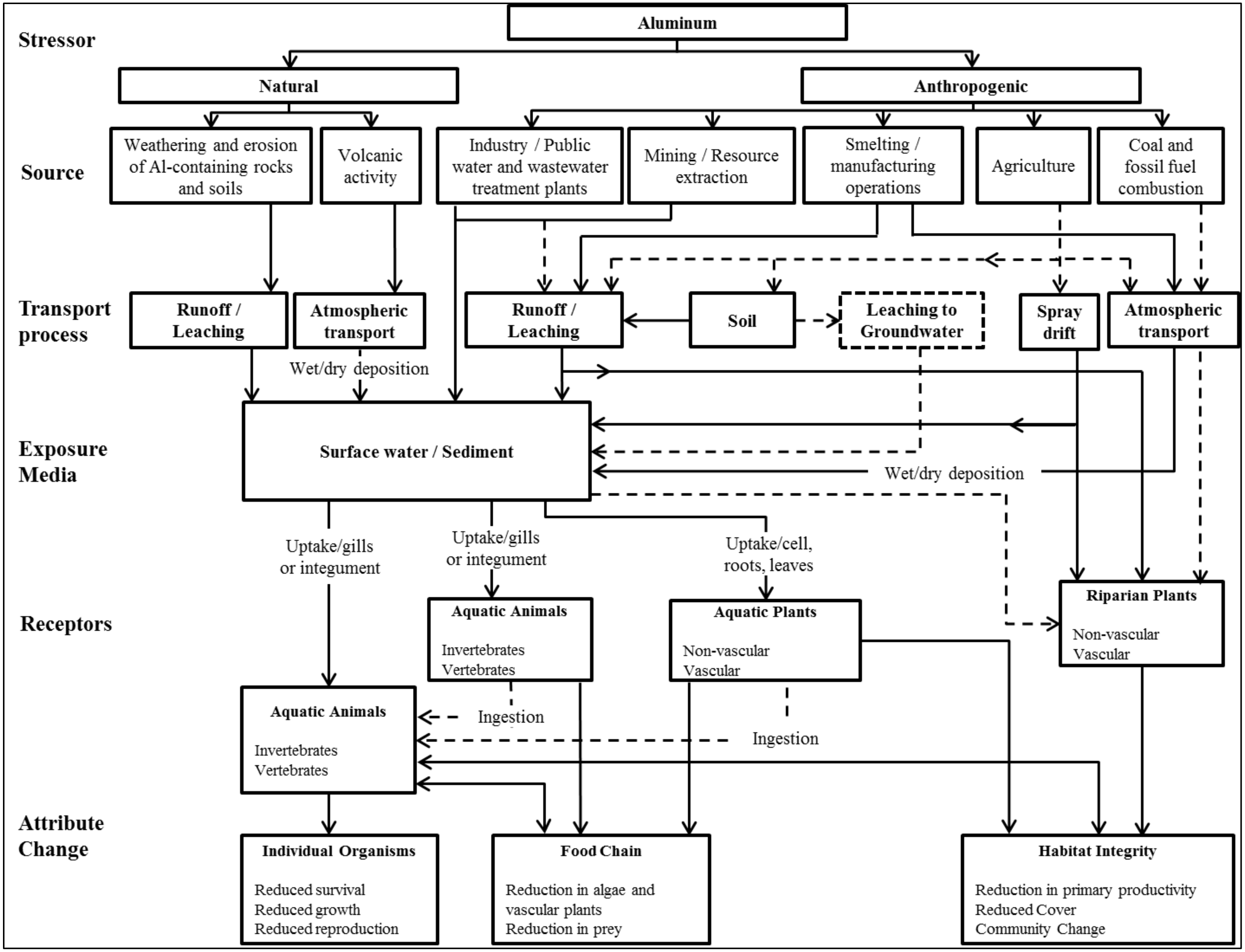

Figure 3. Conceptual Model for Aluminum Effects on Aquatic Organisms.
(Dotted lines indicate exposure pathways that have a lower likelihood of contributing to ecological effects).

2.5 Assessment Endpoints

Assessment endpoints are defined as the explicit expressions of the environmental values to be protected and are comprised of both the ecological entity (e.g., a species, community, or other entity) and the attributes or characteristics of the entity to be protected (U.S. EPA 1998a). Assessment endpoints may be identified at any level of organization (e.g., individual, population, community). In the context of the CWA, aquatic life criteria for toxic substances are typically determined based on the results of toxicity tests with aquatic organisms, for which adverse effects on growth, reproduction, or survival are measured. This information is aggregated into a genus sensitivity analysis that characterizes an impact to the aquatic community. Criteria are designed to be protective of the vast majority of aquatic animal taxa in an aquatic community (i.e., approximately the 95th percentile of genera based on tested aquatic animals representing the aquatic community per the 1985 Guidelines recommendations (Stephan et al 1985). Assessment endpoints consistent with the criteria developed in this document are summarized in **Table 1**.

The concept of using laboratory toxicity tests to protect North American bodies of water and resident aquatic species is based on the theory that effects occurring to a species in controlled laboratory tests will generally occur to the same species in comparable field situations. Since aquatic ecosystems are complex and diversified, the 1985 Guidelines require acceptable data be available for at least eight genera with a specified taxonomic diversity (the standard eight-family minimum data requirement, or MDR). The intent of the eight-family MDR is to serve as a typical surrogate sample community representative of the larger and generally much more diverse natural aquatic community, not necessarily the most sensitive species in a given environment. For many aquatic life criteria, enough data are available to describe a sensitivity distribution to represent the distribution of sensitivities in natural ecosystems. In addition, since aquatic ecosystems can tolerate some stress and occasional adverse effects, protection of all species at all times and places is not deemed necessary. The intent is to protect approximately 95 percent of a group of diverse taxa, with special consideration given to any commercially and recreationally important species (Stephan et al 1985). Thus, if properly derived and used, the combination of a freshwater or estuarine/marine acute and chronic aquatic life criteria should provide an appropriate degree of protection of aquatic organisms and their uses from acute and chronic toxicity to animals, toxicity to plants, and bioaccumulation by aquatic organisms (Stephan et al. 1985).

Table 1. Summary of Assessment Endpoints and Measures of Effect Used in Criteria Derivation.

Assessment Endpoints for the Aquatic Community	Measures of Effect
Survival, growth, and reproduction of freshwater fish, other freshwater vertebrates, and invertebrates	For acute effects: LC_{50}, EC_{50} For chronic effects: EC_{20}, MATC (only used when an EC_{20} could not be calculated for the genus), EC_{10} (for bioaccumulative compounds)
Survival, growth, and reproduction of estuarine/marine fish and invertebrates	For acute effects: LC_{50}, EC_{50} For chronic effects: EC_{20}, MATC (only used when an EC_{20} could not be calculated for the genus), EC_{10} (for bioaccumulative compounds)
Maintenance and growth of aquatic plants from standing crop or biomass (freshwater and estuarine/marine)	LOEC, EC_{20}, EC_{50}, IC_{50}, reduced growth rate, cell viability, calculated MATC

MATC = Maximum acceptable toxicant concentration (geometric mean of NOEC and LOEC)
NOEC = No observed effect concentration
LOEC = Lowest observed effect concentration
LC_{50} = Lethal concentration to 50% of the test population
EC_{50}/EC_{20}/EC_{10} = Effect concentration to 50%/20%/10% of the test population
IC_{50} = Concentration of aluminum at which growth is inhibited 50% compared to control organism growth

2.6 Measurement Endpoints

Measurement endpoints (**Table 1**) are the measures of ecological effect used to characterize or quantify changes in the attributes of an assessment endpoint or changes in a surrogate entity or attribute, in this case a response to chemical exposure (U.S. EPA 1998a). Toxicity data are used as measures of direct and indirect effects on representative biological receptors. The selected measures of effects for the development of aquatic life criteria encompass changes in the growth, reproduction, and survival of aquatic organisms (Stephan et al. 1985).

The toxicity data used for the development of aquatic life criteria depend on the availability of applicable toxicity test outcomes, the acceptability of test methodologies, and an in-depth evaluation of the acceptability of each specific test, as performed by the EPA. Measurement endpoints for the development of aquatic life criteria are derived using acute and chronic toxicity studies for representative test species, which are then quantitatively and qualitatively analyzed, as described in the Analysis Plan below. Measurement endpoints considered for each assessment endpoint in this criteria document are summarized in **Table 1**. The following sections discuss toxicity data requirements for the fulfillment of these measurement endpoints.

2.6.1 Overview of Toxicity Data Requirements

The EPA has specific data requirements to assess the potential effects of a stressor on an aquatic ecosystem and develop CWA section 304(a) aquatic life criteria as described in the 1985 Guidelines (Stephan et al 1985). Acute toxicity test data (short term effects on survival) for species from a minimum of eight diverse taxonomic groups are required for the development of acute criteria to ensure the protection of various components of an aquatic ecosystem.

- Acute toxicity test data for species from a minimum of eight diverse taxonomic groups. The diversity of tested species is intended to ensure protection of various components of an aquatic ecosystem.
    - The acute freshwater requirement is fulfilled with the following eight minimum data requirements:
        - the family Salmonidae in the class Osteichthyes
        - a second family in the class Osteichthyes, preferably a commercially or recreationally important warmwater species (e.g., bluegill, channel catfish, etc.)
        - a third family in the phylum Chordata (may be in the class Osteichthyes or may be an amphibian, etc.)
        - a planktonic crustacean (e.g., cladoceran, copepod, etc.)
        - a benthic crustacean (e.g., ostracod, isopod, amphipod, crayfish, etc.)
        - an insect (e.g., mayfly, dragonfly, damselfly, stonefly, caddisfly, mosquito, midge, etc.)
        - a family in a phylum other than Arthropoda or Chordata (e.g., Rotifera, Annelida, Mollusca, etc.)
        - a family in any order of insect or any phylum not already represented
    - The acute estuarine/marine requirement is fulfilled with the following eight minimum data requirements:
        - two families in the phylum Chordata
        - a family in a phylum other than Arthropoda or Chordata
        - either the Mysidae or Penaeidae family
        - three other families not in the phylum Chordata (may include Mysidae or Penaeidae, whichever was not used above)
        - one from any other family
- Chronic toxicity test data (longer-term survival, growth, or reproduction) are required for a minimum of three taxa, with at least one chronic test being from an acutely-sensitive species.

- Acute-chronic ratios (ACRs) can be calculated with data from species of aquatic animals from at least three different families if the following data requirements are met:
    - at least one is a fish
    - at least one is an invertebrate
    - for freshwater chronic criterion: at least one is an acutely sensitive freshwater species (the other two may be estuarine/marine species) or for estuarine/marine chronic criterion: at least one is an acutely sensitive estuarine/marine species (the other two may be freshwater species).

The 1985 Guidelines also require at least one acceptable test with a freshwater alga or vascular plant. If plants are among the aquatic organisms most sensitive to the chemical, results of a plant in another phylum should also be available. Data on toxicity to aquatic plants are examined to determine whether plants are likely to be unacceptably affected by concentrations below those expected to cause unacceptable effects on aquatic animals. As discussed in **Section 3.4** and **Section 5.2**, based on available data the relative sensitivity of fresh and estuarine/marine algae and plants to aluminum (**Appendix E** *Acceptable Toxicity Data of Aluminum to Freshwater Aquatic Plants* and **Appendix F** *Acceptable Toxicity Data of Aluminum to Estuarine/Marine Aquatic Plants*) is less than vertebrates and invertebrates, so plant criteria were not developed. This trend was apparent for all conditions, as vertebrate and invertebrate generated criteria values were always less than alga EC_{20}s (DeForest et al. 2018a), except at unrealistically high pH and very high total hardness.

2.6.2 Measures of Effect

The assessment endpoints for aquatic life criteria are based on survival, growth and reproduction of the assessed taxa per the 1985 Guidelines (Stephan et al 1985). The measures of effect are provided by the acute and chronic toxicity data. These toxicity endpoints (expressed as genus mean values) are used in the sensitivity distribution of the aquatic community at the genus level to derive the aquatic life criteria. Endpoints used in this assessment are listed in **Table 1**. Studies that had unacceptable control survival were not used (i.e., studies where acute and chronic control mortality was >10% and >20%, respectively), regardless of test conditions.

Measure of Aluminum Exposure Concentration

Only data from toxicity tests conducted using chloride, nitrate and sulfate salts (either anhydrous or hydrated) are used in this effects assessment. This is consistent with the EPA's previous 1988 aluminum aquatic life AWQC document. This document addresses the toxicity of total aluminum to freshwater organisms in the pH range of 5.0 to 10.5. The 1988 AWQC addressed waters with a pH between 6.5 and 9.0 (U.S. EPA 1988) to be consistent with the recommended aquatic life pH criteria (U.S. EPA 1986). The pH range for freshwater was expanded, in part, because of the complex chemistry of aluminum in surface waters, the available toxicity data demonstrated an increased sensitivity of freshwater aquatic species in low pH (i.e., pH<6.5), and the expanded range represents a fuller range of pH conditions in natural waters. Tests conducted in pH water less than 5 were deemed too low to be used quantitatively due to a mixture effect from the combined stress of both low pH and aluminum on the test organisms, and the inability to discern a particular effect level to either low pH or elevated aluminum concentration.

Aluminum chemistry in surface waters is extremely complex, and so measurement uncertainty can be high if only one form of aluminum is taken into account. A thorough understanding of aluminum toxicity is complicated by the need to distinguish between aqueous and particulate aluminum, and between inorganic and organic forms of aluminum (Driscoll and Postek 1996; Gensemer and Playle 1999). Laboratory dilution waters do not contain suspended solids, clays or particulate matter where aluminum may be bound (unless specifically investigated). Therefore, a distinction needs to be made in how the EPA interprets the measurements of aluminum in water, so that extrapolating laboratory data to natural waters is better understood. There is also a complication as the available measurement methods (i.e., total, total recoverable, acid soluble, pH 4 extractable and dissolved) present different challenges when applied to natural and laboratory waters. In application to natural waters, total, total recoverable, and acid soluble methods may be confounded by measuring aluminum in aluminum silicate (i.e., clay).

Laboratory Exposures

The 1988 AWQC considered using dissolved aluminum concentrations to set aquatic life criteria, however not enough data were available to allow derivation of a criterion based on dissolved aluminum. The EPA also noted at the time that organisms would be exposed to both dissolved and undissolved aluminum from laboratory exposures. The lack of data prevented any definitive analysis.

Data are now available to compare toxicity of aluminum using total aluminum (unfiltered test samples that were acidified) and dissolved aluminum (operationally defined as filtered with typically a 0.45 µm filter before acidification). The total aluminum concentrations in laboratory test solutions will contain dissolved monomeric and precipitated forms (e.g., aluminum hydroxides) of aluminum. Dissolved concentrations will not contain these precipitated forms.

In tests with brook trout at low pH and total hardness, toxic effects increased with increasing concentrations of total aluminum even though the corresponding concentration of dissolved aluminum was relatively constant (Cleveland et al. 1989). This phenomenon was also observed in several chronic studies with widely varying test concentrations and conditions (renewal and flow-through exposures) at pH 6 conducted by the Oregon State University (e.g., 2012a,e), where toxic effects increased with increasing total aluminum concentrations, while measured concentrations of dissolved and monomeric aluminum changed very little with increasing total aluminum concentrations.

In filtration studies at pH 8 with the fathead minnow, both acute and chronic toxicity tests indicated no toxicity when the test water was 0.2 µm filtered prior to exposure (Gensemer et al. 2018). Toxicity was only observed when the test solutions were unfiltered. Furthermore, dose-response relationships were only observed using total aluminum; relationships were not observed using measurements of dissolved or monomeric forms (Gensemer et al. 2018). This same effect was observed in 7-day exposures at pH 7 and 8 with the daphnid (*Ceriodaphnia dubia*) where filtered test solutions were less toxic than unfiltered solutions (Gensemer et al. 2018).

Therefore, because measurements of dissolved aluminum do not reflect the full spectrum of forms of aluminum that results in toxicity, all laboratory exposure data used for criteria derivation will be based on measurements of total aluminum. Measurements with methods using lesser degrees of acidification (that is, acid soluble and pH 4 extractable) are generally not available. If aluminum criteria are based on dissolved concentrations, toxicity will be underestimated, because aluminum hydroxide precipitates that contribute to toxicity would not be measured (GEI Consultants, Inc. 2010; U.S. EPA 1988). All concentrations from toxicity tests are expressed as total aluminum in this document (unless otherwise specified).

Natural Waters

Researchers rely on operationally defined procedures to evaluate the concentration and forms of aluminum in natural waters, and the accuracy of these methods is difficult to evaluate, resulting in uncertainty regarding the actual amount of aluminum present in various forms (Driscoll and Postek 1996). Total aluminum concentrations in natural waters are determined using a wide variety of digestion procedures at varied extraction times, resulting in a range of operational methods and uncertainty in measured values (Driscoll and Postek 1996). Furthermore, particulate material comprises a continual size distribution making measurement of dissolved concentrations dependent on the filter-pore size used (Driscoll and Postek 1996).

A major complication for extrapolating total aluminum concentrations measured in laboratory waters to natural waters is the test method used. The 1988 AWQC for aluminum were based on acid-soluble concentrations (operationally defined as the aluminum that passes through a 0.45 µm filter after the sample has been acidified with nitric acid to a pH between 1.5 and 2.0). In the early 1990s, the EPA converted most metals criteria (excluding aluminum) to the dissolved measurement. With the acid-soluble method seldom used and insufficiently different from total, (U.S. EPA 1999c) the EPA expressed the aluminum criterion as total recoverable aluminum, with a caution that a Water-Effect Ratio would often be needed. The EPA uses the terms “total” and “total recoverable” synonymously for effluent guidelines and permitting under NPDES programs (U.S. EPA 1988b). The current EPA Test Method for measuring total recoverable aluminum in ambient water and wastewater uses inductively coupled plasma-atomic emission spectrometry and inductively-coupled plasma-mass spectrometry (U.S. EPA 1994a,b). The methods recommend that the sample first be solubilized by gentle refluxing with nitric and hydrochloric acids (i.e., digestion to pH<2) when an aqueous sample contains undissolved material. After cooling, the sample is made up to volume, then mixed and either centrifuged or allowed to settle overnight prior to analysis. This process dissolves the monomeric and polymeric forms of aluminum, in addition to colloidal, particulate and clay-bound aluminum. Applying the aluminum criteria to total recoverable aluminum is considered conservative because it includes monomeric (both organic and inorganic) forms, polymeric and colloidal forms, as well as particulate forms and aluminum sorbed to clays (Wilson 2012). However, under natural conditions not all of these forms would be biologically available to aquatic species (e.g., clay-bound aluminum).

EPA Methods 200.7 and 200.8 are the only currently approved methods for measuring aluminum in natural waters and wastewater for NPDES permits (U.S. EPA 1994a,b). Research on new analytical methods is ongoing to address concerns with including aluminum bound to particulate matter (i.e., clay) in the total recoverable aluminum concentrations (OSU 2018c). One approach would not acidify the sample to pH less than 2 but rather to pH 4 (pH 4 extracted method) to better capture the bioavailable fraction of aluminum (CIMM 2016, OSU 2018c). In the pH 4 extraction method, sodium acetate buffer is added to the sample to reach the desired pH, followed by sample agitation for a specified period of time, and finally 0.45 µm sample filtration. The sample is then acidified with nitric acid before inductively coupled plasma-optical emission spectrometry analysis.

To further explore this issue, researchers conducted an aluminum analysis of 12 natural freshwater sources throughout the United States with various concentrations of total suspended solids using four different aluminum methods (i.e., total, acid-soluble, pH 4 extracted and dissolved) (OSU 2018c). The total method (consistent with EPA methods 200.7 and 200.8) acidified the sample to pH 2 before analysis; the acid soluble method acidified the sample to pH<2, held the sample for 16 hours and then filtered the sample with a 0.45 µm filter; the pH extraction method acidified the sample to pH 4.0-4.2, held the sample for three hours, and then filtered the sample with a 0.45 µm filter; and lastly, the dissolved method filtered the sample before acidification. As expected, the total method typically had elevated measured aluminum concentrations compared to the levels quantified by the three other test methodologies. This trend was most evident with natural waters that had high total suspended solids. The validation of the pH 4 extraction method is still on-going, with the expectation that this approach will better estimate the bioavailable fraction of aluminum in natural waters.

Acute Measures of Effect

The acute measures of effect on aquatic organisms are the LC_{50}, EC_{50}, and IC_{50}. LC stands for “Lethal Concentration,” and a LC_{50} is the concentration of a chemical that is estimated to kill 50 percent of the test organisms. EC stands for “Effect Concentration,” and the EC_{50} is the concentration of a chemical that is estimated to produce a specific effect in 50 percent of the test organisms. IC stands for “Inhibitory Concentration,” and the IC_{50} is the concentration of a chemical that is estimated to inhibit some biological process (e.g., growth) in 50 percent of the test organisms. Acute data that were determined to have acceptable quality and to be useable in the derivation of water quality criteria as described in the 1985 Guidelines for the derivation of a freshwater and estuarine/marine criteria are presented in **Appendix A** (*Acceptable Acute Toxicity*

Data of Aluminum to Freshwater Aquatic Animals) and **Appendix B** (*Acceptable Acute Toxicity Data of Aluminum to Estuarine/Marine Aquatic Animals*), respectively.

Chronic Measures of Effect

The endpoint for chronic exposure for aluminum is the EC_{20}, which represents a 20 percent effect/inhibition concentration. This is in contrast to a concentration that causes a low level of reduction in response, such as an EC_5, which is rarely statistically significantly different from the control treatment. A major reduction, such as 50 percent, is not consistent with the intent of establishing chronic criteria to protect populations from long-term effects. The EPA selected an EC_{20} to estimate a low level of effect for aluminum that would typically be statistically different from control effects, but not severe enough to cause chronic effects at the population level (see U.S. EPA 1999b). Reported NOECs (No Observed Effect Concentrations) and LOECs (Lowest Observed Effect Concentrations) were only used for the derivation of a chronic criterion when an EC_{20} could not be calculated for the genus. A NOEC is the highest test concentration at which none of the observed effects are statistically different from the control. A LOEC is the lowest test concentration at which the observed effects are statistically different from the control. When LOECs and NOECs are used, a Maximum Acceptable Toxicant Concentration (MATC) is calculated, which is the geometric mean of the NOEC and LOEC.

Regression analysis was used to characterize a concentration-effect relationship and to estimate concentrations at which chronic effects are expected to occur. For the calculation of the chronic criterion, point estimates (e.g., EC_{20}s) were selected for use as the measure of effect rather than MATCs, as MATCs are highly dependent on the concentrations tested (as are the NOECs and LOECs from which they are derived). Point estimates also provide additional information that is difficult to determine with an MATC, such as a measure of magnitude of effect across a range of tested concentrations. Author reported EC_{20}s were used when provided, otherwise point estimates were calculated from raw toxicity data using the EPA's Toxicity Relationship Analysis Program (TRAP). Chronic toxicity data that met the test acceptability and quality assurance and quality control (QA/QC) criteria in the 1985 Guidelines for the derivation of freshwater and estuarine/marine criteria are presented in **Appendix C** (*Acceptable Chronic Toxicity Data of Aluminum to Freshwater Aquatic Animals*) and **Appendix D** (*Acceptable Chronic Toxicity Data of Aluminum to Estuarine/Marine Aquatic Animals*), respectively.

2.7 Analysis Plan

During CWA section 304(a) criteria development, the EPA reviews and considers all relevant toxicity test data. Information available for all relevant species and genera are reviewed to identify whether: 1) data from acceptable tests meet data quality standards; and 2) the acceptable data meet the minimum data requirements (MDRs) as outlined in the 1985 Guidelines (Stephan et al. 1985; U.S. EPA 1986). The taxa represented by the different MDR groups represent taxa with different ecological, trophic, taxonomic and functional characteristics in aquatic ecosystems, and are intended to be a representative subset of the diversity within a typical aquatic community. In most cases, data on freshwater and estuarine/marine species are grouped separately to develop separate freshwater and estuarine/marine criteria. Thus, where data allow, four criteria are developed (acute freshwater, acute estuarine/marine, chronic freshwater, and chronic estuarine/marine). If plants are more sensitive than vertebrates and invertebrates, plant criteria are developed.

Table 2 provides a summary of the toxicity data used to fulfill the MDRs for calculation of acute and chronic criteria for both freshwater and estuarine/marine organisms. For aluminum, there are acceptable toxicity data for derivation of a freshwater acute criterion with all of the freshwater MDRs being met. The acceptable acute toxicity data encompass four phyla, 14 families, 20 genera and 22 species (**Table 2**). Acceptable estuarine/marine acute toxicity data are only available for three phyla, five families, five genera and five species. Consequently, only five of the eight MDRs are met for the estuarine/marine acute criterion; and no acceptable acute test data on fish species were available. Therefore, the EPA cannot develop an acute estuarine/marine criterion at this time. The chronic toxicity data for direct calculation of the FCV for the freshwater criterion consisted of seven of the eight freshwater MDRs (the missing MDR was the “other chordate”). However, the 1985 Guidelines still allow derivation of a chronic criterion (see **Section 2.6.1**). Because derivation of a chronic freshwater criterion is important for environmental protection, the EPA examined qualitative data for the Chordate MDR from **Appendix H** (*Other Data on Effects of Aluminum to Freshwater Aquatic Organisms*) and selected an amphibian test to fulfill that MDR. The species did not rank in the lowest four normalized Genus Mean Chronic Values (GMCVs) (the numeric-criteria-driving portion of the sensitivity distribution), and thus its use to fulfill the missing MDR is considered justified (U.S. EPA 2008). There are not enough chronic toxicity data for direct calculation of the FCV for the estuarine/marine criteria (no acceptable estuarine/marine chronic studies), thus the EPA did not derive chronic estuarine/marine criterion. Aluminum toxicity data on estuarine/marine species remain a data gap; additional acute and chronic toxicity testing on estuarine/marine taxa would be needed in order to derive estuarine/marine criteria for aluminum.

Table 2. Summary of Acceptable Toxicity Data Used to Fulfill the Minimum Data Requirements in the 1985 Guidelines for Aluminum.

Family Minimum Data Requirement (Freshwater)	Acute (Phylum / Family / Genus)	Chronic (Phylum / Family / Genus)
Family Salmonidae in the class Osteichthyes	Chordata / Salmonidae / Oncorhynchus	Chordata / Salmonidae / Salvelinus
Second family in the class Osteichthyes	Chordata / Centrarchidae / Lepomis	Chordata / Cyprinidae / Pimephales
Third family in the phylum Chordata	Chordata / Cyprinidae / Pimephales	Chordata / Ranidae / Rana*
Planktonic Crustacean	Arthropoda / Daphniidae / Ceriodaphnia	Arthropoda / Daphniidae / Ceriodaphnia
Benthic Crustacean	Arthropoda / Crangonyctidae / Crangonyx	Arthropoda / Hyalellidae / Hyalella
Insect	Arthropoda/ Chironomidae/ Chironomus	Arthropoda / Chironomidae / Chironomus
Family in a phylum other than Arthropoda or Chordata	Mollusca / Physidae / Physa	Mollusca / Lymnaeidae / Lymnaea
Family in any order of insect or any phylum not already represented	Annelida / Naididae / Nais	Annelida / Aeolosomatidae / Aeolosoma
Family Minimum Data Requirement (Estuarine/Marine)	**Acute (Phylum / Family / Genus)**	**Chronic (Phylum / Family / Genus)**
Family in the phylum Chordata	No acceptable data	No acceptable data
Family in the phylum Chordata	No acceptable data	No acceptable data
Either the Mysidae or Penaeidae family	No acceptable data	No acceptable data
Family in a phylum other than Arthropoda or Chordata	Mollusca / Ostreidae / Crassostrea	No acceptable data
Family in a phylum other than Chordata	Annelida / Nereididae / Neanthes	No acceptable data
Family in a phylum other than Chordata	Annelida / Capitellidae / Capitella	No acceptable data
Family in a phylum other than Chordata	Annelida / Ctenodrilidae / Ctenodrilus	No acceptable data
Any other family	Arthropoda / Ameiridae / Nitokra	No acceptable data

* Data used qualitatively, see Section 3.2.1.

	Freshwater Acute			Freshwater Chronic			Estuarine/Marine Acute			Estuarine/Marine Chronic		
Phylum	**Families**	**GMAVs**	**SMAVs**	**Families**	**GMCVs**	**SMCVs**	**Families**	**GMAVs**	**SMAVs**	**Families**	**GMCVs**	**SMCVs**
Annelida	1	1	1	1	1	1	3	3	3	-	-	-
Arthropoda	5	7	9	3	4	4	1	1	1	-	-	-
Chordata	5	9	9	2	4	4	-	-	-	-	-	-
Mollusca	3	3	3	2	2	2	1	1	1	-	-	-
Rotifera	-	-	-	1	1	1	-	-	-	-	-	-
Total	**14**	**20**	**22**	**9**	**12**	**12**	**5**	**5**	**5**	**0**	**0**	**0**

2.7.1 pH, Total Hardness and DOC Normalization

Although many factors might affect the results of toxicity tests of aluminum to aquatic organisms (Sprague 1985), water quality criteria can quantitatively take into account only factors for which enough data are available to show that the factor similarly affects the results of tests with a variety of species. A variety of approaches were evaluated for the development of the freshwater aluminum criteria due to aluminum's unique chemistry and geochemical effects on its bioavailability. These included empirical models that directly relate water chemistry conditions to metal bioavailability and include single parameter regression models (e.g., hardness adjustment equations) and a variety of MLRs. The mechanistic models evaluated included an aluminum BLM model and a simplified aluminum BLM model. For further discussion, see **Section 5.3.5**.

A recent publication by Gensemer et al. (2018) summarized short-term aluminum chronic toxicity data across a range of pH, total hardness, and DOC values. Three-day toxicity tests measuring growth with the green alga (*Pseudokirchneriella subcapitata*), 7-day reproduction tests with the cladoceran (*Ceriodaphnia dubia*), and 7-day mean biomass tests with the fathead minnow (*Pimephales promelas*) were compiled to evaluate how the effect of pH, total hardness, and DOC alters aluminum bioavailability. The *P. subcapitata* data consisted of 27 tests with dilution water parameters that ranged from 6.14-8.0 for pH, 22-121 mg/L total hardness and 0.3-4.0 mg/L DOC (DeForest et al. 2018a). The *C. dubia* data consisted of 23 tests with test parameters that ranged from 6.3-8.1 for pH, 9.8-123 mg/L total hardness and 0.1-4 mg/L DOC (DeForest et al. 2018a). The fathead minnow data consisted of 22 tests with test parameters that ranged from 6.0-8.0 for pH, 10.2-127 mg/L total hardness and 0.08-5.0 mg/L DOC (DeForest et al. 2018a). DeForest et al. (2018a) used these data to evaluate the ability of MLR models to predict chronic toxicity of aluminum as a function of multiple combinations of pH, total hardness, and DOC conditions. These three parameters are thought to be the most influential for aluminum bioavailability and can be used to explain the scale of differences in the observed toxicity values (Cardwell et al. 2018; Gensemer et al. 2018). As a result of the public comments on the draft of this document released into the Federal Register, data on an additional nine *C. dubia* and nine *P. promelas toxicity* tests were obtained in order to expand the ranges of water chemistry conditions for model development. The new toxicity data expanded the DOC range up to 12.3 mg/L for *C. dubia* and 11.6 mg/L for *P. promelas* and the hardness range up to 428 mg/L and 422 mg/L, respectively. These new data were subjected to an independent, external expert peer review, and an EPA quality review, prior to their use in the aluminum criteria. The external expert peer review comments on these new data obtained by the EPA in 2018 and the EPA's response to the external expert peer reviews can be found on the EPA website for the aluminum criteria (https://www.epa.gov/wqc/aquatic-life-criteria-aluminum).

The approach described by DeForest et al. (2018a,b) incorporated pH, total hardness, and DOC into MLR models to determine if the estimation of aluminum bioavailability to animals in freshwater aquatic systems could be applicable in the development of aluminum water quality criteria. The approach resulted in the creation of multiple MLR models that could be used for the development of aluminum water quality criteria following European Union (EU) (ECB 2003) and the EPA methodologies (Stephan et al. 1985). Only the MLR model development for the fathead minnow and *C. dubia* using EC_{20} effects concentrations is described below. Note that while a 7-day survival and growth test for *P. promelas* is not defined as an early-life stage (ELS) test per the 1985 Guidelines, testing demonstrated that it produced sensitivity values for total aluminum comparable to those generated via an acceptable ELS test (DeForest et al. 2018a, Table S1), and therefore, is considered appropriate to use for MLR model development.

MLR models for each species were developed using a multi-step process and the general approach is briefly described below. For more detailed information, figures, tables, and statistical results, please see DeForest et al. (2018a,b) and Brix et al. (2017). The authors first examined if any of the relationships between the dependent variable (total aluminum effect concentrations) and the three main effect terms (pH, total hardness and DOC; all independent variables) were non-linear. Effect concentrations (EC_{20}s) for each species were plotted against each independent variable using data where the other two parameters were held constant. Overall, EC_{20}s increased with each independent variable. However, there was some evidence of a unimodal relationship with pH, with increased EC_{20}s around pH 7 and decreasing EC_{20}s at low and high pH, as well as potential differences regarding the effects of total hardness at low and high pH (DeForest et al. 2018a). To account for these potential nonlinearities, the three potential two-way interactions (i.e., pH:hardness, DOC:hardness and pH:hardness) for each of the three main effect terms were added. Finally, a squared pH term was included in the initial models to account for the potential unimodal relationship between pH and aluminum bioavailability (DeForest et al. 2018a).

Beginning with a seven-parameter model consisting of the three main effect terms (pH, total hardness and DOC), the three two-way interactions for the main effects, and a squared pH term, a final model was developed for each species using a step-wise procedure. In this procedure, the original model was compared to a series of simpler models by removing one or more of the four "higher-level" terms (i.e., the three interaction terms and the squared pH term), until the most parsimonious model was developed. Each potential model was evaluated using Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The overall goodness of fit of a model increases with each additional model term. AIC and BIC penalize a model's goodness-of-fit by a factor related to the number of parameters in the model (DeForest et al. 2018a). AIC and BIC are minimized for the model that best balances overall goodness-of-fit and model complexity, as too many terms in the model may over extrapolate from the dataset making it less useful, whereas too few terms reduces its precision.

DeForest et al. (2018b) re-evaluated the original published models supplemented with the new data and developed a pooled MLR model based on the combined *C. dubia* and *P. promelas* datasets. A pooled model approach is described in Brix et al. (2017) for copper. In a pooled MLR model approach, species-specific intercepts are used to account for the differences in species sensitivity. The same procedures were used to develop a pooled model as was done for the individual species MLR models.

For *C. dubia*, the final individual MLR model, based on AIC and BIC, included both the pH:hardness interaction and the squared pH term (DeForest et al. 2018b). The negative pH^2 term accounts for the fact that aluminum bioavailability decreases from pH 6 to pH 7 and then increases from pH 7 to pH 8, which is expected given the unique solubility chemistry of aluminum (DeForest et al. 2018a). The negative pH:hardness term is reflective of the decreasing effects of total hardness mitigating toxicity as pH increases (DeForest et al. 2018a). The adjusted R^2 for the final model was 0.880, compared to an R^2 of 0.67 for the model consisting of the three main independent variables [pH, ln(total hardness), and ln(DOC)]. In the final MLR model, predicted EC_{20}s were within a factor of two of observed values used to create the model for 97% of the tests (DeForest et al. 2018b). The comparison of MLR predicted versus observed *C. dubia* values where one water chemistry parameter was varied is seen in **Figure 4** and **Figure 5**. No clear pattern was observed in the residuals over a wide range of water chemistry conditions or relative to single independent variables (Figure S3-Figure S6, DeForest et al. 2018a). The final individual MLR model for *C. dubia* is:

$$C.dubia\ EC_{20} = e^{\left[-32.523+[0.597\times\ln(DOC)]+[2.089\times\ln(hard)]+(8.802\times pH)-\left(0.491\times pH^{2}\right)-[0.230\times pH:\ln(hard)]\right]}$$

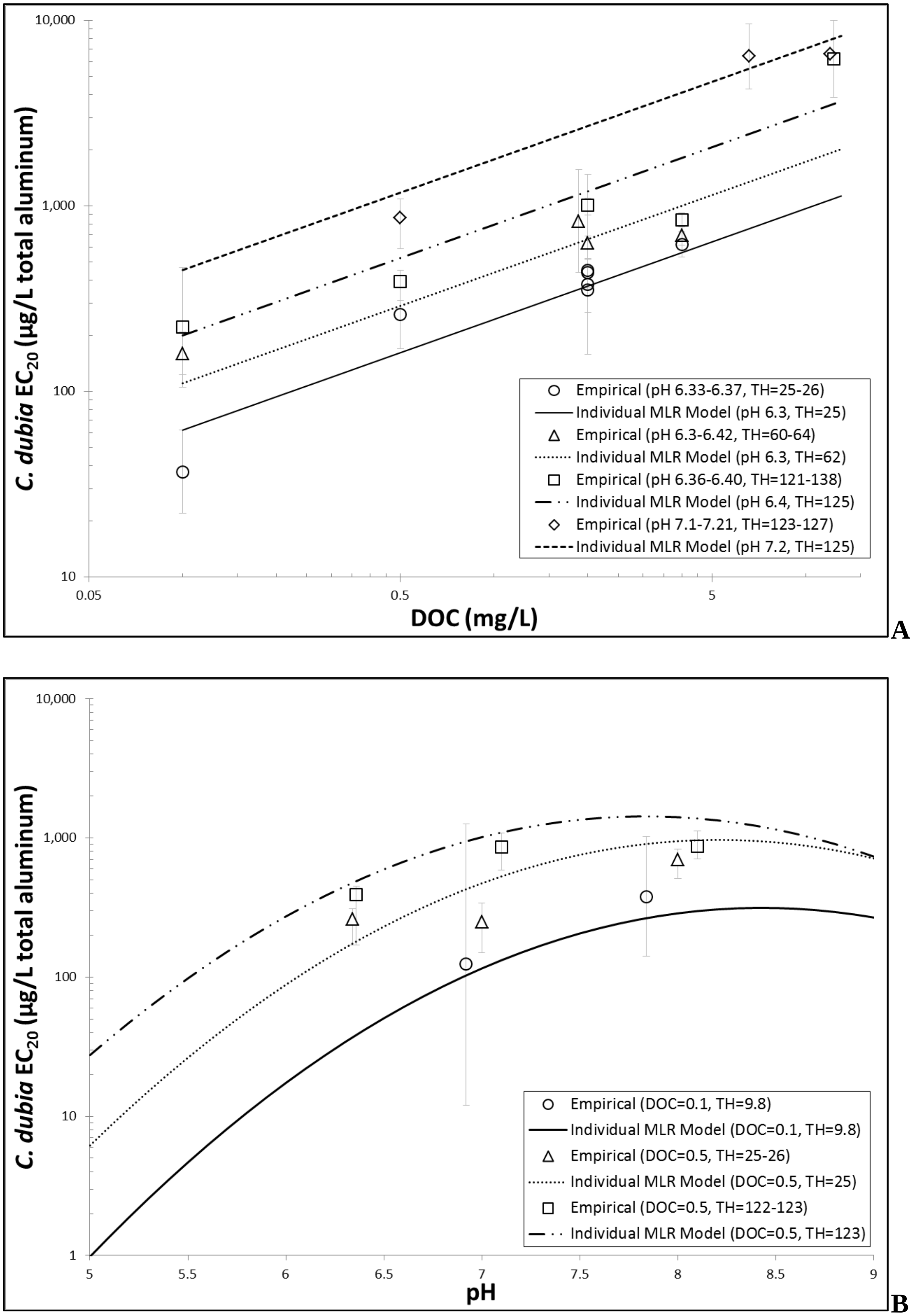

Figure 4. Observed and Individual MLR-Predicted Aluminum EC_{20}s (±95% CLs) for *C. dubia* where DOC or pH was Varied.

(Panel A: DOC is varied; Panel B: pH is varied; Adapted from Figure 2, from DeForest et al. 2018a, used with permission).

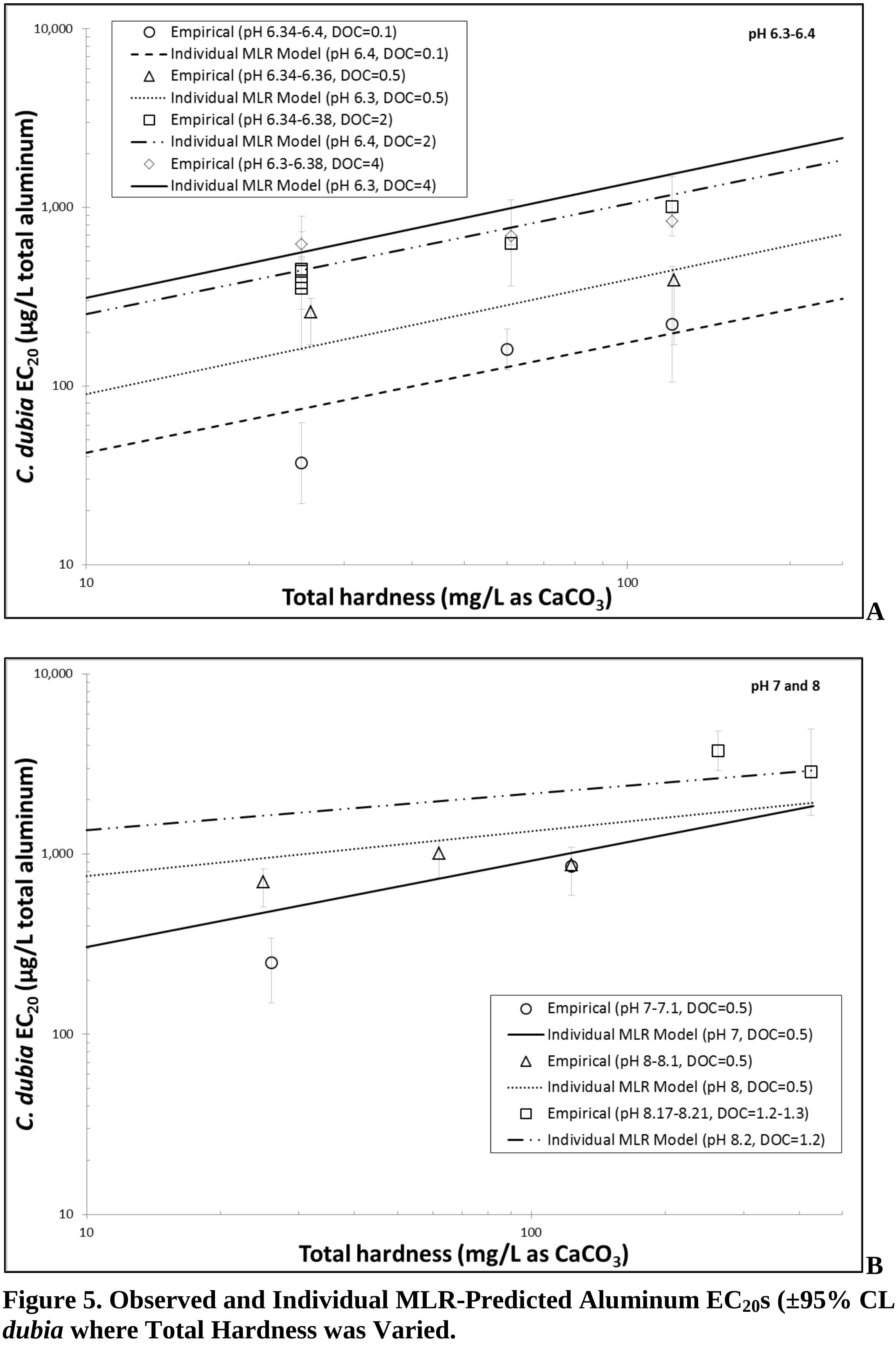

Figure 5. Observed and Individual MLR-Predicted Aluminum EC$_{20}$s (±95% CLs) for *C. dubia* where Total Hardness was Varied.

(Panel A: pH 6.3-6.4, Panel B: pH 7 and 8; Adapted from Figure 2, from DeForest et al. 2018a, used with permission).

For *P. promelas*, the final individual model, based on AIC and BIC, included the pH:hardness and pH:DOC interaction terms (DeForest et al. 2018b). The pH:hardness interaction term was retained because of the unique chemistry of aluminum where total hardness has less of a mitigating effect on bioavailability at higher pH levels (DeForest et al. 2018a; Gensemer et al. 2018). The adjusted R^2 for the final model was 0.923, compared to an R^2 of 0.85 for the model consisting of the three main independent variables [ln(DOC), pH, and ln(hardness)]. In the final MLR model, predicted EC_{20}s were within a factor of two of observed values used to create the model for 97% of the tests (DeForest et al. 2018b). The comparison of MLR predicted versus observed *P. promelas* values where one water chemistry parameter was varied is provided in **Figure 6** and **Figure 7**. Again, no clear pattern was observed in the residuals over a wide range of water chemistry conditions or relative to single independent variables (Figure S3-Figure S6, DeForest et al. 2018a). The final individual MLR model for *P. promelas* is:

$$P.promelas\ EC_{20} = e^{[-7.371+[2.209\times\ln(DOC)]+[1.862\times\ln(hard)]+(2.041\times pH)-[0.232\times pH{:}\ln(hard)]-[0.261\times pH{:}\ln(DOC)]]}$$

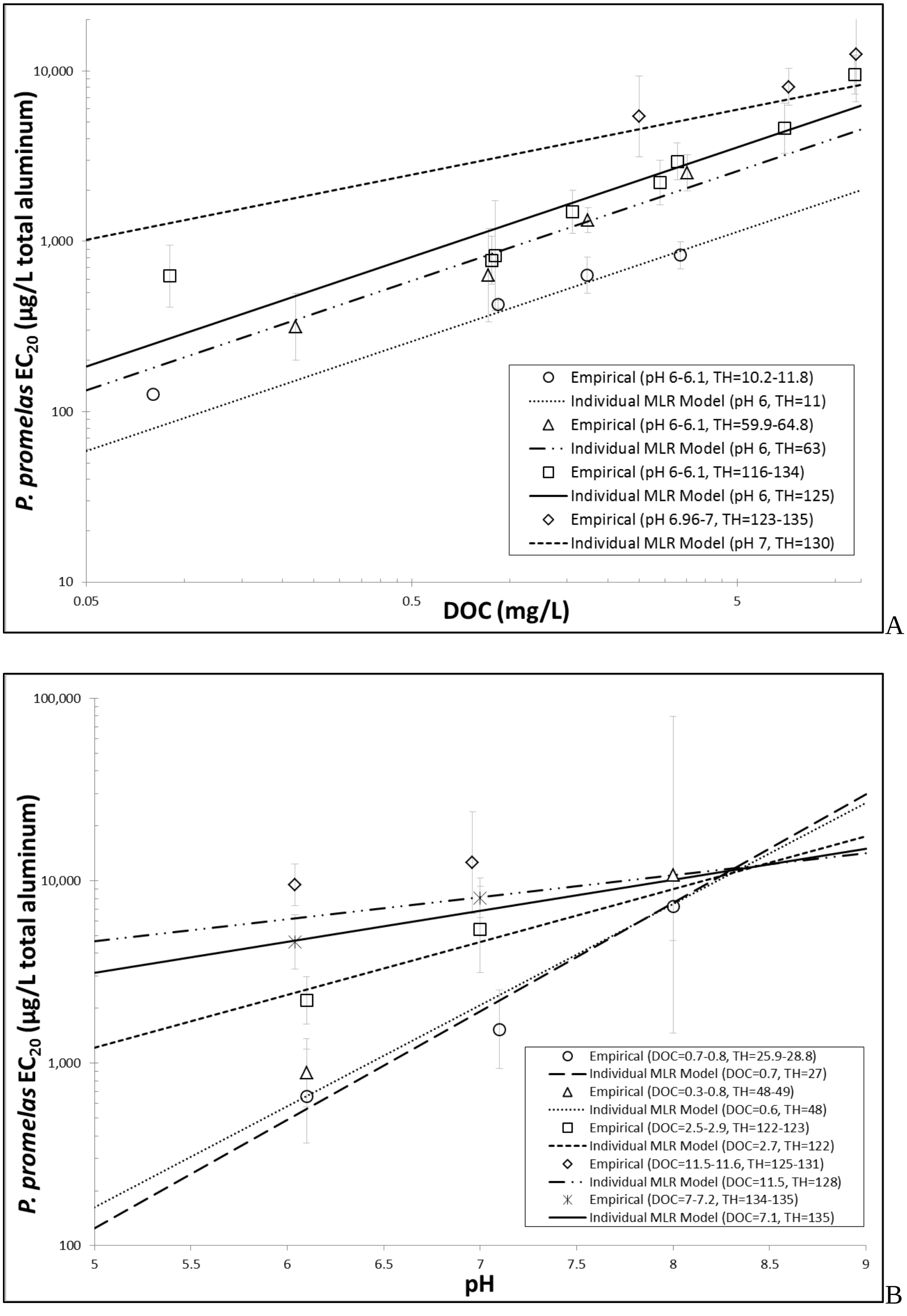

Figure 6. Observed and Individual MLR-Predicted Aluminum EC_{20}s (±95% CLs) for *P. promelas* where DOC or pH was Varied.

(Panel A: DOC, Panel B: pH; Adapted from Figure 3, from DeForest et al. 2018a, used with permission).

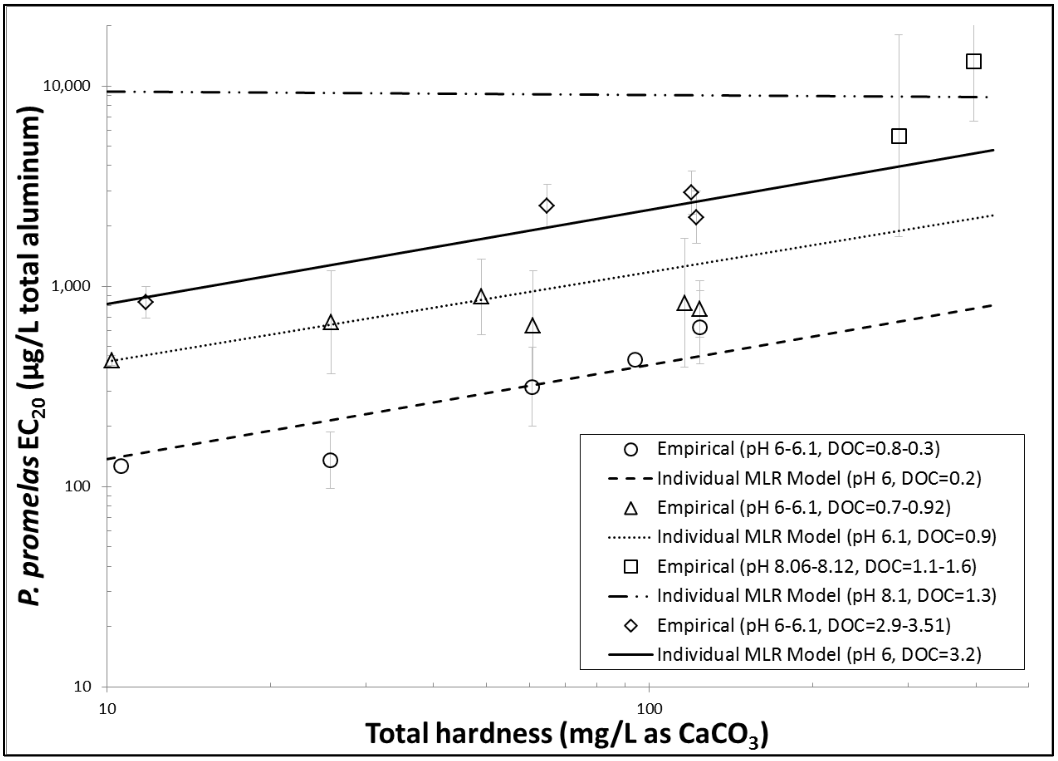

Figure 7. Observed and Individual MLR-Predicted Aluminum EC_{20}s (±95% CLs) for *P. promelas* where Total Hardness was Varied.
(Adapted from Figure 3, from DeForest et al. 2018a, used with permission).

The pooled MLR model performed similarly as the individual (fish and invertebrate) MLR models (DeForest et al. 2018b). The adjusted R^2 value, based on the BIC, was 0.882 and includes the pH:hardness interaction term. The pooled MLR model had a similar to identical level of accuracy as the individual MLR models with 97% of *C. dubia* and 94% of *P. promelas* predicted EC_{20}s within a factor of two of observed values (DeForest et al. 2018b). However, a comparison of the residuals between the observed and predicted values for the two models (individual vs. pooled MLR) showed that the individual models' residuals had smaller standard deviations. Additionally, the pooled model had some patterns in the residuals of the predictions relative to the independent variables (e.g., pH). There were no patterns in the residuals for either the *C. dubia* or *P. promelas* individual MLR models. The EPA elected to use the individual fish and invertebrate models in the final recommended aluminum aquatic life AWQC, instead of a pooled model for the above reasons. This modeling approach is also consistent with the approach in the draft 2017 aluminum criteria document. Additional analysis comparing the performance to the two model approaches (individual vs. pooled MLR) is presented in **Appendix L** (*EPA's MLR Model Comparison of DeForest et al. (2018b) Pooled and Individual-Species Model Options*).

The models developed followed the trends seen in the empirical data, 1) at pH 6 predicted effects concentrations increased with both total hardness and DOC concentrations, 2) at pH 7 predicted effect concentrations increased with DOC concentrations, but not total hardness, and 3) at pH 8 predicted effect concentrations increased with DOC concentrations, but predicted effect concentrations decreased with increased total hardness concentrations (DeForest et al. 2018a). The individual species models developed by DeForest et al. (2018b) were used to normalize the freshwater acute and chronic data in **Appendix A** and **Appendix C**, respectively. Invertebrate data were normalized using the individual MLR model for *C. dubia*, and vertebrate data were normalized using the individual MLR model for *P. promelas*. Invertebrate and vertebrate freshwater aluminum toxicity data were normalized with the following equations:

$$\begin{aligned}&Invertebrate\ Normalized\ EC_{20}/LC_{50}\\&= e^{\left[\begin{gathered}(\ln EC_{20,test}/LC_{50,test})-[0.597\times(\ln DOC_{test}-\ln DOC_{target})]-[8.802\times(pH_{test}-pH_{target})]-[2.089\times(\ln hard_{test}-\ln hard_{target})]\\+[0.491\times(pH_{test}^{2}-pH_{target}^{2})]+\left[0.230\times[(pH_{test}\times\ln hard_{test})-(pH_{target}\times\ln hard_{target})]\right]\end{gathered}\right]}\end{aligned}$$

$$\begin{aligned}&Vertebrate\ Normalized\ EC_{20}/LC_{50}\\&= e^{\left[\begin{gathered}\left(\ln\frac{EC_{20,test}}{LC_{50,test}}\right)-[2.209\times(\ln DOC_{test}-\ln DOC_{target})]-[2.041\times(pH_{test}-pH_{target})]-[1.862\times(\ln hard_{test}-\ln hard_{target})]\\+\left[0.261\times[(pH_{test}\times\ln DOC_{test})-(pH_{target}\times\ln DOC_{target})]\right]\\+\left[0.232\times[(pH_{test}\times\ln hard_{test})-(pH_{target}\times\ln hard_{target})]\right]\end{gathered}\right]}\end{aligned}$$

where:

$EC_{20,test}$ = reported chronic total aluminum effect concentration in µg/L
$LC_{50,test}$ = reported acute total aluminum effect concentration in µg/L
DOC_{test} = reported test DOC concentration in mg/L
pH_{test} = reported test pH
$hard_{test}$ = reported test total hardness concentration in mg/L as $CaCO_3$
DOC_{target} = DOC value to normalize to in mg/L
pH_{target} = pH value to normalize to
$hard_{target}$ = total hardness value to normalize to in mg/L as $CaCO_3$

Throughout this document, unless otherwise stated, effect concentrations were normalized to pH 7, total hardness of 100 mg/L and DOC of 1 mg/L. This example scenario is illustrative only and is not meant to represent water quality characteristics typical of U.S. natural waters. Normalized values will be different under differing water chemistry conditions as identified in this document.

2.7.2 Acute Criterion

Acute criteria are derived from the sensitivity distribution of compiled genus mean acute values (GMAVs), calculated from species mean acute values (SMAVs) of acceptable data. SMAVs are calculated using the geometric mean for all acceptable toxicity tests within a given species (e.g., all tests for *Daphnia magna*). If only one test is available, the SMAV is that test value by default. As stated in the 1985 Guidelines, flow-through measured test data are normally given preference over other test exposure types (i.e., renewal, static, unmeasured) for a species, when available. When relationships are apparent between life-stage and sensitivity, only values for the most sensitive life-stage are considered. GMAVs are then calculated using the geometric means of all SMAVs within a given genus (e.g., all SMAVs for genus *Daphnia - Daphnia pulex, Daphnia magna*). If only one SMAV is available for a genus, then the GMAV is represented by that value. GMAVs are then rank-ordered by sensitivity from most sensitive to least sensitive.

Acute criteria are based on the Final Acute Value (FAV). The FAV is determined by regression analysis based on the four most sensitive genera (reflected as GMAVs) in the data set to interpolate or extrapolate (as appropriate) to the 5th percentile of the sensitivity distribution represented by the tested genera. The intent of the eight MDRs is to serve as a representative sample of the aquatic community. These MDRs represent different ecological, trophic, taxonomic and functional differences observed in the natural aquatic ecosystem. Use of a sensitivity distribution where the criteria values are based on the four most sensitive taxa in a triangular distribution represents a censored statistical approach that improves estimation of the lower tail (where most sensitive taxa are) when the shape of the whole distribution is uncertain, while accounting for the total number of genera within the whole distribution.

The acute criterion, defined as the Criterion Maximum Concentration (CMC), is the FAV divided by two, which is intended to provide an acute criterion protective of nearly all individuals in such a genus. The use of the factor of two to reduce the FAV to the criterion magnitude is based on analysis of 219 acute toxicity tests on a range of chemicals, as described in the *Federal Register* on May 18, 1978 (43 FR 21506-18). For each of these tests, mortality data were used to determine the highest test concentration that did not cause mortality greater than that observed in the control for that particular test (which would be between 0 and 10% for an acceptable acute test). Thus, dividing the LC_{50}-based FAV by two decreases potential acute effects to a level comparable to control mortality levels. Therefore, the acute criterion is expected to protect 95% of species in a representative aquatic community from acute effects.

2.7.3 Chronic Criterion

The chronic criterion, defined as the Criterion Continuous Concentration (CCC), may be determined by one of two methods. If all eight MDRs are met with acceptable chronic test data, then the chronic criterion is derived using the same method used for the acute criterion, employing chronic values (e.g., EC_{20}) estimated from acceptable toxicity tests. In cases where fewer chronic data are available (i.e., must have at least three chronic tests from taxa that also have appropriate acute toxicity data), the chronic criterion can be derived by determining an appropriate acute-chronic ratio (ACR).

The criteria presented are the EPA's estimate of maximum concentrations of aluminum to protect most aquatic organisms from any unacceptable short- or long-term effects. Results of such intermediate calculations such as Species Mean Acute Values (**Appendix A** and **Appendix B**) and chronic values (**Appendix C** and **Appendix D**) are specified to four significant figures to prevent round-off error in subsequent calculations; the number of places beyond the decimal point does not reflect the precision of the value. The acute and chronic criteria are rounded to two significant figures.

3 EFFECTS ANALYSES

Data for aluminum were obtained from studies published in the open literature and identified in a literature search using the ECOTOXicology database (ECOTOX) as meeting data quality standards. ECOTOX is a source of high quality toxicity data for aquatic life, terrestrial plants, and wildlife. The database was created and is maintained by the EPA, Office of Research and Development, and the National Health and Environmental Effects Research Laboratory's Mid-Continent Ecology Division. The latest comprehensive literature search for this document via ECOTOX was conducted in 2017 and supplemented by additional data researchers made available to the EPA in 2018.

A further evaluation of the quality of the available data was performed by the EPA to determine test acceptability for criteria development. Appendix A of *Quality Criteria for Water*

1986 (U.S. EPA 1986) provides an in-depth discussion of the minimum data requirements and data quality requirements for aquatic life criteria development.

3.1 Acute Toxicity to Aquatic Animals

All available reliable data relating to the acute effects of total aluminum on aquatic animals were considered in deriving the aluminum criteria. Data suitable (in terms of test acceptability and quality in a manner consistent with the 1985 Guidelines) for the derivation of a freshwater and an estuarine/marine FAV are presented in **Appendix A** (*Acceptable Acute Toxicity Data of Aluminum to Freshwater Aquatic Animals*) and **Appendix B** (*Acceptable Acute Toxicity Data of Aluminum to Estuarine/Marine Aquatic Animals*), respectively. Most fish and invertebrate data are LC_{50} measures from acute toxicity tests that were 96 hours in duration, except the tests for cladocerans, midges, mysids and certain embryos and larvae of specific estuarine/marine groups, which were 48 hours in duration and typically EC_{50} endpoints (per the 1985 Guidelines).

3.1.1 Freshwater

Twenty-two freshwater species encompassing 20 genera are represented in the dataset of acceptable data for acute toxicity to aluminum. The water quality conditions for these 118 toxicity tests ranged from 5.0-8.3 for pH, 2-220 mg/L as $CaCO_3$ for total hardness, and 0.48-4.0 mg/L for DOC. Since these three parameters affect the bioavailability, and hence toxicity of aluminum, all of the acceptable acute toxicity data presented in **Appendix A** were normalized to standardized water quality conditions using the MLR equations described in the Analysis Plan (**Section 2.7.1**). However, the dilution water DOC concentration was not reported for a number of acute studies presented in **Appendix A**. In this situation, where only the DOC was lacking, default values were used for several different dilution waters using a methodology documented in the 2007 freshwater copper AWQC document (see Appendix C, U.S. EPA 2007b). Specifically, the default DOC value for: 1) laboratory prepared reconstituted water is 0.5 mg/L, 2) Lake Superior water is 1.1 mg/L, 3) city tap and well water is 1.6 mg/L, and 4) Liberty Lake, Washington water is 2.8 mg/L. These values were determined from empirical data obtained for each source water.

Once normalized, the toxicity data were compiled (i.e., based on the geometric mean for each species and genus) and ranked by GMAV into a sensitivity distribution. Normalizing the toxicity data to the same pH, total hardness and DOC levels allows comparisons to be made because the MLR derived equations address the differences seen in the magnitude of effects when comparing across conditions. However, because the 118 toxicity tests were each conducted at different water quality conditions, the MLR derived equations may have either a minor or major effect on the magnitude of the observed reported effects depending on the set of conditions to which the tests are normalized. Thus, the relative sensitivity rankings can change depending on what pH, hardness and DOC concentrations are selected for normalization (see **Appendix K** for examples).

All values reported in this section are normalized to pH 7, total hardness of 100 mg/L as $CaCO_3$, and DOC of 1.0 mg/L (see **Section 2.7.1** for more information). Several species tested were not exposed to aluminum concentrations high enough or low enough to allow calculation of an LC_{50} (i.e., the LC_{50} is a “greater than” or “less than” value). The decision rule for using these non-definitive LC_{50}s to calculate SMAVs is consistent with methods used previously in criteria development. The freshwater ammonia AWQC document explains how chronic values (e.g., EC_{20}s) can be evaluated for potential use in deriving SMCVs (U.S. EPA 2013). The methodology is based on the finding that “greater than” values for concentrations of low magnitude, and “less than” values for concentrations of high magnitude do not generally add significant information to the toxicity analysis. The decision rule was applied as follows: “greater than” (>) low chronic values and “less than” (<) high chronic values were not used in the calculation of the SMCV; but “less than” (<) low chronic values and a “greater than” (>) high chronic values were included in the SMCV (U.S. EPA 2013). This approach was also followed for acute SMAV calculations.

While non-definitive SMAVs were ranked in **Table 3** according to the highest concentration used in the test, the value does not necessarily imply a accurate ranking of sensitivities. Again, in this section and below, the relative rankings are presented for comparative purposes and only apply when the set of chemistry conditions are pH 7, total hardness of 100 mg/L and DOC of 1.0 mg/L. SMAVs ranged from 1,836 µg/L for the cladoceran, *Daphnia pulex,* to 119,427 µg/L for the snail, *Melanoides tuberculata*. There is no apparent trend between freshwater taxon and acute sensitivity to aluminum (**Table 3**). The smallmouth bass, *Micropterus dolomieu*, represents the second most sensitive genus; cladocerans represent the first and fourth most sensitive genera; fish genera rank second, third, sixth and seventh in the sensitivity distribution; and an ostracod (*Stenocypris*) ranks fifth.

Other fish species were less sensitive with SMAVs of 18,913 µg/L for the brook trout, *Salvelinus fontinalis*, greater than 22,095 µg/L for the fathead minnow, *Pimephales promelas*, greater than 31,087 µg/L for the green sunfish, *Lepomis cyanellus*, and greater than 21,779 µg/L for the Rio Grande silvery minnow, *Hybognathus amarus.* The midge (*Chironomus plumosus*, SMAV = 25,216 µg/L), the aquatic air-breathing snail (*Physa sp.*, SMAV = 41,858 µg/L), and the freshwater juvenile mussel (*Lampsilis siliquoidea*, SMAV = >29,492 µg/L) were comparatively insensitive to aluminum.

Summary of Studies Used in Acute Freshwater Determination

The taxa used in calculating the acute criterion (the lowest four ranked GMAVs) depends on the set of water quality conditions for which the criterion is being derived. Based on the analysis in **Appendix K** (*Recommended Criteria for Various Water Chemistry Conditions*), a combination of several genera will rank in the lowest four. Those acute studies used to calculate the GMAVs are summarized below. The normalized values mentioned below are for pH of 7, total hardness of 100 mg/L as $CaCO_3$ and DOC of 1.0 mg/L.

Invertebrates

Cladoceran, *Daphnia*

The pH/total hardness/DOC-normalized GMAV of 2,325 µg/L aluminum for *Daphnia* is based on the SMAVs for two cladoceran species, *Daphnia magna* and *D. pulex*. The *D. magna* normalized SMAV (2,944 µg/L) is based on the geometric mean of five 48-hr EC_{50}s (ranged from 713.2 to 15,625 µg/L aluminum) as reported by Biesinger and Christensen (1972), European Aluminum Association (2009), Kimball (1978) and Shephard (1983). All tests were static that exposed <24-hr old neonates, and only the Kimball (1978) test measured aluminum concentrations and did not use nominal concentrations. The *D. pulex* normalized SMAV (1,836 µg/L) is based on only one static-renewal unmeasured toxicity test conducted by Griffitt et al. (2008).

Cladoceran, *Ceriodaphnia*

Two species of *Ceriodaphnia*, *C. dubia* and *C. reticulata*, are used to derive the pH/total hardness/DOC-normalized GMAV of 7,771 µg/L aluminum. The *C. dubia* SMAV of 5,863 µg/L aluminum is calculated from 52 normalized EC_{50} values that ranged from 322.4 to greater than 88,933 µg/L aluminum (ENSR 1992d; European Aluminum Association 2009, 2010; Fort and Stover 1995; Gensemer et al. 2018; Griffitt et al. 2008; McCauley et al. 1986; Soucek et al.

2001). The tests were a mix of static or renewal exposures with either measured or unmeasured aluminum concentrations. The *C. reticulata* normalized SMAV of 10,299 µg/L aluminum is based on the two flow-through measured test results reported by Shephard (1983).

Ostracod, *Stenocypris major*

Shuhaimi-Othman et al. (2011a, 2013) reported a 96-hr LC_{50} of 3,102 µg/L aluminum for the ostracod, *S. major*, which equates to a pH/total hardness/DOC-normalized LC_{50}/SMAV/GMAV of 8,000 µg/L total aluminum. The adult organisms were exposed to static-renewal conditions and the test solutions were measured.

Worm, *Nais elinguis*

Shuhaimi-Othman et al. (2012a, 2013) reported a 96-hr LC_{50} of 3,874 µg/L aluminum for the worm, *Nais elinguis* which equates to a pH/total hardness/DOC-normalized LC_{50}/SMAV/GMAV of 9,224 µg/L total aluminum. Adult worms were exposed to aluminum sulfate under static-renewal conditions and the test solutions were measured.

Vertebrates

Rainbow trout, *Oncorhynchus mykiss*

Eight acute toxicity tests for the rainbow trout (*O. mykiss*) were used to calculate the pH/total hardness/DOC-normalized SMAV of 3,312 µg/L aluminum reported by Gundersen et al. (1994). The eight flow-through measured normalized LC_{50}s ranged from 1,680 to 7,216 µg/L aluminum.

Atlantic salmon, *Salmo salar*

Two acceptable acute values reported by Hamilton and Haines (1995) were used to calculate the SMAV/GMAV for the Atlantic salmon, *S. salar*. The sac fry were exposed in static, unmeasured chambers at a total hardness of 6.8 mg/L (as $CaCO_3$) and two different pH levels. The 96-hr LC_{50} values were 584 and 599 µg/L total aluminum conducted at pH levels of 5.5 and 6.5, respectively. The corresponding pH/total hardness/DOC-normalized values are 20,749 and 3,599 and the resulting normalized SMAV/GMAV for the species is 8,642 µg/L total aluminum.

Smallmouth bass, *Micropterus dolomieu*

Three acceptable acute values from one study (reported in both Kane 1984; Kane and Rabeni 1987) are available for the smallmouth bass, *M. dolomieu*. The 48-hr post hatch larva were exposed in static, measured concentration chambers at a total hardness of ~12 mg/L (as $CaCO_3$) and three different pH levels. The LC_{50} values were 130, greater than 978.4 and greater than 216.8 µg/L total aluminum conducted at pH levels of 5.05, 6.25 and 7.5, respectively. The corresponding pH/total hardness/DOC-normalized values are 2,442, greater than 3,655 and greater than 153.4 µg/L. The SMAV/GMAV of 2,988 µg/L for the species/genus is based on the geometric mean of the normalized LC_{50} of 2,442 and greater than 3,655 µg/L total aluminum since the other value (greater than 153.4) is unbounded (i.e., greater than value), and is considered a "greater than" (>) low acute value.

GMAVs for 20 freshwater genera are provided in **Table 3**, and the four most sensitive genera were within a factor of 3.3 of each other. The freshwater FAV (the 5th percentile of the genus sensitivity distribution, intended to protect 95 percent of the genera) for aluminum normalized to a pH 7, total hardness of 100 mg/L and DOC of 1.0 mg/L is 1,961 µg/L, calculated using the procedures described in the 1985 Guidelines. The FAV is an estimate of the concentration of aluminum corresponding to a cumulative probability of 0.05 in the acute toxicity values for the genera with which acceptable acute tests have been conducted (**Table 4**). The FAV is lower than all of the GMAVs for the tested species. The FAV is then divided by two for reasons described above (see **Section 2.7.2**). Based on the above, the FAV/2, which is the freshwater continuous maximum concentration (CMC), for aluminum normalized to a pH 7, total hardness of 100 mg/L and DOC of 1.0 mg/L is 980 µg/L total aluminum (rounded to two significant figures) and is expected to be protective of 95% of freshwater genera potentially exposed to aluminum under short-term conditions (**Figure 8**). However, the freshwater acute toxicity data are normalized using MLR equations that predict the bioavailability and hence toxicity of aluminum under different water chemistry conditions. Thus, the value of the criterion for a given site will depend on the specific pH, total hardness, and DOC concentrations at the site (see **Appendix K** *Recommended Criteria for Various Water Chemistry Conditions* for additional criteria values and four most sensitive genera for each set of conditions).

Table 3. Ranked Freshwater Genus Mean Acute Values at pH 7, Total Hardness of 100 mg/L, and DOC of 1.0 mg/L.

(Note: Values will be different under differing water chemistry conditions as identified in this document).

Rank[a]	GMAV (µg/L total Al)	Genus	Species	SMAV[b] (µg/L total Al)
20	119,427	Melanoides	Snail, *Melanoides tuberculata*	119,427
19	>70,647	Paratanytarsus	Midge, *Paratanytarsus dissimilis*	>70,647
18	41,858	Physa	Snail, *Physa sp.*	41,858
17	>31,087	Lepomis	Green sunfish, *Lepomis cyanellus*	>31,087
16	>29,492	Lampsilis	Fatmucket, *Lampsilis siliquoidea*	>29,492
15	>27,766	Hyalella	Amphipod, *Hyalella azteca*	>27,766
14	25,216	Chironomus	Midge, *Chironomus plumosus*	25,216
13	>22,095	Pimephales	Fathead minnow, *Pimephales promelas*	>22,095
12	>21,779	Hybognathus	Rio Grande silvery minnow, *Hybognathus amarus*	>21,779
11	18,913	Salvelinus	Brook trout, *Salvelinus fontinalis*	18,913
10	>18,563	Hyla	Green tree frog, *Hyla cinerea*	>18,563
9	12,901	Crangonyx	Amphipod, *Crangonyx pseudogracilis*	12,901
8	9,224	Nais	Worm, *Nais elinguis*	9,224
7	9,061	Poecilia	Guppy, *Poecilia reticulata*	9,061
6	8,642	Salmo	Atlantic salmon, *Salmo salar*	8,642
5	8,000	Stenocypris	Ostracod, *Stenocypris major*	8,000
4	7,771	Ceriodaphnia	Cladoceran, *Ceriodaphnia dubia*	5,863
			Cladoceran, *Ceriodaphnia reticulata*	10,299
3	3,312	Oncorhynchus	Rainbow trout, *Oncorhynchus mykiss*	3,312
2	2,988	Micropterus	Smallmouth bass, *Micropterus dolomieu*	2,988
1	2,325	Daphnia	Cladoceran, *Daphnia magna*	2,944
			Cladoceran, *Daphnia pulex*	1,836

[a] Ranked from the most resistant to the most sensitive based on Genus Mean Acute Value.

[b] From Appendix A: Acceptable Acute Toxicity Data of Aluminum to Freshwater Aquatic Animals (all values normalized to pH 7, total hardness of 100 mg/L as $CaCO_3$, and DOC of 1.0 mg/L).

Table 4. Freshwater Final Acute Value and Criterion Maximum Concentration (normalized to pH 7, total hardness of 100 mg/L and DOC of 1.0 mg/L).

(See Appendix K for acute criterion under different water chemistry conditions).

Calculated Freshwater FAV based on 4 lowest values: Total Number of GMAVs in Data Set = 20

Rank	**Genus**	**GMAV** (µg/L)	**lnGMAV**	**$(\mathrm{lnGMAV})^2$**	**P=R/(n+1)**	**SQRT(P)**
4	Ceriodaphnia	7,771	8.96	80.25	0.190	0.436
3	Oncorhynchus	3,312	8.11	65.70	0.143	0.378
2	Micropterus	2,988	8.00	64.04	0.095	0.309
1	Daphnia	2,325	7.75	60.08	0.048	0.218
		Σ (Sum):	**32.82**	**270.1**	**0.476**	**1.34**

S^2 = 31.13
L = 6.334
A = 7.581

S = slope
L = X-axis intercept
A = lnFAV
P = cumulative probability

FAV = 1,961 µg/L total aluminum

CMC (acute criterion) = 980 µg/L total aluminum (rounded to two significant figures)

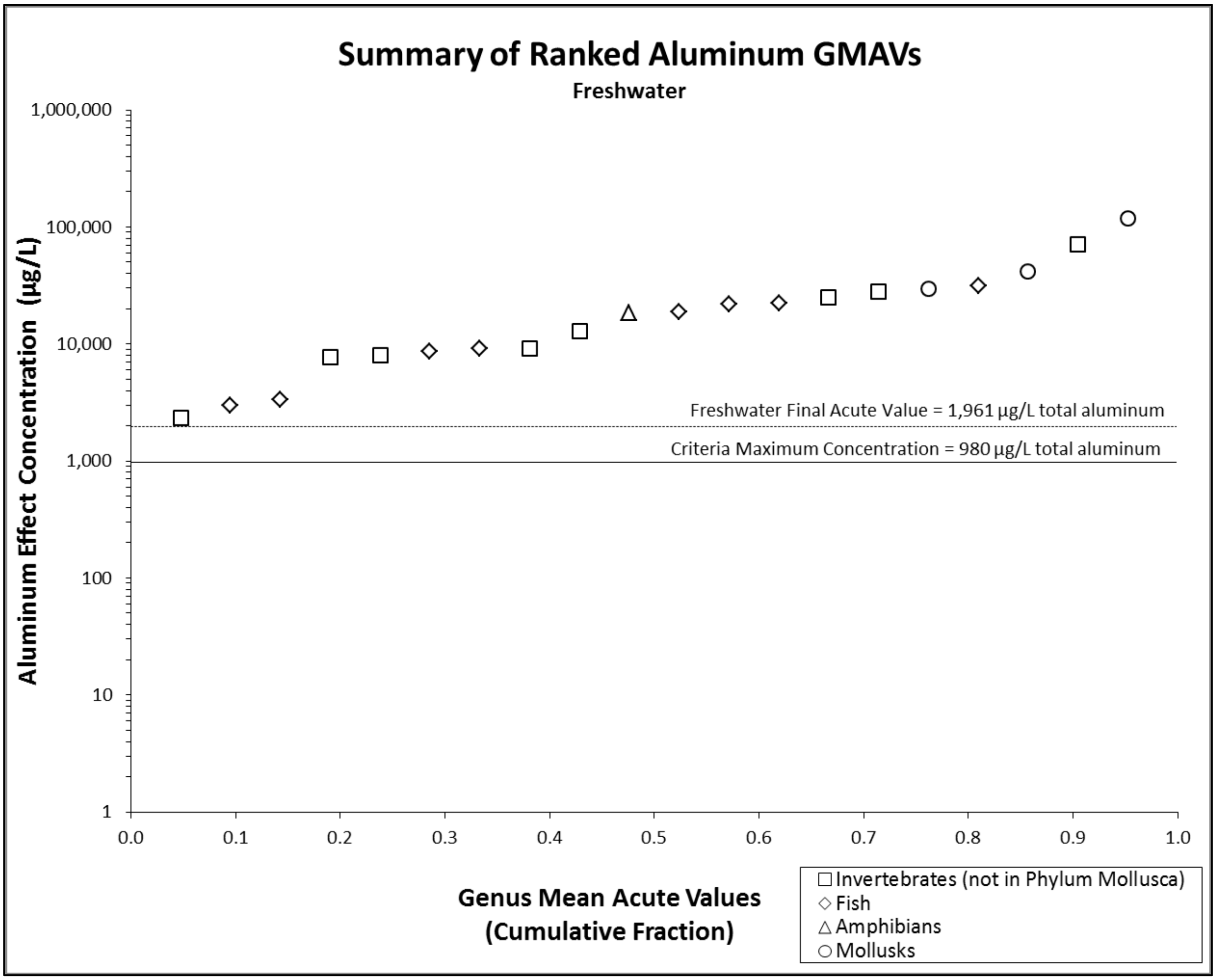

Figure 8. Ranked Summary of Total Aluminum Genus Mean Acute Values (GMAVs) - Freshwater at pH 7, Total Hardness of 100 mg/L, and DOC of 1.0 mg/L.

3.1.2 Estuarine/Marine

The 1985 Guidelines require that data from a minimum of eight families are needed to calculate an estuarine/marine FAV. Notably, no acceptable test data on fish species were available (**Figure 9**). Since data are available for only five families, an estuarine/marine FAV (and consequently the EPA cannot derive an estuarine/marine acute criterion).

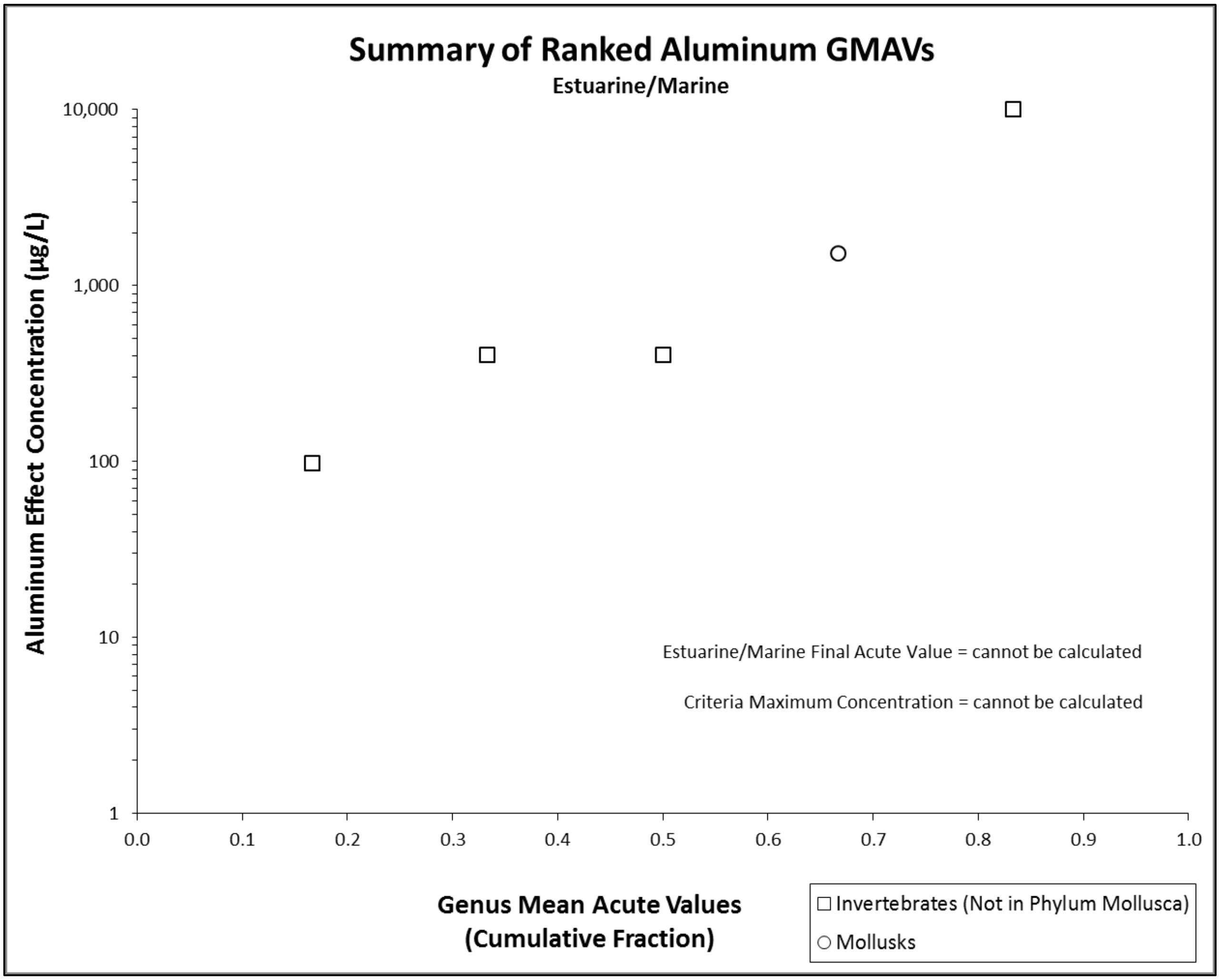

Figure 9. Ranked Summary of Total Aluminum Genus Mean Acute Values (GMAVs) - Estuarine/Marine.

3.2 Chronic Toxicity to Aquatic Animals

3.2.1 Freshwater

Freshwater chronic toxicity data that meet the test acceptability and quality assurance/control criteria (in a manner consistent with the 1985 Guidelines) are presented in **Appendix C** (*Acceptable Chronic Toxicity Data of Aluminum to Freshwater Aquatic Animals*). All tests were conducted with measured concentrations of total aluminum and measurement endpoints are EC_{20}s for all but one test where an EC_{20} could not be calculated. Details on chronic tests are described below. As with the freshwater acute SMAVs/GMAVs, the relative SMCV/GMCV rankings will change depending on the specific pH, total hardness and DOC values selected for data normalization. And as also described for the acute studies, the same

DOC default values were used for select chronic tests where the DOC concentration was lacking for specific dilution waters as provided by U.S. EPA (2007b). In addition, the DOC value reported by Cleveland et al. (1989) was applied to the studies by McKee et al. (1989), Palawski et al. (1989) and Buckler et al. (1995). All four studies used the same dilution water preparation, a mixture of well water and reverse osmosis-treated well water to obtain a low hardness (~13 mg/L as $CaCO_3$), and all four studies reported using the same dilution water preparation from Cleveland et al. (1986).

Aluminum chronic toxicity data are available for twelve species of freshwater organisms: two mollusks (a freshwater mussel and a snail), five other invertebrate species (a rotifer, two cladocerans, a midge, an oligochaete and an amphipod) and four fish species (fathead minnow, zebrafish, Atlantic salmon and brook trout). The water quality conditions for these 59 toxicity tests ranged from 5.1-8.7 for pH, 11.8-428 mg/L as $CaCO_3$ for total hardness, and 0.33-12.3 mg/L for DOC. All chronic values were normalized using the same MLR derived equations as the acute data (see **Section 2.7.1**). If aluminum reduced survival and growth, the product of these variables (biomass) was analyzed (when possible), rather than analyzing them separately (U.S. EPA 2013).

In this section and below, the relative rankings only apply when the set of chemistry conditions are pH 7, total hardness of 100 mg/L and DOC of 1.0 mg/L. Ranked GMCVs are provided in **Table 5**. The fish genus *Salmo*, represented by Atlantic salmon, was the most sensitive genus, and the least sensitive genus was represented by an oligochaete. There is no apparent trend between freshwater taxon and chronic sensitivity to aluminum.

Invertebrates

The chronic toxicity of aluminum to the freshwater unionid mussel, *Lampsilis siliquoidea*, was evaluated by Wang et al. (2016, 2018). Six-week old juvenile mussels were exposed under flow-through measured conditions for 28 days to five aluminum nitrate concentrations and dilution water control composed of a well water/deionized water mix adjusted to a nominal pH of 6.0 and total hardness of 100 mg/L as $CaCO_3$. The calculated biomass EC_{20} of 169 μg/L was reported in the study, with a corresponding normalized EC_{20} of 1,026 μg/L (normalized to pH 7, total hardness = 100 mg/L as $CaCO_3$ and DOC = 1.0 mg/L).

Several chronic aluminum studies were conducted in separate laboratories with the cladoceran, *Ceriodaphnia dubia* (CECM 2014; ENSR 1992b; European Al Association 2010;

Gensemer et al. 2018; McCauley et al. 1986; OSU 2018a). Aluminum chloride was evaluated by McCauley et al. (1986) at the University of Wisconsin-Superior using life cycle studies (*C. dubia* neonates, ≤16-hr old) in Lake Superior water (both raw and treated dechlorinated city water) to determine ACRs at near neutral pH. Five test concentrations plus a dilution water control were renewed three times over seven days, and the number of young per surviving adult was found to be significantly inhibited at 2,600 and 2,400 µg total aluminum/L in each respective dilution water. The EC_{20} and MATC were estimated to be 1,780 and <1,100 µg/L, respectively, or 2,031 and <925.5 µg/L after normalization. Poor dose response in the treated dechlorinated city water exposure prevented calculation of an EC_{20}.

Three-brood, 6-day static-renewal toxicity tests were conducted with aluminum chloride at four hardness levels using <24-hr old *C. dubia* neonates (ENSR 1992b). Reconstituted dilution water was prepared at nominal 25, 50, 100 and 200 mg/L total hardness as $CaCO_3$ and pH of 7.65, 7.7, 8.2 and 8.45, respectively. The mean number of young produced per female was the most sensitive endpoint with normalized (to pH 7, total hardness = 100 mg/L as $CaCO_3$ and DOC = 1.0 mg/L) EC_{20}s of 2,602, 1,077, 708.8 and 746.8 µg/L, respectively (**Appendix C**).

The Center for the Ecotoxicology and Chemistry of Metals (CECM 2014) and the European Al Association (2010) also evaluated the effect of aluminum on the survival and reproduction of *C. dubia* at different pH and total hardness levels. Less than 24-hr old neonates were exposed to aluminum nitrate for seven days using reconstituted laboratory water established at different nominal total hardness (25, 60 or 120 mg/L as $CaCO_3$), DOC (0.5, 2 or 4 mg/L) and pH (6.3, 7.0 or 8.0) levels. Test solutions were renewed daily and the pH was maintained with synthetic buffers (as summarized in Gensemer et al. 2018). Reproduction was the most sensitive endpoint, with EC_{20}s ranging from 36.6 to 1,011.6 µg/L aluminum, and corresponding normalized (to pH 7, total hardness = 100 mg/L as $CaCO_3$ and DOC = 1.0 mg/L) EC_{20}s ranging from 291.7 to 2,072 µg/L (**Appendix C**). A similar experiment was run with another cladoceran, *Daphnia magna,* except water chemistry parameters were not varied (European Al Association 2010; Gensemer et al. 2018). Less than 24-hr old neonates were exposed to aluminum nitrate for 21 days at a total hardness of 140 mg/L as $CaCO_3$, pH 6.3 and DOC of 2 mg/L. Again, reproduction (young per female) was the most sensitive endpoint with a reported EC_{20} of 791.0 µg/L total aluminum. The normalized SMCV/GMCV for the species is 985.3 µg/L.

Oregon State University researchers conducted nine additional aluminum toxicity studies with *Ceriodaphnia dubia* in 2018. The results of these tests allowed the EPA to expand on the bounds of the MLR model. Less than 24-hr old neonates were exposed to one of five aluminum nitrate concentrations for seven days using reconstituted laboratory water established at different nominal total hardness (60-400 mg/L as $CaCO_3$), DOC (1.0-14.0 mg/L) and pH (6.3-8.8) levels (OSU 2018a). Reproduction was the most sensitive endpoint with effect concentrations ranging from 828.6 to 6,612 µg/L total aluminum (1,170 to 2,308 µg/L when normalized using the MLR equation).

Two acceptable *Hyalella azteca* chronic studies are available for aluminum based on recently recommended culture and control conditions (Mount and Hockett 2015; U.S. EPA 2012). Researchers at Oregon State University exposed 7-9 day old juvenile amphipods to five aluminum nitrate concentrations diluted with a well water/reverse osmosis water mix for 42 days under flow-through conditions and a nominal pH of 6 (Cardwell et al. 2018; OSU 2012h). A small amount of artificially-formulated sediment was provided as substrate during the test. Biomass was the most sensitive endpoint, with a 28-day EC_{20} of 199.3 µg/L and a normalized EC_{20} of 665.9 µg/L aluminum (the 28-day results were used since the 79 percent control survival after 42 days was slightly below the 80 percent minimum requirement).

Wang et al. (2016, 2018) also conducted a *H. azteca* chronic test where 7-day old juvenile amphipods were exposed under flow-through measured conditions for 28 days to five aluminum nitrate concentrations and dilution water control composed of a well water/deionized water mix adjusted to a nominal pH of 6.0 and total hardness of 100 mg/L as $CaCO_3$. Silica sand was provided as a substrate. The calculated biomass EC_{20} was 425 µg/L, with a corresponding normalized EC_{20} of 2,890 µg/L (normalized to pH 7, total hardness = 100 mg/L as $CaCO_3$ and DOC = 1.0 mg/L).

Oregon State University (2012f) conducted a 28-day life cycle test with the midge, *Chironomus riparius*, in a mixture of well water and reverse osmosis water (pH range of 6.3-6.9). The authors reported an EC_{20} for the number of eggs per case to be 3,387 µg/L, or 8,181 µg total aluminum/L when normalized to pH 7, total hardness of 100 mg/L as $CaCO_3$ and DOC of 1.0 mg/L. Palawski et al. (1989) also exposed *C. riparius*, but for 30 days at two pH levels (5.6 and 5.0). Larval midge (<24-hr) were exposed to five aluminum sulfate concentrations with a control under flow-through conditions. Adult midge emergence was significantly inhibited at

61.4 and 235.2 µg/L aluminum, at pH 5.6 and 5.0, with calculated EC_{20}s of 29.55 and 84.42 µg/L and normalized EC_{20}s of 1,075 and 15,069 µg/L, respectively. The resultant normalized SMCV of 5,099 µg/L is calculated from all three test results.

Oregon State University also conducted chronic studies for three invertebrate species: an oligochaete, *Aeolosoma sp.*; a rotifer, *Brachionus calyciflorus*; and the great pond snail, *Lymnaea stagnalis* (Cardwell et al. 2018; OSU 2012b,c,e). All tests were conducted with aluminum nitrate, and at a nominal pH of 6.0. The normalized EC_{20}s from the aforementioned studies are 20,514 (oligochaete 17-day population count), 1,845 (48-hr rotifer population count) and 5,945 (pond snail 30-day biomass) µg/L, respectively (**Appendix C**). The researchers also conducted a series of validation studies in 2018 with the rotifer and great pond snail at nominal pH 6.3, with various hardness and DOC levels (OSU 2018e,f). The normalized EC_{20}s ranged from 2,132 to 6,653 µg/L for *Brachionus calyciflorus* and 1,812 to 3,902 µg/L for *Lymnaea stagnalis*.

Vertebrates

Kimball (1978) conducted an early life stage test using fathead minnow (*Pimephales. promelas*) fertilized eggs (16 to 40-hr old) in flowing hard well water. Six treatments of aluminum sulfate plus control replicated four times were used to expose fish for 28 days post-hatch, and aluminum concentrations were measured three times per week during the study. Biomass was more sensitive to the aluminum exposures than percent hatchability, growth and survival, with a resulting EC_{20} of 6,194 µg/L, or 2,690 µg/L when normalized.

The chronic toxicity of aluminum to fathead minnows and zebrafish (*Danio rerio*) was also evaluated by OSU (2012g, 2013) and summarized in Cardwell et al. (2018). Fish were exposed under flow-through conditions in the same dilution water and pH as described above for the amphipod and midge tests (OSU 2012f,h). Less than 24-hr old fertilized fathead minnow eggs and less than 36-hr post fertilization zebrafish were exposed to aluminum nitrate for 33 days. Fathead minnow fry survival was the most sensitive endpoint with a calculated EC_{20} of 428.6 µg/L, and normalized EC_{20} of 2,154 µg/L. Zebrafish biomass was the most sensitive endpoint with a calculated EC_{20} of 234.4 µg/L (1,342 µg/L when normalized).

An early life cycle test was also conducted with brook trout (*Salvelinus fontinalis*). Brook trout eyed eggs were exposed to four aluminum sulfate concentrations at pH 5.7 and 6.5 for 60 days (Cleveland et al. 1989). Both exposures were conducted using flow-through conditions and soft water (total hardness = 12.5 mg/L as $CaCO_3$). The survival and hatching of eyed eggs and the survival, growth, behavioral and biochemical responses of the resultant larvae and juveniles were measured during the exposure. The incomplete hatch endpoint reported in the study was not used after further analysis and communication with the authors because the incomplete hatch endpoint may or may not be a transient effect. The incompletely hatched larvae (based on chorion attachment) were removed daily from the study and not fully evaluated further for survivability. In addition, exposure to acidic waters increased the percentage of incomplete hatched larvae (Cleveland et al. 1986; Ingersoll et al. 1990c), and therefore it is difficult to distinguish between the effects of pH versus aluminum. Therefore, the lack of information and uncertainty with the endpoint led to the decision to not use the data from the study to develop the criteria document. The biomass EC_{20} for the test conducted at pH 5.7 was 143.5 µg/L, and at pH 6.5 the biomass EC_{20} was 164.4 µg/L. The normalized EC_{20}s at pH 5.7 and 6.5 were 1,076 µg/L and 378.7 µg/L, respectively.

Atlantic salmon eyed eggs were exposed to flow-through conditions for 60 days at pH 5.7 and a total hardness of 12.7 mg/L as $CaCO_3$ in reconstituted water (McKee et al. 1989). Salmon weight and survival NOEC and LOEC were 71 and 124 µg aluminum/L, respectively. The calculated biomass EC_{20} for the study was 61.56 µg/L (**Appendix C**). Buckler et al. (1995) also reported a chronic *Salmo salar* study initiated with eyed eggs in reconstituted water (total hardness of 12.7 mg/L as $CaCO_3$) that continued for 60 days post-hatch under flow-through exposure conditions. Time to hatch was not significantly affected at pH 5.7 and 264 µg/L, the highest test concentration evaluated. Survival at 60 days post hatch was reduced at 124 µg/L, with an estimated EC_{20} of 154.2 µg/L (normalized EC_{20} = 1,088 µg/L).

When calculating the Atlantic salmon EC_{20}s for the two studies (Buckler et al. 1995 and McKee et al. 1989), it was observed that the studies listed the same test concentrations and similar dose response for the same test measurements, but reported different endpoints between the two studies. It appears that the Buckler et al. (1995) study was a republication of the previous study performed by McKee et al. (1989), and therefore, only the most sensitive EC_{20} was used in the calculation of the SMCV. The most sensitive EC_{20} of 61.56 µg/L (or 434.4 µg/L when normalized to pH 7, total hardness of 100 mg/L as $CaCO_3$ and DOC of 1.0 mg/L), was based on a 60-day reduction in fish biomass.

Only seven of the eight MDRs are met for direct calculation of the FCV, with the third family in the phylum Chordata missing. Because derivation of a chronic freshwater criterion is important for environmental protection, the EPA examined qualitative data in **Appendix H** (*Other Data on Effects of Aluminum to Freshwater Aquatic Organisms*) to determine if any "Other Data" can be used to fulfill the missing MDR group, and selected an amphibian test to fulfill that MDR.

The MDR for the third family in the phylum Chordata was fulfilled using results of an abbreviated life cycle test initiated with wood frog (*Rana sylvatica*) larvae (Gosner stage 25) and continued through metamorphosis (Peles 2013). The NOEC for survival and growth normalized to a pH 7, total hardness of 100 mg/L and DOC of 1.0 mg/L was 10,684 µg/L, with a chronic value of greater than 10,684 µg/L. The study was not included in **Appendix C** because the test pH (4.68-4.70) was lower than 5. If not for the marginally lower pH (Peles 2013), this study would have been an acceptable chronic test for criterion derivation. The addition of this other chronic test does not directly affect the calculation of the FCV as the species does not rank in the lowest four GMCVs (the numeric-criteria-driving portion of the sensitivity distribution). The species was the most sensitive value from the qualitative data that could be used to fulfill the MDR and the test had a minor deviation in pH. After adding this additional study, the chronic dataset consists of 13 freshwater species representing 13 freshwater genera (**Table 5**).

The four most sensitive GMCVs are from the core quantitative chronic dataset and represent taxa which have been determined to be the most sensitive to aluminum. Based on these rankings, the resultant chronic criterion is 380 µg/L total aluminum at pH 7, total hardness of 100 mg/L (as $CaCO_3$) and DOC of 1.0 mg/L (**Table 6**). The chronic toxicity data are normalized using the MLR equations described in the Analysis Plan that account for the effects of pH, total hardness, and DOC on bioavailability and hence toxicity of aluminum. Thus, the value of the criterion for a given site will depend on the specific pH, total hardness, and DOC concentrations at the site (see **Appendix K** *Recommended Criteria for Various Water Chemistry Conditions* for additional criteria values and four most sensitive genera for each set of conditions). The EPA is confident that the criteria values generated using the MLR models are protective of approximately 95% of freshwater genera in an ecosystem that are potentially exposed to aluminum under long-term conditions (**Figure 10**).

Table 5. Ranked Genus Mean Chronic Values at pH 7, Total Hardness of 100 mg/L, and DOC of 1.0 mg/L.

(Note: Values will be different under differing water chemistry conditions as identified in this document).

Rank[a]	GMCV (µg/L total Al)	Genus	Species	SMCV[b] (µg/L total Al)
13	20,514	Aeolosoma	Oligochaete, *Aeolosoma sp.*	20,514
12	>10,684	Rana	Wood frog,[c] *Rana sylvatica*	>10,684
11	5,099	Chironomus	Midge, *Chironomus riparius*	5,099
10	3,539	Brachionus	Rotifer, *Brachionus calyciflorus*	3,539
9	3,119	Lymnaea	Great pond snail, *Lymnaea stagnalis*	3,119
8	2,407	Pimephales	Fathead minnow, *Pimephales promelas*	2,407
7	1,387	Hyalella	Amphipod, *Hyalella azteca*	1,387
6	1,342	Danio	Zebrafish, *Danio rerio*	1,342
5	1,181	Ceriodaphnia	Cladoceran, *Ceriodaphnia dubia*	1,181
4	1,026	Lampsilis	Fatmucket, *Lampsilis siliquoidea*	1,026
3	985.3	Daphnia	Cladoceran, *Daphnia magna*	985.3
2	638.2	Salvelinus	Brook trout, *Salvelinus fontinalis*	638.2
1	434.4	Salmo	Atlantic salmon, *Salmo salar*	434.4

[a] Ranked from the most resistant to the most sensitive based on Genus Mean Chronic Value.

[b] From Appendix C: Acceptable Chronic Toxicity Data of Aluminum to Freshwater Aquatic Animals (all values normalized to pH 7, total hardness of 100 mg/L as $CaCO_3$, and DOC of 1.0 mg/L).

[c] Fulfills MDR for third family in phylum Chordata, used only qualitatively.

Table 6. Freshwater Final Chronic Value and Criterion Continuous Concentration (normalized to pH 7, total hardness of 100 mg/L and DOC of 1.0 mg/L).

(See Appendix K for chronic criterion under different water chemistry conditions).

Calculated Freshwater FCV based on 4 lowest values: Total Number of GMCVs in Data Set = 13

Rank	Genus	GMCV (µg/L)	lnGMCV	$(\text{lnGMCV})^2$	P=R/(n+1)	SQRT(P)
4	Lampsilis	1,026	6.93	48.07	0.286	0.535
3	Daphnia	985.3	6.89	47.51	0.214	0.463
2	Salvelinus	638.2	6.46	41.71	0.143	0.378
1	Salmo	434.4	6.07	36.89	0.071	0.267
		Σ (Sum):	**26.36**	**174.2**	**0.714**	**1.64**

S^2 = 12.423

L = 5.142

A = 5.930

S = slope

L = X-axis intercept

A = lnFCV

P = cumulative probability

FCV = 376.3 µg/L total aluminum

CCC (chronic criterion) = 380 µg/L total aluminum (rounded to two significant figures)

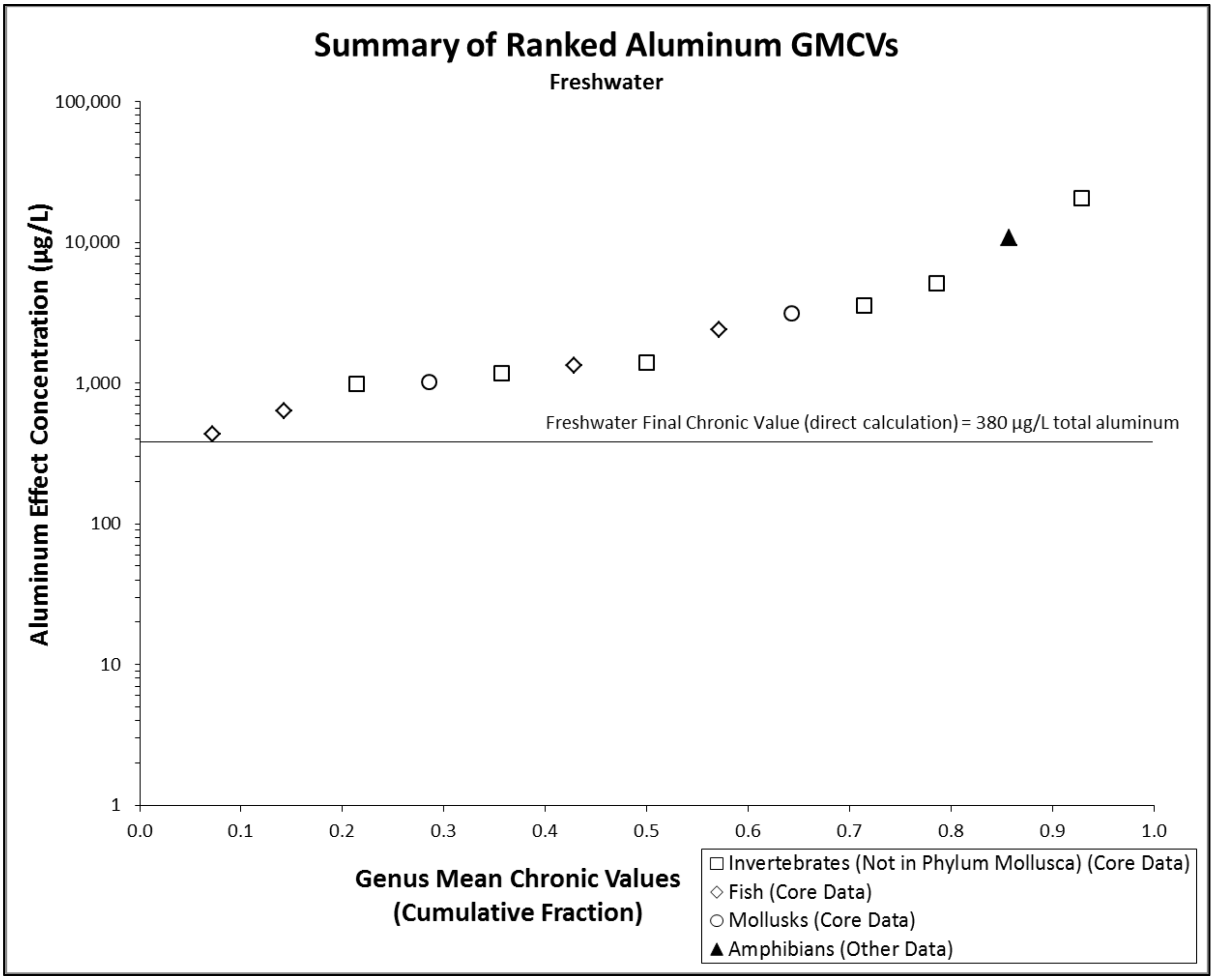

Figure 10. Ranked Summary of Total Aluminum Genus Mean Chronic Values (GMCVs) – Freshwater Supplemented with Other Data to Fulfill Missing MDRs at pH 7, Total Hardness of 100 mg/L, and DOC of 1.0 mg/L.

3.2.2 *Estuarine/Marine*

There are no estuarine/marine chronic toxicity data that meet the test acceptability and quality assurance/control criteria in a manner consistent with the 1985 Guidelines in **Appendix D** (*Acceptable Chronic Toxicity Data of Aluminum to Estuarine/Marine Aquatic Animals*).

3.3 Bioaccumulation

Aluminum bioaccumulates in aquatic organisms, although increased accumulation through trophic levels in aquatic food chains (i.e., biomagnification) is not usually observed (Suedel et al. 1994, U.S. EPA 2007a). Total uptake generally depends on the environmental aluminum concentration, exposure route and the duration of exposure (McGeer et al. 2003).

Desouky et al. (2002) reported that the bioavailability of aluminum to a grazing invertebrate is influenced by both oligomeric silica and humic acid, and that aluminum bound to humic acid may still be bioavailable via grazing. Bioconcentration Factors (BCFs) and bioaccumulation factors (BAFs) typically vary with the bioavailable concentration of metals in water, with higher BCFs occurring at lower metal concentrations (McGeer et al. 2003). In marine sediments, metal bioavailability is altered by increased acid volatile sulfide (AVS) content (Casas and Crecelius 1994), and ligand concentration (Skrabal et al. 2000). Bioaccumulation and toxicity via the diet are considered unlikely relative to direct waterborne aluminum toxicity (Handy 1993; Poston 1991). This conclusion is also supported by the lack of any biomagnification within freshwater invertebrates that are likely to be prey of fish in acidic, aluminum-rich rivers (Herrmann and Frick 1995; Otto and Svensson 1983; Wren and Stephenson 1991). The opposite phenomena, trophic dilution up the food chain, has been suggested (King et al. 1992). A more detailed discussion of bioaccumulation factors is provided in the Effects Characterization section (**Section 5.1.6**).

No U.S. Food and Drug Administration (FDA) action level or other maximum acceptable concentration in tissue, as defined in the 1985 Guidelines, is available for aluminum. Therefore, a Final Residue Value cannot be calculated for fish tissue.

3.4 Toxicity to Aquatic Plants

No aluminum toxicity tests with important aquatic plant species in which the concentrations of test material were measured and the endpoint was biologically important are available in the literature. Therefore, the EPA could not determine a Final Plant Value. However, analysis of plant data provides evidence that criteria magnitudes that are protective of aquatic animals will also be protective of aquatic plants. Effects on aquatic plants are discussed qualitatively in the Effects Characterization section (**Section 5.2**).

4 SUMMARY OF NATIONAL CRITERIA

4.1 Freshwater

The 2018 final aluminum criteria are derived using multiple linear regression (MLR) models that incorporate pH, total hardness, and DOC as input parameters to normalize the acute and chronic toxicity data to a set of predetermined water quality conditions. The MLR equations account for the effects of pH, total hardness and DOC on the bioavailability, and hence toxicity of aluminum. The numeric magnitude of the criteria (acute or chronic criterion) for a given set of conditions, therefore, will depend on the specific pH, total hardness and DOC concentrations used for normalization. The relative GMAVs/GMCVs rankings and subsequent four most sensitive genera used to calculate the criteria will depend on the data normalization conditions selected. The acute and chronic criteria for a given set of input conditions (pH, total hardness and DOC) are numeric magnitude values that are protective for that set of input conditions. The recommended criteria for aluminum can be calculated in two different ways: 1) use the lookup tables provided (see **Appendix K** *Recommended Criteria for Various Water Chemistry Conditions*) to find the numeric aluminum acute and chronic criteria corresponding to the pH, total hardness and DOC conditions of interest, or 2) use the Aluminum Criteria Calculator V.2.0 (*Aluminum Criteria Calculator V.2.0.xlsm*) to enter the pH, total hardness and DOC conditions of interest.

For the purposes of illustration, the following criteria magnitude values are provided at pH 7, total hardness 100 mg/L and DOC of 1.0 mg/L. The resulting numeric values represent the concentrations at which freshwater aquatic organisms would have an appropriate level of protection if the one-hour average concentration of total aluminum does not exceed (in µg/L):

<u>Criterion Maximum Concentration</u> (CMC) =
980 µg/L total aluminum at a pH 7, total hardness of 100 mg/L as $CaCO_3$ and DOC of 1.0 mg/L;

and if the four-day average concentration of total aluminum does not exceed (in µg/L):

<u>Criterion Continuous Concentration</u> (CCC) =
380 µg/L total aluminum at pH 7, total hardness of 100 mg/L as $CaCO_3$ and DOC of 1.0 mg/L.

The criteria value for the specific water chemistry conditions of interest are recommended not to be exceeded more than once every three years on average.

The above illustrative criteria values would vary under other water chemistry conditions for the three water quality parameters (pH, total hardness and DOC) that affect the expression of aluminum toxicity (see **Appendix K** *Recommended Criteria for Various Water Chemistry Conditions*). **Table 7** provides a detailed break-down of the freshwater acute (CMC) and chronic

(CCC) criteria across different pH and total hardness levels when the DOC = 1.0 mg/L. **Appendix K** provides additional criteria values across pH and total hardness levels when DOC = 0.1, 0.5, 2.5, 5, 10 and 12 mg/L, and provides the four most sensitive genera for both the acute and chronic criteria. The empirical toxicity test data that the EPA used to develop the MLR models were developed under a specific range of water chemistry conditions as described below.

The pH of toxicity test waters ranged from 6.0-8.7. Specifically, *Ceriodaphnia dubia* toxicity test data ranged 6.3-8.7 for pH (only one *C. dubia* toxicity test was conducted at pH 8.7; the majority of tests were conducted at pH less than 8.3); *Pimephales promelas* toxicity test data ranged 6.0-8.12 for pH. The EPA has determined that for pH it is reasonable to allow the user to extrapolate beyond these values for criteria derivations. The criteria calculator can be used to address all waters within a pH range of 5.0 to 10.5. Thus, criteria values for pH input values beyond the range of the underlying empirical pH data used for model development (pH 6.0 to 8.2) can be generated using the criteria calculator. This is also reflected in the criteria lookup tables in **Appendix K**. The EPA took this approach for pH so that the recommended criteria can be provided for, and thus are protective of, a broader range of U.S. natural waters. Extrapolated criteria values outside of the empirical pH data tend to be more protective of the aquatic environment (i.e., lower criteria values) in situations where pH plays a critical role in aluminum toxicity. However, criteria values generated outside of the range of the pH conditions of the toxicity tests underlying the MLR models are more uncertain than values within the pH conditions of the MLR toxicity tests, and thus should be considered carefully and used with caution. Although the EPA has provided model predictions of criteria values outside the empirical range for pH, these values may warrant further exploration and consideration for site-specific criteria. Additional information regarding the uncertainty associated with the MLR models is provided in **Section 5.3.6** and **Appendix L**.

The total hardness of toxicity test waters ranged from 9.8 to 428 mg/L. More specifically, total hardness (as $CaCO_3$) ranged from 9.8-428 mg/L for *Ceriodaphnia dubia* toxicity tests and from 10.2-422 mg/L for *Pimephales promelas* toxicity tests. Since a decrease in total hardness tends to increase aluminum toxicity, the EPA has determined it is reasonable to extrapolate on the lower bound of the hardness data to enable generation of more stringent criteria at low hardnesses beyond the limit of the empirical data. Thus, hardness input values in the criteria calculator can be entered that are less than 9.8 mg/L down to a limit of 0.01 mg/L. This is consistent with existing EPA approaches to low end hardness (U.S. EPA 2002). However, criteria values are bounded at the approximate upper limit of the empirical MLR models' underlying hardness data, at a maximum of 430 mg/L total hardness (as $CaCO_3$). The user can input hardness values into the criteria calculator that are greater than 430 mg/L for total hardness, but the criteria magnitude will reach its maximum value at 430 mg/L total hardness (as $CaCO_3$), and criteria magnitudes will not increase or decrease by increasing the hardness above 430 mg/L total hardness (as $CaCO_3$). This is also consistent with existing EPA guidance on high end hardness "caps" (U.S. EPA 2002). These total hardness bound approaches are also reflected in the criteria lookup tables in **Appendix K**. The EPA took this approach so that the recommended criteria can be provided for, and will be protective of, a broader range of natural waters found in the U.S. Criteria values generated beyond the lower bound of the hardness conditions of the toxicity tests underlying the MLR models are more uncertain than values within the hardness bounds of the MLR toxicity test data.

The DOC of toxicity test waters ranged from 0.08 to 12.3 mg/L. More specifically DOC ranged from 0.1-12.3 mg/L for *Ceriodaphnia dubia* toxicity tests and 0.08-11.6 mg/L for *Pimephales promelas* toxicity tests. Since most natural waters contain some DOC, the lower bound of the empirical toxicity test data (0.08 mg/L) is the lowest value that can be entered into the criteria calculator; thus no extrapolation below the lowest empirical DOC of 0.08 mg/L is provided. The criteria values generated with the criteria calculator are bounded at the upper limit of the empirical MLR models' underlying DOC data, at a maximum 12.0 mg/L DOC. The user can input DOC values greater than 12.0 mg/L into the calculator, but the criteria magnitude will reach its maximum value at 12.0 mg/L DOC, and criteria magnitudes will not increase or decrease by increasing the DOC above 12.0 mg/L. This is also reflected in the criteria lookup tables in **Appendix K**. This is consistent with the existing approach for hardness (U.S. EPA 2002) to provide for protection of aquatic organisms through the use of protective, conservative values when water chemistry conditions are beyond the upper limits of the empirical toxicity test data.

The EPA created the Aluminum Criteria Calculator V.2.0 (*Aluminum Criteria Calculator V.2.0.xlsm*) that allows users to enter the pH, total hardness and DOC based on water sampling and automatically calculates freshwater criteria for these site-specific parameters based on the bounds described above. Existing data on these water chemistry parameters may be helpful in determining criteria calculator input values. The criteria calculator gives a warning when any of the water quality parameters entered are “outside MLR model inputs,” to alert end users. As noted above, total hardness and DOC concentrations entered into the calculator that are greater than the bounds recommended will automatically default to a maximum limit; pH values that are outside the bounds recommended (i.e., pH<6, pH>8.2) can be used, but should be considered carefully and used with caution. As displayed in **Table 7** and **Appendix K**, total hardness and DOC are bounded at a maximum of 430 mg/L as $CaCO_3$ and 12.0 mg/L, respectively. **Table 7** shows example freshwater acute (CMC) and chronic (CCC) criteria at DOC of 1.0 mg/L and various water total hardness levels and pH, with additional tables for other DOC values are provided in **Appendix K**.

Table 7. Freshwater Acute and Chronic Criteria at Example Conditions of DOC of 1.0 mg/L and Various Water Total Hardness Levels and pH.
(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Total Hardness	Acute Criteria (µg/L total aluminum)												
	pH												
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.2	8.5	9.0	9.5	10.0	10.5
10	*4.0*	*19*	70	190	430	810	1,200	1,200	*1,300*	*1,100*	*720*	*370*	*150*
25	*9.5*	*40*	130	310	620	1,100	1,400	1,500	*1,400*	*1,100*	*660*	*310*	*110*
50	*18*	*72*	210	430	790	1,300	1,700	1,700	*1,600*	*1,100*	*610*	*270*	*90*
75	*27*	*100*	260	520	900	1,400	1,800	1,800	*1,700*	*1,100*	*590*	*240*	*79*
100	*35*	*130*	320	590	980	1,500	1,900	1,900	*1,700*	*1,100*	*570*	*230*	*72*
150	*51*	*170*	400	700	1,100	1,600	2,100	2,100	*1,800*	*1,100*	*550*	*210*	*63*
200	*67*	*220*	470	790	1,200	1,700	2,200	2,200	*1,900*	*1,100*	*540*	*200*	*57*
250	*82*	*260*	540	870	1,300	1,800	2,200	2,200	*1,900*	*1,100*	*530*	*190*	*53*
300	*98*	*300*	600	950	1,400	1,900	2,300	2,300	*2,000*	*1,100*	*520*	*180*	*50*
350	*110*	*340*	650	1,000	1,500	1,900	2,300	2,300	*2,000*	*1,200*	*510*	*180*	*48*
400	*130*	*380*	700	1,100	1,600	2,000	2,400	2,400	*2,100*	*1,200*	*500*	*170*	*46*
430	*140*	*400*	730	1,100	1,600	2,000	2,400	2,400	*2,100*	*1,200*	*500*	*170*	*45*

Total Hardness	Chronic Criteria (µg/L total aluminum)												
	pH												
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.2	8.5	9.0	9.5	10.0	10.5
10	*2.5*	*12*	47	110	240	500	730	770	*790*	*670*	*450*	*230*	*95*
25	*5.9*	*25*	81	160	300	580	970	930	*890*	*680*	*410*	*190*	*71*
50	*11*	*46*	110	200	340	620	1,100	1,100	*980*	*690*	*380*	*170*	*56*
75	*17*	*66*	140	220	360	640	1,100	1,200	*1,000*	*700*	*370*	*150*	*49*
100	*22*	*85*	160	240	380	650	1,100	1,300	*1,100*	*700*	*360*	*140*	*45*
150	*32*	*120*	190	260	400	660	1,100	1,300	*1,100*	*710*	*350*	*130*	*39*
200	*42*	*140*	210	290	420	670	1,100	1,300	*1,200*	*710*	*340*	*120*	*36*
250	*51*	*160*	230	300	430	670	1,100	1,300	*1,300*	*720*	*330*	*120*	*33*
300	*61*	*180*	250	320	440	680	1,100	1,300	*1,300*	*720*	*320*	*110*	*31*
350	*71*	*200*	260	330	450	680	1,100	1,300	*1,400*	*720*	*320*	*110*	*30*
400	*80*	*220*	280	340	470	680	1,100	1,300	*1,400*	*720*	*310*	*110*	*29*
430	*86*	*230*	290	350	470	680	1,100	1,300	*1,400*	*720*	*310*	*110*	*28*

4.2 Estuarine/Marine

Insufficient data are available to fulfill the MDRs for estuarine/marine criteria development, therefore no criteria are recommended at this time.

5 EFFECTS CHARACTERIZATION

This section characterizes the potential effects of aluminum on aquatic life based on available test data and describes additional lines of evidence not used directly in the criteria calculations, but which support the 2018 criteria values. This section also provides a summary of the uncertainties and assumptions associated with the criteria derivation and explanations for the decisions the EPA made regarding data acceptability and usage in the effects assessment. Finally, this section describes substantive differences between the 1988 aluminum AWQC and the 2018 update.

5.1 Effects on Aquatic Animals

5.1.1 *Freshwater Acute Toxicity*

The EPA identifies several acute studies that did not meet data quality screening guidelines for inclusion in criterion calculations (**Appendix H** *Other Data on Effects of Aluminum to Freshwater Aquatic Organisms*), but showed similar ranges of toxicity and are presented here to provide additional supporting evidence of the observed toxicity of aluminum to aquatic organisms.

Among Mollusca studies where the pH was greater than or equal to 5, Harry and Aldrich (1963) observed adverse 24-hr effects to the snail *Taphius glabratus* exposed to aluminum at concentrations between 1,000-5,000 µg/L in distilled water (**Appendix J** *List of Aluminum Studies Not Used in Document Along with Reasons*). In contrast, the 24-hr LC_{50} of 130,500 µg/L (65,415 µg/L when normalized to conditions in **Appendix A**) for the zebra mussel *Dreissena polymorpha* (Mackie and Kilgour 1995) was insensitive, similar to the mollusk *Physa sp.* (**Appendix A**). In a series of 96-hr tests conducted at low pH and total hardness (15.3 mg/L as $CaCO_3$) levels, Mackie (1989) found that *Pisidium casertanum* and *Pisidium compressum* did not reach 50% mortality at 1,000 µg/L when pH was 3.5, and 400 µg/L when pH was 4.0 and 4.5; the highest concentrations tested. When these concentrations are normalized to the conditions in **Appendix A**, LC_{50}s for the species would be greater than 412,645 to greater than 72,075,634 µg/L.

Among cladocerans, Call et al. (1984) observed an unidentified *Ceriodaphnia* species to be similarly acutely sensitive to identified *Ceriodaphnia* species in acceptable tests, with pH/total hardness/DOC-normalized 48-hr LC_{50} values of 2,277 µg/L and 3,083 µg/L. Also similar to results observed among acceptable tests and supporting studies, *Daphnia sp.* was more acutely sensitive than *Ceriodaphnia sp.* For example, Havas and Likens (1985b) observed reduced survival in *Daphnia catawba* for a test with a non-standard test duration (72 hours) at a pH/total hardness/DOC-normalized concentration of 4,341 µg/L; Khangarot and Ray (1989) observed a normalized 48-hr LC_{50} of 23,665 µg/L for *Daphnia magna* exposed to an unacceptable form of aluminum (aluminum ammonium sulfate); and Havas (1985) observed a normalized 48-hr LOEC based on survival of 1,343 µg/L in *Daphnia magna* using lake water as dilution water.

Although no data from benthic crustaceans were used to calculate the freshwater acute criterion (not one of the four most sensitive genera), evidence suggests they are somewhat acutely sensitive to aluminum. The isopod *Asellus aquaticus* was found to be somewhat sensitive to aluminum, with a pH/total hardness/DOC-normalized 72-hr LC_{50} of 12,284 µg/L that was not included because of the test duration (Martin and Holdich 1986). The isopod values would fall 8th out of 20 in relative acute sensitivity to aluminum, despite the decreased length of the acute test over standard acute invertebrate test durations. Both Borgmann et al. (2005) and Mackie (1989) conducted acute toxicity tests with the amphipod *Hyalella azteca*. Seven-day LC_{50}s from the two Borgmann et al. (2005) studies comparing soft reconstituted water and dechlorinated tap water were 212.7 and greater than 2,978 µg/L, respectively (values normalized to **Appendix A** conditions), but these data were not included because of both test length and unacceptable control mortality. Three (pH/total hardness/DOC) adjusted unbounded *H. azteca* LC_{50} values reported by Mackie (1989) ranged from greater than 4,455 to greater than 178,365 µg/L, the highest concentrations tested. The lowest of these values would rank this taxon 4th in the acute genus sensitivity. These data were included in **Appendix H** because of uncertainty regarding whether bromide and chloride concentrations in dilution water met the recently established testing requirements for *H. azteca* (Mount and Hockett 2015; U.S. EPA 2012). The author was not able to provide details regarding bromide and chloride water concentrations, but noted that there was 100% survival in the experiment, suggesting that conditions were met (Gerry Mackie, personal communication, March 2013). In addition, no substrate was provided for the test organisms. Although some substrate is recommended for water only tests with *H. azteca*, the absence of substrate does not invalidate a test result (Mount and Hockett 2015; U.S. EPA 2012). Because the value is unbounded (i.e., a greater than value), the study most likely overestimates the toxicity of aluminum to this species, since the test failed to reach 50% mortality at the highest concentrations tested.

Studies by Vuori (1996) (caddisfly), Mackie (1989) (damselfly) and Rockwood et al. (1990) (dragonfly) suggest some insects may be acutely sensitive to aluminum, but these tests were either conducted at pH<5 (Mackie 1989), or used an atypical endpoint for acute exposures (Rockwood et al. 1990; Vuori 1996). However, when the concentrations are normalized to the conditions in **Appendix A**, LC_{50}s for the damselfly would be greater than 412,645 to greater than 72,075,634 µg/L. (Note: Rockwood et al. and Vuori did not report test hardness so values could not be normalized).

Consistent with data used to calculate the freshwater acute criterion, vertebrates were no more or less sensitive overall to aluminum than invertebrates. Also consistent with vertebrate data from **Appendix H**, acute toxicity data for fish, while variable, provide additional evidence that freshwater fish are acutely sensitive to aluminum. DeLonay et al. (1993) observed reduced 7-day survival of *Oncorhynchus aguabonita* alevin and swim-up larvae exposed to 18,359 µg/L aluminum (pH/total hardness/DOC-normalized). Cutthroat trout (*O. clarkii*) alevin and swim-up larvae also exposed at pH 5 for seven days exhibited reduced survival at 482.0 µg/L (60% reduction) and 340.8 µg/L (~50% reduction) (pH/total hardness/DOC-normalized), respectively (Woodward et al. 1989). Both studies were excluded from acute criteria calculations because of the atypical acute test duration.

In two studies examining the effects of aluminum on rainbow trout survival, pH/total hardness/DOC-normalized *O. mykiss* LC_{50}s after 6 and 7-12 days, respectively, were 2,837 and 460.0 µg/L (Birge et al. 2000; Orr et al. 1986). In two tests with embryo/larva rainbow trout at pH 6.5 and 7.2, Holtze (1983) observed no reduction in survival after an 8-day exposure to 2,544 and 1,023 µg/L aluminum, respectively, when normalized. While these studies demonstrated the sensitivity of rainbow trout survival to aluminum, they were excluded from acute criteria calculations because of atypical acute test durations. In contrast, Hunter et al. (1980) observed 40% mortality at pH/total hardness/DOC-normalized concentration of 18,009 µg/L for rainbow trout, suggesting that rainbow trout could possibly be more tolerant to aluminum than reported by the previous studies. However, this study had only one treatment concentration, did not provide information regarding replicates or the number of fish per replicate, and the fish were fed during the study, precluding it from consideration as a reliable toxicity prediction and for criteria derivation.

Unlike the observed results of the acceptable acute studies, other data for the Family Salmonidae appears to be acutely insensitive to aluminum. In a series of eight 4- and 5-day tests with juvenile Atlantic salmon (*Salmo salar)* conducted at pH 4.42-5.26, Roy and Campbell (1995, 1997) observed pH/total hardness/DOC-normalized LC_{50}s ranging from 2,170-47,329 µg/L. Similarly, Wilkinson et al. (1990) observed a 7-day LC_{50} at pH 4.5 of 88 µg/L (or 13,060 µg/L when normalized to **Appendix A** conditions) for juvenile Atlantic salmon. These studies were not included in the acute criteria calculations because of either a non-standard duration, exposure at pH<5, or both.

Among warm water fishes, goldfish embryos (*Carassius auratus*) were highly sensitive to aluminum, with a 7- to 12-day pH/total hardness/DOC-normalized LC_{50} of 271.1 µg/L (Birge et al. 2000). While this value is below the acute criterion at the same normalized conditions (980 µg/L), the study provided little exposure details and exceeded the duration for an acceptable acute exposure toxicity test, therefore, it is likely overestimating the acute toxicity of aluminum to the species. Fathead minnow (*Pimephales promelas*) sensitivity, however, was variable across studies. In two tests that were excluded because test fish were fed, pH/total hardness/DOC-normalized 96-hr and 8-day LC_{50}s were 19,324 and 12,702 µg/L, respectively (Kimball 1978). In a 96-hour test that was excluded because measured total dissolved aluminum concentrations were greater than reported nominal total aluminum concentrations for all but the highest two treatment concentrations, suggesting total aluminum exposures were greater than reported, the pH/total hardness/DOC-normalized 96-hour LC_{50} was greater than 572.8 µg/L (Palmer et al. 1989). In contrast, Buhl (2002) observed a pH/total hardness/DOC-normalized 96-hr EC_{50} for death and immobility of greater than 21,779 µg/L for this species. Birge et al. (1978) and Birge et al. (2000) found largemouth bass (*Micropterus salmoides*) to be sensitive to aluminum, with 8-day and 7- to 12-day pH/total hardness/DOC-normalized LC_{50}s of 124.6 and 156.1 µg/L, respectively. In contrast, Sanborn (1945) observed no mortality in juvenile *M. salmoides* after a 7-day exposure to a pH/total hardness/DOC-normalized concentration of 45,181 µg/L.

Amphibians appear to be less acutely sensitive to aluminum than fish based on the very limited data available, but their sensitivity is highly variable and appears to depend upon life stage, with embryos being more sensitive than tadpoles. In a series of tests with leopard frogs

(*Rana pipiens*) of different tadpole life stages conducted at low (4.2-4.8) pH and low (2.0 mg/L) total hardness, Freda and McDonald (1990) observed pH/total hardness/DOC-normalized 4 to 5-day LC_{50}s ranging from greater than 57,814 to greater than 490,582 µg/L. In two separate studies conducted at pH 4.5 and low total hardness, the pH/total hardness/DOC-normalized 96-hr LC_{50} for American toad (*Bufo americanus*) tadpoles was 358,450 µg/L (Freda et al. 1990); and the pH/total hardness/DOC-normalized 96-hr LC_{50} for the green tree frog (*Hyla cinerea*) was 200,373 µg/L (Jung and Jagoe 1995). In contrast, when *R. pipiens* embryos were exposed to aluminum for 10-11 days at a higher pH range (7.0-7.8), Birge et al. (2000) observed a normalized LC_{50} of 73.94 µg/L. Birge et al. (2000) also found embryonic spring peepers (*Pseudacris crucifer*) and embryonic Fowler's toads (*Bufo fowleri*) to be highly sensitive to aluminum, with a 7-day normalized LC_{50} of 73.94 and 230.0 µg/L, respectively. These values exceed the typical duration for an acute exposure for the species and therefore overestimate the toxicity of aluminum when comparing them to the acute criterion. However, aluminum sensitivity among amphibian embryos was not always greater than tadpole life stages, as the pH/total hardness/DOC-normalized 96-hr LC_{50} for *R. pipiens* embryos at pH 4.8 was 74,782 µg/L (Freda et al. 1990), similar to the LC_{50}s of *R. pipiens* tadpoles (Freda and McDonald 1990).

5.1.2 Freshwater Chronic Toxicity

Several chronic studies were identified as not meeting quality screening guidelines for inclusion in criterion calculations (**Appendix H** *Other Data on Effects of Aluminum to Freshwater Aquatic Organisms*), but showed similar ranges of toxicity and are presented here to provide additional supporting evidence of the potential toxicity of aluminum to aquatic organisms.

In two unmeasured lifecycle (3-brood) tests, IC_{25}s based on reproduction for *Ceriodaphnia dubia* were 566 and 641 µg/L (pH not reported so values could not be normalized), were within the range of observed acceptable chronic values for this species (Zuiderveen and Birge 1997). In three unmeasured 21-day *Daphnia magna* tests, LC_{50} and reproductive EC_{16} and EC_{50} pH/total hardness/DOC-normalized endpoints were 1,162, 265.6 and 564.3 µg/L, respectively (Biesinger and Christensen 1972). These values are within the range of acceptable chronic data reported for the cladoceran *C. dubia* (**Appendix C**).

Among fish species, the pH/total hardness/DOC-normalized 28-day EC_{50} (death and deformity) for *O. mykiss* of 457.4 µg/L (Birge 1978; Birge et al. 1978) was similar to chronic values for acceptable tests with other cold water test species. In addition, the 16-day normalized LC_{50}s for rainbow trout at two different test total hardness levels (20.3 and 103 mg/L as $CaCO_3$) observed by Gundersen et al. (1994) were 485.2 and 1,084 µg/L, respectively. However, the 16-day exposures were about one-fourth the duration of an acceptable ELS test for a salmonid (ASTM 2013). In a 28-day test of *S. fontinalis* conducted at pH 4.4, the pH/total hardness/DOC-normalized MATC for survival was 2,523 µg/L (Ingersoll et al. 1990a). Even though the duration of this test was insufficient and the pH was below 5, it provides additional evidence of the sensitivity of brook trout, a commercially and recreationally important species. Several short-term (7-day) chronic tests conducted by Oregon State University (OSU 2012a) with the fathead minnow at pH 6 and across a range of total hardness and DOC concentrations revealed that both an increase in total hardness and DOC reduced the toxicity of aluminum (non-normalized EC_{20}s ranged from 127.2 to 2,938 µg/L or 1,718 to 7,220 µg/L when normalized to the test conditions in **Appendix C**).

5.1.3 Freshwater Field Studies

Field studies have been conducted to measure effects of aluminum additions to control phosphorus concentrations in lakes, to validate parallel laboratory exposures, and to investigate the effects of acid deposition in aquatic systems. Aluminum sulfate was continuously added for 35 days to the Cuyahoga River 500 meters upstream of Lake Rockwell to control phosphorus concentrations in the reservoir. Artificial colonization substrata were placed at five locations along the treatment reach five weeks before the release, sampled on the day of the release, redeployed after collecting invertebrates immediately before the release, and then sampled weekly throughout the 35-day aluminum addition. After one week of treatment, invertebrate densities declined throughout the study reach, and were completely absent from a site 60 meters downstream of the release point. Once treatment was stopped, invertebrate densities recovered and replaced after approximately three weeks by rapidly colonizing oligochaete taxa (Barbiero et al. 1988).

In Little Rock Lake, WI, sulfuric acid was added to half of the lake between 1984-1990, resulting in a decrease in pH from 6.05 to 4.75 and an increase in aqueous aluminum from 7 to 42 µg/L. The other half of the lake served as a control, where aluminum increased from 7 to 14 µg/L and pH decreased from 6.04 to 5.99 during the same time period (Eaton et al. 1992). In parallel laboratory experiments in 1988, eggs of several fish species were exposed to aluminum concentrations ranging from 8.1-86.9 µg/L and pH values ranging from 4.5-5.5 until seven days' post hatch. In both the acidified portion of the lake and in laboratory exposures at comparable aluminum and pH levels, mortality was higher than in controls (Eaton et al. 1992). However, mortality of control fish in both the *in-situ* and laboratory exposures exceeded the minimum 80 percent survival acceptable guideline for tests of this duration.

Additional field studies have evaluated the effects of aluminum and acidification on different trophic level communities. Havens and Decosta (1987) acidified the circumneutral Lake O'Woods (WV) to pH 4.8 and compared phytoplankton and zooplankton assemblages with and without the addition of 300 µg/L aluminum. They observed similar species in all conditions, but the aluminum dosed water exhibited a decrease in chlorophyll *a* concentrations and a drop in zooplankton abundances over the 49-day observation period, while the acidified condition without aluminum addition only exhibited a drop in chlorophyll *a*. The algal biomass decrease was attributed to the initial co-precipitation of phosphorus and/or algal cells with the aluminum hydroxide at circumneutral pH. Bukaveckas (1989) reported similar declines in algal biomass when acidic, aluminum-rich waters are neutralized with lime. In contrast, aluminum addition produced a more pronounced difference in algal community structure and succession when Havens and Heath (1990) gradually acidified (pH 4.5) and dosed East Twin Lake (OH) with 200 µg/L aluminum.

Increased drift of invertebrates (Ephemeroptera, Diptera and Orthocladiinae chironomids) in an acidified (pH~5) stream dosed with 280 µg/L aluminum was observed relative to a non-dosed stream at the same ~5 pH level (Hall et al. 1987). Ormerod et al. (1987), however, found little added effect of 350 µg/L aluminum on stream invertebrates compared with the effects of acidification alone (pH~4.3). In contrast, brown trout and Atlantic salmon showed significantly increased mortalities in the acidified aluminum condition (50 to 87%) relative to the acid-only treatment (7 to 10%). Baldigo and Murdoch (1997) deployed caged brook trout in selected New York Catskill Mountain streams where the pH, aluminum concentration and other stream conditions fluctuated naturally over time. They noted that fish mortality correlated best with high inorganic aluminum concentrations and low water pH (4.4-5.2), with 20 percent mortality observed for brook trout exposed to greater than or equal to 225 µg/L inorganic monomeric aluminum for two days. They also observed, based on regression analysis, that a vast majority (74-99%) of the variability in mortality could be explained by either the mean or median inorganic monomeric aluminum concentration, and that the mortality was highly related to inorganic monomeric aluminum, pH, dissolved organic carbon, calcium and chloride concentrations. Bulger et al. (1993) also reported that water pH and monomeric inorganic aluminum concentrations best predicted brown trout populations of 584 Norwegian lakes. Lakes with 133 µg/L aluminum and a pH of 4.8 were devoid of brown trout (39% of the 584 lakes), whereas lakes with 11 µg/L aluminum and a pH of 6.0 had healthy brown trout populations.

5.1.4 Estuarine/Marine Acute Toxicity

SMAVs for five genera representing five species of estuarine/marine organisms were calculated for aluminum (**Table 8**). SMAVs and GMAVs were equal since there is only one species present per genus. The most sensitive genus was the polychaete worm (*Ctenodrilus serratus*), with a SMAV of 97.15 µg/L, followed by two other polychaete worms (*Capitella capitata* and *Neanthes arenaceodentata*) with SMAVs of 404.8 and greater than 404.8 µg/L, respectively. The most tolerant genus was a copepod (*Nitokra spinipes*) with a SMAV of 10,000 µg/L (**Figure 9**). However, the freshwater acute criterion (980 µg/L total aluminum) is much higher than the most sensitive acute estuarine/marine species LC_{50} (97.15 µg/L total aluminum). Thus, at least some invertebrate estuarine/marine species would not be protected if the freshwater acute aluminum criterion was applied in those systems.

Table 8. Ranked Estuarine/Marine Genus Mean Acute Values.

Rank[a]	**GMAV (µg/L total Al)**	**Species**	**SMAV (µg/L total Al)**[b]
5	10,000	Copepod, *Nitokra spinipes*	10,000
4	>1,518	American oyster, *Crassostrea virginica*	>1,518
3	>404.8	Polychaete worm, *Neanthes arenaceodentata*	>404.8
2	404.8	Polychaete worm, *Capitella capitata*	404.8
1	97.15	Polychaete worm, *Ctenodrilus serratus*	97.15

[a] Ranked from the most resistant to the most sensitive based on Genus Mean Acute Value.
[b] From Appendix B: Acceptable Acute Toxicity Data of Aluminum to Estuarine/Marine Aquatic Animals.

In contrast to freshwater, only a few acute studies were identified as not meeting screening guidelines for inclusion in criterion calculations (**Appendix I** *Other Data on Effects of Aluminum to Estuarine/Marine Aquatic Organisms*), but showed similar ranges of toxicity. As with other non-conforming studies previously described, the results are presented here to provide additional supporting evidence of the potential toxicity of aluminum to estuarine/marine organisms. In one of these studies, a cohort of sea urchin embryos (*Paracentrotus lividus*) exposed to 539.6 µg/L aluminum for 72-hr exhibited increased developmental defects by 69.7% (Caplat et al. 2010). Although this study was not considered acceptable because the control group exhibited 19.3% defects indicative of some health deficiency, the effect level was comparable to the acute effect levels observed in **Appendix B**. In 24-hr exposures to aluminum added as potassium aluminum sulfate, LC_{50}s for the crab species *Eupagurus bernhardus* and *Carcinus maenas*, the snail *Littorina littorea*, and the mussel *Mytilus edulis* were extremely high, ranging from a low of 250,000 µg/L for *E. bernhardus* to greater than 6,400,000 µg/L for the two mollusk species (Robinson and Perkins 1977). Although these studies were unacceptable because of the atypical acute test duration, they suggest that some saltwater taxa are highly tolerant to acute aluminum exposure.

5.1.5 Estuarine/Marine Chronic Toxicity

There are no acceptable saltwater chronic data available for aluminum (**Appendix D**). However, the EPA identified several chronic studies that did not meet screening guidelines for inclusion in criterion calculations, but provided supporting evidence of potential chronic toxicity of aluminum to aquatic organisms in estuarine/marine environments (**Appendix I** *Other Data on Effects of Aluminum to Estuarine/Marine Aquatic Organisms*). Petrich and Reish (1979) observed a 21-day MATC for reproduction in the polychaete *C. serratus* of 28.28 µg/L. Consistent with acceptable acute test results for this species, this chronic test suggests that polychaetes may be chronically sensitive to aluminum. This study was excluded because of the test duration. In a “semi-chronic” 12-day study of the effects of aluminum on daggerblade grass shrimp (*Palaemonetes pugio*) embryos, the LC_{50} was 1,079 µg/L (Rayburn and Aladdin 2003). This study was not included because it was longer than an acceptable 48-hr acute test, and it was not a full life cycle test.

5.1.6 Bioaccumulation

Three acceptable studies examined the effects of waterborne aluminum bioaccumulation in aquatic organisms (**Appendix G** *Acceptable Bioaccumulation Data of Aluminum by Aquatic Organisms*). Cleveland et al. (1991a) exposed 30-day old brook trout to 200 µg/L of aluminum in test waters at three pH levels (5.3, 6.1, and 7.2) for 56 days. After 56 days, trout were transferred to water of the same pH with no aluminum amendments and held for 28 days. Fish were sampled for whole body aluminum on days 3, 7, 14, 28 and 56 of the exposure; and on days 3, 7, 14 and 28 of the depuration period. The estimated time to achieve steady state whole body aluminum concentrations was 1.5 days at pH 5.3, 4.2 days at pH 6.1, and 1.7 days at pH 7.2. Bioconcentration factors (BCF) were inversely related to pH: 142 at pH 5.3, 104 at pH 6.1, and 14.2 at pH 7.2. Mortality was also highest at pH 5.3 and lowest at pH 7.2. In a separate study, Buckler et al. (1995) continuously exposed Atlantic salmon beginning as eyed eggs to four aluminum treatment levels (33, 71, 124, 264 µg/L) at pH 5.5 for 60 days after the median hatch date. Fish were sampled for whole body aluminum after 15, 30, 45, and 60 days post median hatch. After 60 days, average mortality was 15% in the 124 µg/L treatment and 63% in the 264 µg/L treatment. The mortality NOEC and LOEC were 71 and 124 µg/L, respectively. BCFs were directly related to exposure concentration, and were 76, 154, and 190 at treatment levels 33, 71, and 124 µg/L, respectively. A BCF could not be calculated for the 264 µg/L treatment level because there were insufficient surviving fish to analyze. Snails, *Lymnaea stagnalis,* held in neutral pH for 30 days and 242 µg/L total aluminum reached steady with a reported BCF of 4.26 in the digestive gland (Dobranskyte et al. 2004).

As reported in the literature, aquatic organisms can accumulate metals from both aqueous and dietary exposure routes. The relative importance of each, however, is dependent upon the chemical. Aluminum adsorbs rapidly to gill surface from the surrounding water, but cellular uptake from the water is slow, with gradual accumulation by the internal organs over time (Dussault et al. 2001). Bioaccumulation and toxicity via the diet are considered highly unlikely based on studies by Handy (1993) and Poston (1991), and also supported by the lack of any biomagnification within freshwater invertebrates that are likely to be prey of fish in acidic, aluminum-rich rivers (Herrmann and Frick 1995; Otto and Svensson 1983; Wren and Stephenson 1991). The opposite phenomena, trophic dilution up the food chain, has been suggested based on the lowest aluminum accumulation exhibited by fish predators (perch) and highest by the phytoplankton that their zooplankton prey were consuming (King et al. 1992). Thus, the low aluminum BCFs reported in the literature are supported by the slow waterborne uptake and the lack of dietary accumulation.

5.2 Effects on Aquatic Plants

Aquatic plant data are not used to derive the criteria for aluminum. However, a summary of available data is presented below. For freshwater algae, aluminum effect concentrations ranged from 50 µg/L to 6,477 µg/L, with most effect levels below 1,000 µg/L (**Appendix E** *Acceptable Toxicity Data of Aluminum to Freshwater Aquatic Plants*). Studies for freshwater macrophytes are limited, but available data suggest freshwater macrophytes are more tolerant to aluminum than freshwater algae. The effect concentration for Eurasian watermilfoil is 2,500 µg/L based on root weight (Stanley 1974), which is near the upper range of freshwater algae sensitivities. Several 3-day tests with the green alga *Pseudokirchneriella subcapitata* at pH 6, 7 and 8 across a range of total hardness and DOC concentrations revealed that both an increase in pH, total hardness and DOC reduced the toxicity of aluminum (European Aluminum Association 2009). DeForest et al. (2018a) used these 27 toxicity tests (as summarized in Gensemer et al. 2018) to develop a MLR model to explain the effects of water chemistry on algal toxicity. The MLR model developed was:

$$P.\,subcapitata\ EC_{20} = e^{\left[-61.952+[1.678\times\ln(DOC)]+[4.007\times\ln(hard)]+(17.019\times pH)-(1.020\times pH^{2})-[0.204\times pH{:}\ln(DOC)]-[0.556\times pH{:}\ln(hard)]\right]}$$

The MLR model for *P. subcapitata* was within a factor of two for 100% of the predicted versus observed values (DeForest et al. 2018a). Most of the acceptable toxicity data for freshwater aquatic plants (**Appendix E**) did not report all three water quality parameters (i.e., pH, total hardness and DOC) preventing the use of applying the alga based MLR equation to the data. The EPA contacted authors and in limited cases, the authors were able to provide rough estimates of some of the missing information. Normalized lowest observed effect concentrations (LOECs) for the twenty-one day tests as reported by Pilsbury and Kingston (1990) were 3,482 µg/L, while normalized 4-day EC_{50}s for *P. subcapitata* were 620 and 1,067 µg/L (Call et al. 1984). These values are above the chronic criterion at the same test conditions, suggesting that the criteria developed using aquatic animals will also be protective of aquatic plants. This was also observed when normalizing the 3-day *P. subcapitata* test in **Appendix H** (*Other Data on Effects of Aluminum to Freshwater Aquatic Organisms*) with normalized effect concentrations ranging from 161 to 5,113 µg/L. The geometric mean of these values was 1,653 µg/L (Note:

these tests were excluded from the acceptable table due to the insufficient test duration, less than 4 days).

In contrast to other freshwater plants, duckweed is highly tolerant to aluminum, with an effect concentration based on reduced growth of greater than 45,700 µg/L (Call et al. 1984). For the one acceptable study of a saltwater plant (Seagrass, *Halophila stipulacea*), less than 50% mortality of teeth cells was observed at 26.98 µg/L, and more than 50% mortality of teeth cells observed at 269.8 µg/L (Malea and Haritonidis 1996). In a shorter duration study, the saltwater algal species, *Dunaliella tertiolecta*, also exhibited sensitivity to aluminum, but the effect concentration was higher at 18,160 µg/L (**Appendix I** *Other Data on Effects of Aluminum to Estuarine/Marine Aquatic Organisms*). Although aquatic plant data are not normalized using the alga based MLR equation, the effect levels observed are similar to the available animal data, and the recommended criteria should therefore be protective for algae and aquatic plants.

5.3 Identification of Data Gaps and Uncertainties for Aquatic Organisms

Data gaps and uncertainty were identified for the aluminum criteria. A number of uncertainties are associated with calculation of the freshwater Final Acute Value (FAV) as recommended by the 1985 Guidelines, and include use of limited data for a species or genus, acceptability of widely variable data for a genus, application of adjustment factors, extrapolation of laboratory data to field situations, and data normalization with a MLR model.

5.3.1 Acute Criteria

There are a number of cases in the acute database where only one acute test is used to determine the Species Mean Acute Value (SMAV) and subsequently the Genus Mean Acute Value (GMAV) is based on the one acute test. In this situation, there is a level of uncertainty associated with the GMAV based on the one test result since it does not incorporate the range of values that would be available if multiple studies were available. Such a GMAV is still valid, however, in spite of the absence of these additional data because it represents the best available data and to exclude this data would create an unnecessary data gap. Additionally, many of the acute studies did not report a definitive LC_{50} (i.e., yielded greater than values) because the highest concentration used did not cause more than 50% mortality. This adds more uncertainty since the true LC_{50} is unknown.

The acute criterion is set as equal to half of the FAV to represent a low level of effect for the fifth percentile genus, rather than a 50% effect. This adjustment factor was derived from an analysis of 219 acute toxicity tests with a variety of chemicals (see 43 FR 21506-21518 for a complete description) where mortality data were used to determine the highest tested concentration that did not cause mortality greater than that observed in the control (or between 0 and 10%). Application of this adjustment factor is justified because that concentration represents minimal acute toxicity to the species.

5.3.2 Chronic Criteria

The freshwater FCV calculation is also influenced by the limited availability of data and the use of qualitative data to fulfill the one remaining family (Chordata) MDR. The aluminum freshwater chronic database is comprised of 12 species and subsequently 12 genera that provide seven of the eight MDR families as recommended in the 1985 Guidelines. In order to satisfy the eight-family requirement, the dataset included a wood frog (*Rana sylvatica*) chronic study that was relegated to **Appendix H** due to minor methodology issues (pH<5). While this study does not quantitatively affect the criterion value, it was used to fulfill the MDRs per the 1985 Guidelines, thereby allowing direct calculation of the FCV (see **Section 2.7.3**). Additional testing of other species and families in the Phylum Chordata would reduce the uncertainty in the FCV.

5.3.3 Laboratory to Field Exposures

Application of water-only laboratory toxicity tests to develop water quality criteria to protect aquatic species is a basic premise of the 1985 Guidelines, supported by the requirements of a diverse assemblage of eight families and the intended protection goal of 95 percent of all genera. Confirmation has been reported by a number of researchers (Clements and Kiffney 1996; Clements et al. 2002; Mebane 2006; Norberg-King and Mount 1986), thereby indicating that on the whole, extrapolation from the laboratory to the field is a scientifically valid and protective approach for aquatic life criteria development.

The unique chemistry of aluminum (speciation changes and the transient precipitates formed during toxicity testing) and difference between geological aluminum materials suspended in natural water are additional areas of uncertainty (Angel et al. 2016; Cardwell et al. 2018; Gensemer et al. 2018). The use of total aluminum concentrations is justified for laboratory toxicity test data (see **Section 2.6.2**); where the total aluminum concentration is in either a dissolved or precipitated form (Santore et al. 2018). However, natural water samples may also contain other species of aluminum that are not biologically available (i.e., suspended particles, clays and aluminosilicate minerals) (Santore et al. 2018; Wilson 2012). This creates uncertainty because the total recoverable aluminum concentrations measured in natural waters may overestimate the potential risks of toxicity to aquatic organisms.

EPA Methods 200.7 and 200.8 are the only currently approved methods for measuring aluminum in natural waters and wastes for NPDES permits (U.S. EPA 1994a,b). Research on new analytical methods is ongoing to address concerns with including aluminum bound to particulate matter (i.e., clay) in the total recoverable aluminum concentrations (OSU 2018c). One approach would not acidify the sample to pH less than 2 but rather to pH 4 (pH 4 extracted method) to better capture the bioavailable fraction of aluminum (CIMM 2016, OSU 2018c). Thus, this draft pH 4 extracted method under development is expected to reduce the uncertainty regarding bioavailable aluminum measurements in the aquatic environment.

5.3.4 Lack of Toxicity Data for Estuarine/Marine Species and Plants

Since limited acceptable acute and chronic data are available for estuarine/marine species, the EPA could not derive estuarine/marine acute and chronic aluminum criteria at this time. In addition, very few acceptable aquatic vascular plant studies are available.

5.3.5 Bioavailability Models

Aluminum toxicity is strongly affected by water chemistry, through its effects on bioavailability. The understanding of the interactions between aluminum species, water characteristics, and aquatic toxicity data has led to the development of several bioavailability models. There are currently two different approaches that take into account aluminum bioavailability in relation to aquatic toxicity that are considered applicable to the development of aquatic life criteria: empirical models that relate toxicity to water chemistry; and Biotic Ligand Models that encompass both abiotic and biotic mechanistic factors determining toxicity.

Initially in considering the array of approaches for criteria development, the EPA considered using an empirical total hardness adjustment equation for criteria development. However, studies that tested aluminum at pH 6 for a variety of organisms (OSU 2012a, 2012b, 2012c, 2012d, 2012e, 2012f, 2012g, 2012h, 2013) indicated additional water chemistry parameters affected bioavailability, and hence aquatic effects of aluminum. In addition, new data are available that supported the development of MLR models that incorporate pH and total hardness. Also, a mechanistic BLM model for aluminum was recently developed (Santore et al. 2018). Finally, an approach described in DeForest et al. (2018a,b) incorporated pH, total hardness and DOC into empirical MLR models to determine if the estimation of aluminum bioavailability to animals in freshwater aquatic systems could be applicable in the development of aluminum water quality criteria. The approach resulted in the creation of multiple MLR models that could be used for the development of aluminum water quality criteria methodologies. Both MLR models and the BLM model include the same toxicity test data, with the BLM including additional data on the accumulation of aluminum on the gills of Atlantic salmon (Santore et al 2018). The MLR approach empirically curve-fits log-log pH, total hardness and DOC relationships (with interaction terms) to the empirical data. The BLM uses a mechanistic model based on an underlying theory of how water chemistry input parameters affect aluminum toxicity, although it still has empirically derived factors.

An external peer review of the different aluminum aquatic life criteria approaches was conducted in November 2016 to provide a comparison of the several available approaches to generating aluminum criteria that reflect water quality condition impacts on toxicity. Approaches compared included a 10-parameter BLM, a simplified-BLM approach (e.g., pH, total hardness, dissolved organic carbon, temperature), and MLR models to facilitate evaluation of the most appropriate approaches to consider for aluminum toxicity modeling. The EPA conducted three additional external peer reviews in 2018 regarding the new toxicity data and re-fitted MLR models on: 1) the new invertebrate toxicity tests on *C. dubia* (OSU 2018a); 2) the new fish toxicity tests on *P. promelas* (OSU 2012b); and 3) the new individual and pooled MLRs developed by Deforest et al. (2018b). Based on external peer review comments, ease of use, and transparency, the EPA applied the DeForest et al. (2018b) individual species MLR model to normalize the freshwater acute and chronic data (**Appendix A** and **Appendix C**) and derived the aluminum criteria using the criteria development approaches described in the 1985 Guidelines. The EPA independently examined and verified the quality and fit of the DeForest et al. (2018a,b) MLR models before applying them in this final criteria document.

5.3.6 pH, Total Hardness and DOC MLR Models

There are additional uncertainties, beyond those described above, associated with the normalization of aluminum toxicity data using the MLR models developed by DeForest et al. (2018b). The models were developed with chronic toxicity data from two animal species, one invertebrate (*C. dubia*; a sensitive species) and one fish (fathead minnow; a moderately sensitive species). Incorporating additional species in the model development would improve the representativeness of all species and further validate the MLR model use across species. Though the pH, total hardness, and DOC do explain the majority of differences seen in the toxicity data between the two species, there are two MLR models developed (invertebrate *C. dubia* model and vertebrate *P. promelas* model), which better delineate the differences in their uptake of aluminum. Because the arthropod phylum is highly diverse, there is some uncertainty in the application of the *C. dubia* model across other invertebrate taxa. However, among fish (and amphibians), the MLR approach that uses a model optimized solely for those taxa is the best model to use as opposed to a BLM which uses one model to normalize the data for multiple taxa for criteria calculations. Thus, the MLR-based criteria derivation specific to the most sensitive taxa may address additional uncertainty because some of the model differences may be a function of the species physiology in addition to bioavailability, and hence the MLR approach may better capture taxa physiologic differences in sensitivity across different water chemistry conditions. The models are, however, applied across gross taxonomy (vertebrate vs. invertebrate), creating some additional uncertainty. Finally, only chronic data were used in model development, and application to acute toxicity data assumes that the same relationships are present. All of these uncertainties associated with the model are areas where additional research would be helpful.

The models were developed using data that encompass a pH range of 6.0-8.7, DOC range of 0.08-12.3 mg/L and total hardness range of 9.8-428 mg/L (as $CaCO_3$). The authors (DeForest et al. 2018a) noted that the empirical data evaluated support a reduced total hardness effect at higher pH levels (i.e., 8-9), but limited data are available. Additional chronic aluminum toxicity testing at higher pH levels would be useful for further validating the MLR models (i.e., there is a limited amount of data at pH>8). When any of the water quality parameters selected is outside model inputs, the Aluminum Criteria Calculator V.2.0 (*Aluminum Criteria Calculator V.2.0.xlsm*) flags these values and defaults to the maximum bounds for DOC and total hardness. Values generated outside the recommended water quality parameter for pH (6.0-8.2) should be treated with caution because extrapolating beyond the conditions used for model development is highly uncertain. Of particular concern is the quadratic term (pH^2) in the *C. dubia* MLR model which can compound issues with extrapolating. Additional toxicity tests conducted and pH<6.0 and pH> 8.5 would further define behavior of this model.

5.4 Protection of Endangered Species

Although the dataset for aluminum is not extensive, it does include some data representing species that are listed as threatened or endangered by the U.S. Fish and Wildlife Service and/or National Oceanic and Atmospheric Administration (NOAA) Fisheries. Summaries are provided here describing the available aluminum toxicity data for listed species indicating that the 2018 aluminum criteria are expected to be protective of these listed species, based on available scientific data.

5.4.1 *Key Acute Toxicity Data for Listed Fish Species*

Tests relating to effects of aluminum on several threatened and endangered freshwater fish species are available (certain populations threatened, and others endangered): rainbow trout, *Oncorhynchus mykiss* with a normalized SMAV of 3,312 µg/L (Call et al. 1984; Gundersen et al. 1994; Holtze 1983); Rio Grande silvery minnow, *Hybognathus amarus* with a normalized SMAV of greater than 21,779 µg/L (Buhl 2002); and Atlantic salmon, *Salmo salar* with a SMAV of 8,642 µg/L (Hamilton and Haines 1995). For this comparison, all SMAVs are normalized to a pH 7, a total hardness of 100 mg/L as $CaCO_3$ and a DOC of 1.0 mg/L. All of the normalized SMAVs are above the recommended acute criterion (CMC) of 980 µg/L at the same pH, total hardness and DOC levels. There are no acceptable acute toxicity data for endangered or threatened estuarine/marine aquatic fish species.

5.4.2 *Key Chronic Toxicity Data for Listed Fish Species*

While there are no acceptable chronic toxicity data for estuarine/marine endangered and/or threatened fish species, there is one acceptable early life-stage test conducted with the endangered freshwater fish, Atlantic salmon, *Salmo salar*. The test, conducted at a pH of 5.7, yielded a pH/total hardness/DOC-normalized species mean chronic value (SMCV) of 434.4 µg/L (McKee et al. 1989). This value is greater than the recommended chronic criterion of 380 µg/L at the same total hardness, DOC and pH.

5.4.3 *Concerns about Federally Listed Endangered Mussels*

Some researchers have expressed concerns that mussels may be more sensitive to the effects of aluminum than other organisms. A study by Kadar et al. (2001) indicated that adult *Anodonta cygnea* mussels may be sensitive to aluminum at concentrations above 250 µg/L, with reductions in mean duration of shell opening of 50% at 500 µg/L aluminum in the water column (at circumneutral pH) when compared to paired controls. This suggests that chronic elevated aluminum concentrations could lead to feeding for shorter durations with potential implications for survival and growth, and possibly even reproduction. Pynnonen (1990) conducted toxicity tests with two freshwater mussels in the Unionidae family (*Anodonta anatina* and *Unio pictorum*). In both species, pH had a significant effect on accumulation of aluminum in the gills. The *Anodonta* mussel species in the two studies described above are not native to the United States and are included in **Appendix J** (*List of Aluminum Studies Not Used in Document Along with Reasons*). While the *Anodonta* mussel species in these two studies are not native, there are species of the *Anodonta* genus present in the United States. Simon (2005) provides an additional line of evidence that indicates mussels may be more sensitive to the effects of aluminum than other organisms. In a 21-day chronic aluminum toxicity test conducted at circumneutral pH with juvenile unionid freshwater mussel *Villosa iris*, growth was significantly reduced at aluminum levels above 337 µg/L.

New data are available for this update on aluminum toxicity to the fatmucket mussel (*Lampsilis siliquoidea*), another freshwater mussel in the family Unionidae. While the 96-hr LC_{50} juvenile test failed to elicit an acute 50% response at the highest concentration tested (6,302 µg/L total aluminum, or 29,492 µg/L when normalized), the 28-day biomass-normalized SMCV ranked as the fourth most sensitive genus in the dataset. The SMCV is greater than the most sensitive species, Atlantic salmon, and the freshwater criterion value. Thus, the chronic criterion is expected to be protective of this and related species. The fatmucket mussel tested is not a threatened and/or endangered species, but the genus *Lampsilis* contains several listed species with a wide distribution across the United States, and is also member of the family Unionidae.

Freshwater mussels in the family Unionidae are known to be sensitive to a number of chemicals, including metals and organic compounds (Wang et al 2018; U.S. EPA 2013). The EPA’s 2013 Aquatic Life Ambient Water Quality Criteria for Ammonia in Freshwater indicates many states in the continental U.S. have freshwater unionid mussel fauna in at least some of their waters (Abell et al. 2000; Williams and Neves 1995; Williams et al. 1993). Roughly one-quarter of the approximately 300 freshwater unionid mussel taxa in the United States are Federally-listed as endangered or threatened species. Additional testing on endangered mussel species, or closely related surrogates, would be useful to further examine the potential risk of aluminum exposures to endangered freshwater mussels.

5.5 Comparison of 1988 and 2018 Criteria Values

The 1988 aluminum freshwater acute criterion was based on data from eight species of invertebrates and seven species of fish grouped into 14 genera. This 2018 update now includes 13 species of invertebrates, eight species of fish, and one frog species for a total of 22 species grouped into 20 genera. The data in the previous AWQC were not normalized to any water chemistry conditions making it difficult to compare the magnitude of the two criteria.

The 1988 aluminum freshwater chronic criterion was set at 87 µg/L across a pH range 6.5 to 9.0, and across all total hardness and DOC ranges, based on a dataset that included two species of invertebrates and one fish species. This 2018 criteria update includes new data for an additional nine species, and consists of eight invertebrates and four fish species grouped into 12 genera and is a function of pH, total hardness and DOC. Addition of the frog (*Rana sylvatica*) data from **Appendix H** satisfied the MDR for the one missing family (Chordata), thereby allowing for direct calculation of the FCV.

Like the previous AWQC for aluminum, there are still insufficient data to fulfill the estuarine/marine MDRs as per the 1985 Guidelines, therefore the EPA did not derive estuarine/marine criteria at this time. New toxicity data for five genera representing five species of estuarine/marine organisms are presented in this update; no data were available in 1988.

Table 9. Comparison of the 2018 Recommended Aluminum Aquatic Life AWQC and the 1988 Criteria.

Version	**Freshwater Acute**[a] (1-hour, total aluminum)	**Freshwater Chronic**[a] (4-day, total aluminum)
2018 AWQC (vary as a function of a site's pH, DOC and total hardness)	1-4,800 µg/L	0.63-3,200 µg/L
1988 AWQC (pH 6.5 – 9.0, across all total hardness and DOC ranges)	750 µg/L	87 µg/L

[a] Values are recommended not to be exceeded more than once every three years on average.

Note: 2018 Criteria values will be different under differing water chemistry conditions as identified in this document, and can be calculated using the Aluminum Criteria Calculator V.2.0 (*Aluminum Criteria Calculator V.2.0.xlsm*) or found in the tables in Appendix K. See Appendix K for specific comparisons of 1988 and 2018 criteria values across water chemistry parameter ranges.

6 UNUSED DATA

For this 2018 criteria update document, the EPA considered and evaluated all available data that could be used to derive the new acute and chronic criteria for aluminum in fresh and estuarine/marine waters. A substantial amount of those data were associated with studies that did not meet the basic QA/QC requirements in a manner consistent with the 1985 Guidelines (see Stephan et al. 1985) and reflecting best professional judgments of toxicological effects. A list of all other studies considered, but removed from consideration for use in deriving the criteria, is provided in **Appendix J** (*List of Aluminum Studies Not Used in Document Along with Reasons*) with rationale indicating the reason(s) for exclusion. Note that unused studies from previous AWQC documents were not re-evaluated.

7 REFERENCES

Aarab, N., D.M. Pampanin, A. Naevdal, K.B. Oysaed, L. Gastaldi and R.K. Bechmann. 2008. Histopathology alterations and histochemistry measurements in mussel, *Mytilus edulis* collected offshore from an aluminium smelter industry (Norway). Mar. Pollut. Bull. 57(6-12): 569-574.

Abdelhamid, A.M. and S.A. El-Ayouty. 1991. Effect on catfish (*Clarias lazera*) composition of ingestion rearing water contaminated with lead or aluminum compounds. Arch. Anim. Nutr. 41(7/8): 757-763.

Abdel-Latif, H.A. 2008. The influence of calcium and sodium on aluminum toxicity in Nile tilapia (*Oreochromis niloticus*). Aust. J. Basic. Appl. Sci. 2(3): 747-751.

Abell, R.A., D.M. Olson, E. Dinerstein, P.T. Hurley, J. Diggs, W. Eichbaum, S. Walters, W. Wettengel, T. Allnutt, C. Loucks and P. Hedao. 2000. Freshwater ecoregions of North America. A conservation assessment. Island Press (WWF), Washington, DC.

Abraham, J.V., R.D. Butler and D.C. Sigee. 1997. Quantified elemental changes in *Aspidisca cicada* and *Vorticella convallaria* after exposure to aluminium, copper, and zinc. Protoplasma 198(3/4): 143-154.

Adokoh, C.K., E.A. Obodai, D.K. Essumang, Y. Serfor-Armah, B.J.B. Nyarko, A. Asabere-Ameyaw and E.A. Obodai. 2011. Statistical evaluation of environmental contamination, distribution and source assessment of heavy metals (aluminum, arsenic, cadmium, and mercury) in some lagoons and an estuary along the Coastal Belt of Ghana. Arch. Environ. Contam. Toxicol. 61(3): 389-400.

Ahsan, N., D.G. Lee, I. Alam, P.J. Kim, J.J. Lee, Y.O. Ahn, S.S. Kwak, I.J. Lee, J.D. Bahk, K.Y. Kang, J. Renaut, S. Komatsu and B.H. Lee. 2008. Comparative proteomic study of arsenic-induced differentially expressed proteins in rice roots reveals glutathione plays a central role during As stress. Proteomics 8: 3561-3576.

Akaike, H. 1974. A new look at the statistical model identification. IEEE Trans. Auto. Cont. 19(6): 716-723.

Al-Aarajy, M.J. and H.A. Al-Saadi. 1998. Effect of heavy metals on physiological and biochemical features of *Anabaena cylindrica*. Dirasat Nat. Eng. Sci. 25(1): 160-166.

Alessa, L. and L. Oliveira. 2001a. Aluminum toxicity studies in *Vaucheria longicaulis* var. *macounii* (Xanthophyta, Tribophyceae). I. Effects on cytoplasmic organization. Environ. Exp. Bot. 45(3): 205-222.

Alessa, L. and L. Oliveira. 2001b. Aluminum toxicity studies in *Vaucheria longicaulis* var. *macounii* (Xanthophyta, Tribophyceae). II. Effects on the F-Actin Array. Environ. Exp. Bot. 45(3): 223-237.

Alexopoulos, E., C.R. McCrohan, J.J. Powell, R. Jugdaohsingh and K.N. White. 2003. Bioavailability and toxicity of freshly neutralized aluminium to the freshwater crayfish *Pacifastacus leniusculus*. Arch. Environ. Contam. Toxicol. 45(4): 509-514.

Allin, C.J. and R.W. Wilson. 1999. Behavioural and metabolic effects of chronic exposure to sublethal aluminum in acidic soft water in juvenile rainbow trout (*Oncorhynchus mykiss*). Can. J. Fish. Aquat. Sci. 56(4): 670-678.

Allin, C.J. and R.W. Wilson. 2000. Effects of pre-acclimation to aluminium on the physiology and swimming behaviour of juvenile rainbow trout (*Oncorhynchus mykiss*) during a pulsed exposure. Aquat. Toxicol. 51(2): 213-224.

Alquezar, R., S.J. Markich and D.J. Booth. 2006. Metal accumulation in the smooth toadfish, *Tetractenos glaber*, in estuaries around Sydney, Australia. Environ. Pollut. 142: 123-131.

Alstad, N.E.W., B.M. Kjelsberg, L.A. Vollestad, E. Lydersen and A.B.S. Poleo. 2005. The significance of water ionic strength on aluminium toxicity in brown trout (*Salmo trutta* L.). Environ. Pollut. 133(2): 333-342.

Amato, F., T. Moreno, M. Pandolfi, X. Querol, A. Alastuey, A. Delgado, M. Pedrero, N. Cots and F. Amato. 2010. Concentrations, sources and geochemistry of airborne particulate matter at a major European airport. J. Environ. Monit. 12(4): 854-862.

Amenu, G.G. 2011. A comparative study of water quality conditions between heavily urbanized and less urbanized watersheds of Los Angeles Basin. World Environ. Water Res. Congress, 680-690.

Anandhan, R. and S. Hemalatha. 2009. Bioaccumulation of aluminum in selected tissues of zebra fish *Brachydanio rerio* (Ham.). Nature Environ. Pollut. Technol. 8(4): 751-753.

Anderson, B.G. 1944. The toxicity thresholds of various substances found in industrial wastes as determined by the use of *Daphnia magna*. Sewage Works J. 16(6): 1156-1165.

Anderson, B.G. 1948. The apparent thresholds of toxicity to *Daphnia magna* for chlorides of various metals when added to Lake Erie water. Trans. Am. Fish. Soc. 78: 96-113.

Anderson, G.L., R.D. Cole and P.L. Williams. 2004. Assessing behavioral toxicity with *Caenorhabditis elegans*. Environ. Toxicol. Chem. 23(5): 1235-1240.

Andersson, M. 1988. Toxicity and tolerance of aluminum in vascular plants. Water Air Soil Pollut. 39: 439-462.

Andren, C.M. and E. Rydin. 2012. Toxicity of inorganic aluminium at spring snowmelt-in-stream bioassays with brown trout (*Salmo trutta* L.). Sci. Total Environ. 437: 422-432.

Andren, C., L. Henrikson, M. Olsson and G. Nilson. 1988. Effects of pH and aluminium on embryonic and early larval stages of Swedish brown frogs *Rana arvalis, R. temporaria* and *R. dalmatina*. Holarct. Ecol. 11(2): 127-135.

Andrews, W.J., M.F. Becker, S.L. Mashburn, S. Smith and W.J. Andrews. 2009. Selected metals in sediments and streams in the Oklahoma part of the Tri-State Mining District, 2000-2006. Scientific Investigations Report. U.S. Geological Survey.

Angel, B.M., S.C. Apte, G.E. Batley and L.A. Golding. 2016. Geochemical controls on aluminium concentrations in coastal waters. Environ. Chem. 13(1): 111-118.

Annicchiarico, C., M. Buonocore, N. Cardellicchio, A. Di Leo, S. Giandomenico, L. Spada and S. Giandomenico. 2011. PCBs, PAHs and metal contamination and quality index in marine sediments of the Taranto Gulf. Chem. Ecol. 27(Suppl.): 21-32.

Appelberg, M. 1985. Changes in haemolymph ion concentrations of *Astacus astacus* L. and *Pacifastacus leniusclus* (Dana) after exposure to low pH and aluminium. Hydrobiol. 121: 19-25.

Arain, M.B., T.G. Kazi, M.K. Jamali, N. Jalbani, H.I. Afridi, A. Shah and M.B. Arain. 2008. Total dissolved and bioavailable elements in water and sediment samples and their accumulation in *Oreochromis mossambicus* of polluted Manchar Lake. Chemosphere 70(10): 1845-1856.

Arenhart, R.A., J.C. De Lima, M. Pedron, F.E.L. Carvalho, J.A.G. Da Silveira, S.B. Rosa, A. Caverzan, C.M.B. Andrade, M. Schunemann, R. Margis and M. Margis-Pinheiro. 2013. Involvement of ASR genes in aluminium tolerance mechanisms in rice. Plant Cell Environ. 36: 52-67.

Arthur D. Little Incorporated. 1971. Water quality criteria data book, volume II, inorganic chemical pollution of freshwater. Water Pollution Control Research Ser. No. DPV 18010, U.S. EPA, Washington, DC, 280 pp.

AScI Corp. 1994. Aluminum water-effect ratio for the 3M Middleway Plant effluent discharge Middleway, West Virginia. Report Submitted to 3M by AScI Corp., McLean, VA, 76 pp.

AScI Corp. 1996. Aluminum water-effect ratio for Georgia-Pacific Corporation Woodland, Maine pulp & paper operations discharge and St. Croix River. ASci Corp., Duluth, MN.

ASTM. 2013. E1241-05(2013), Standard guide for conducting early life-stage toxicity tests with fishes. ASTM International, West Conshohocken, PA.

ATSDR (Agency for Toxic Substances and Disease Registry). 2008. Toxicological profile for aluminum. United States Department of Health and Human Services, Public Health Service, Atlanta, GA. Available online at http://www.atsdr.cdc.gov/toxprofiles/tp22.pdf.

Atland, A. 1998. Behavioural responses of brown trout, *Salmo trutta*, juveniles in concentration gradients of pH and Al - A laboratory study. Environ. Biol. Fish. 53: 331-345.

Atland, A. and B.T. Barlaup. 1996. Avoidance behaviour of Atlantic salmon (*Salmo salar* L.) fry in waters of low pH and elevated aluminum concentration: laboratory experiments. Can. J. Fish. Aquat. Sci. 53(8): 1827-1834.

Auvraya, F., E.D. van Hullebuscha, V. Deluchata and M. Baudua. 2006. Laboratory investigation of the phosphorus removal (SRP and TP) from eutrophic lake water treated with aluminium. Wat. Res. 40(14): 2713-2719.

Avis, T.J., D. Rioux, M. Simard, M. Michaud and R.J. Tweddell. 2009. Ultrastructural alterations in *Fusarium sambucinum* and *Heterobasidion annosum* treated with aluminum chloride and sodium metabisulfite. Phytopathol. 99(2):167-175.

Ayotte, J.D., J.M. Gronberg and L.E. Apodaca. 2011. Trace elements and radon in groundwater across the United States, 1992–2003: U.S. Geological Survey Scientific Investigations Report 2011–5059, 115 p. Available online at http://pubs.usgs.gov/sir/2011/5059.

Azimi, S., A. Ludwig, D.R. Thevenot and J.L. Colin. 2003. Trace metal determination in total atmospheric deposition in rural and urban areas. Sci. Total Environ. 308: 247–256.

Baba, A. and O. Gunduz. 2010. Effect of alteration zones on water quality: a case study from Biga Peninsula, Turkey. Arch. Environ. Contam. Toxicol. 58(3): 499-513.

Bailey, H.C., J.L. Miller, M.J. Miller and B.S. Dhaliwal. 1995. Application of toxicity identification procedures to the echinoderm fertilization assay to identify toxicity in a municipal effluent. Environ. Toxicol. Chem. 14(12): 2181-2186.

Baker, J.P. 1981. Aluminum toxicity to fish as related to acid precipitation and Adirondack surface water quality. Ph.D. Thesis, Cornell University, NY, 441 p.

Baker, J.P. 1982. Effects on fish of metals associated with acidification. Int. Symp.on Acidic Precipitation and Fishery Impacts in Northeastern North America, Aug. 2-5, 1981, Ithaca, NY, 165-176.

Baker, J.P. and C.L. Schofield. 1982. Aluminum toxicity to fish in acidic waters. Water Air Soil Pollut. 18: 289-309.

Baldigo, B.P. and P.S. Murdoch. 1997. Effect of stream acidification and inorganic aluminum on mortality of brook trout (*Salvelinus fontinalis*) in the Catskill Mountains, New York. Can. J. Fish. Aquat. Sci. 54: 603-615.

Ball, J.W., R.B. McCleskey, D.K. Nordstrom and J.W. Ball. 2010. Water-chemistry data for selected springs, geysers, and streams in Yellowstone National Park, Wyoming, 2006-2008. Open-File Report. U.S. Geological Survey.

Ballance, S., P.J. Phillips, C.R. McCrohan, J.J. Powell, R. Jugdaohsingh and K.N. White. 2001. Influence of sediment biofilm on the behaviour of aluminum and its bioavailability to the snail *Lymnaea stagnalis* in neutral freshwater. Can. J. Fish. Aquat. Sci. 58(9): 1708-1715.

Barbiero, R., R.E. Carlson, G.D. Cooke and A.W. Beals. 1988. The effects of a continuous application of aluminum sulfate on lotic benthic invertebrates. Lakes Reservoirs Res. Manag. 4(2): 63-72.

Barbour, M.T. and M.J. Paul. 2010. Adding value to water resource management through biological assessment of rivers. Hydrobiol. 651(1): 17-24.

Barcarolli, I.F. and C.B.R. Martinez. 2004. Effects of aluminum in acidic water on hematological and physiological parameters of the neotropical fish *Leporinus macrocephalus* (Anostomidae). Bull. Environ. Contam. Toxicol. 72: 639-646.

Bargagli, R. 2008. Environmental contamination in Antarctic ecosystems. Sci. Total Environ. 400(1-3): 212-226.

Barnes, R.B. 1975. The determination of specific forms of aluminum in natural water. Chem. Geol. 15: 177-191.

Battram, J.C. 1988. The effects of aluminium and low pH on chloride fluxes in the brown trout, *Salmo trutta* L. J. Fish. Biol. 32(6): 937-947.

Beattie, R.C. and R. Tyler-Jones. 1992. The effects of low pH and aluminum on breeding success in the frog *Rana temporaria*. J. Herpetol. 26(4): 353-360.

Beattie, R.C., R. Tyler-Jones and M.J. Baxter. 1992. The effects of pH, aluminium concentration and temperature on the embryonic development of the European common frog, *Rana temporaria*. J. Zool. (Lond.) 228: 557-570.

Becker Jr., A.J. and E.C. Keller Jr. 1973. The effects of iron and sulfate compounds on the growth of *Chlorella*. Proc. W. Va. Acad. Sci. 45(2): 127-135.

Becker Jr., A.J and E.C. Keller Jr. 1983. Metabolic responses of the crayfish *Procambarus clarkii* to reduced pH and elevated aluminum concentration. Am. Zool. 23(4): 888 (ABS).

Belabed, W., N. Kestali, S. Semsari and A. Gaid. 1994. Toxicity study of some heavy metals with *Daphnia* test (Evaluation de la toxicite de quelques metaux lourds a l'aide du test Daphnie). Tech. Sci. Methodes 6: 331-336.

Bengtsson, B.E. 1978. Use of a harpacticoid copepod in toxicity tests. Mar. Pollut. Bull. 9: 238-241.

Berg, W.A. 1978. Aluminum and manganese toxicities in acid coal mine wastes. In: G.T. Goodman and M.J. Chadwick (*Eds*.), Environmental Management of Mineral Wastes, Netherlands, 141-150.

Berg, D.J. and T.A. Burns. 1985. The distribution of aluminum in the tissues of three fish species. J. Fresh. Ecol. 3(1): 113-120.

Bergman, H. 1992. Development of biologically relevant methods for determination of bioavailable aluminum in surface waters. Final Tech. Rep., USGS Award No.14-08-0001-G1648, U.S. Geological Survey, University of Wyoming, Laramie, WY.

Bergman, H.L. and J.S. Mattice. 1990. Lake acidification and fisheries project: brook trout (*Salvelinus fontinalis*) early life stages. Can. J. Fish. Aquat. Sci. 47: 1578-1579.

Bergman, H.L., J.S. Mattice and D.J.A. Brown. 1988. Lake acidification and fisheries project: adult brook trout (*Salvelinus fontinalis*). Can. J. Fish. Aquat. Sci. 45: 1561-1562.

Berntssen, M.H.G., F. Kroglund, B.O. Rosseland and S.E. Wendelaar Bonga. 1997. Responses of skin mucous cells to aluminum exposure at low pH in Atlantic salmon (*Salmo salar*) smolts. Can. J. Fish. Aquat. Sci. 54: 1039-1045.

Bervoets, L., J. Voets, A. Covaci, S. Chu, D. Qadah, R. Smolders, P. Schepens and R. Blust. 2005. Use of transplanted zebra mussels (*Dreissena polymorpha*) to assess the bioavailability of microcontaminants in Flemish surface waters. Environ. Sci. Technol. 39(6): 1492-1505.

Bexfield, L.M., S.K. Anderholm and L.M. Bexfield. 2008. Potential chemical effects of changes in the source of water supply for the Albuquerque Bernalillo County Water Utility Authority. Scientific Investigations Report, U.S. Geological Survey.

Biesinger, K.E. and G.M. Christensen. 1972. Effects of various metals on survival, growth, reproduction and metabolism of *Daphnia magna*. J. Fish Res. Board Can. 29(12): 1691-1700.

Birchall, J.D., C. Exley, J.S. Chappell and M.J. Phillips. 1989. Acute toxicity of aluminium to fish eliminated in silicon-rich acid waters. Nature 338: 146-148.

Birge, W.J. 1978. Aquatic toxicology of trace elements of coal and fly ash. In: J.H. Thorp and J.W. Gibbons (*Eds*.), Dep. Energy Symp. Ser., Energy and Environmental Stress in Aquatic Systems, Augusta, GA, 219-240.

Birge, W.J., J.E. Hudson, J.A. Black and A.G. Westerman. 1978. Embryo-larval bioassays on inorganic coal elements and in situ biomonitoring of coal-waste effluents. In: Symp., U.S. Fish Wildl. Serv., Dec. 3-6, 1978, Surface Mining Fish Wildlife Needs in Eastern U.S., WV, 97-104.

Birge, W.J., J.A. Black and A.G. Westerman. 1979. Evaluation of aquatic pollutants using fish and amphibian eggs as bioassay organisms. In: S.W. Nielsen, G. Migaki, and D.G. Scarpelli (*Eds*.), Symp. Animals Monitors Environ. Pollut., 1977, Storrs, CT, 108-118.

Birge, W.J., J.A. Black, A.G. Westerman and J.E. Hudson. 1980. Aquatic toxicity tests on inorganic elements occurring in oil shale. In: C. Gale (*Ed*.), EPA-600/9-80-022, Oil Shale Symposium: Sampling, Analysis and Quality Assurance, March 1979, U.S. EPA, Cincinnati, OH, (U.S.NTIS PB80-221435).

Birge, W.J., J.A. Black and B.A. Ramey. 1981. The reproductive toxicology of aquatic contaminants. In: J. Saxena and F. Fisher (*Eds*.), Hazard Assessment of Chemicals: Current Developments, Academic Press, New York, NY, 59-115.

Birge, W.J., R.D. Hoyt, J.A. Black, M.D. Kercher and W.A. Robison. 1993. Effects of chemical stresses on behavior of larval and juvenile fishes and amphibians. Am. Fish. Soc. Symp. 14: 55-65.

Birge, W.J., A.G. Westerman and J.A. Spromberg. 2000. Comparative toxicology and risk assessment of amphibians. In: D.W. Sparling, et al. (*Eds*.), Ecotoxicology of Amphibians and Reptiles, Chapter 14A, SETAC Spec. Publ., 727-791.

Bjerknes, V., I. Fyllingen, L. Holtet, H.C. Teien, B.O. Rosseland and F. Kroglund. 2003. Aluminum in acidic river water causes mortality of farmed Atlantic salmon (*Salmo salar* L.) in Norwegian fjords. Mar. Chem. 83(3/4): 169-174.

Boniardi, N., R. Rota and G. Nano. 1999. Effect of dissolved metals on the organic load removal efficiency of *Lemna gibba*. Water Res. 33(2): 530-538.

Booth, C.E., D.G. McDonald, B.P. Simons and C.M. Wood. 1988. Effects of aluminum and low pH on net ion fluxes and ion balance in the brook trout (*Salvelinus fontinalis*). Can. J. Fish. Aquat. Sci. 45(9): 1563-1574.

Borgmann, U., Y. Couillard, P. Doyle and D.G. Dixon. 2005. Toxicity of sixty-three metals and metalloids to *Hyalella azteca* at two levels of water hardness. Environ. Toxicol. Chem. 24(3): 641-652.

Bowry, S.K. 1985. Relative toxicity of different fumigants against the adults of lesser grain borer *Rhizopertha dominica* Fabr. and rice moth *Corcyra cephalonica* Staint. I. East Afr. Agric. For. J. 51: 101-107.

Boyd, C.E. 1979. Aluminum sulfate (alum) for precipitating clay turbidity from fish ponds. Trans. Am. Fish. Soc. 108: 307-313.

Bradford, D.F., C. Swanson and M.S. Gordon. 1992. Effects of low pH and aluminum on two declining species of amphibians in the Sierra Nevada, California. J. Herpetol. 26(4): 369-377.

Bradford, D.F., C. Swanson and M.S. Gordon. 1994. Effects of low pH and aluminum on amphibians at high elevation in the Sierra Nevada, California. Can. J. Zool. 72: 1272-1279.

Brady, L.D. and R.A. Griffiths. 1995. Effects of pH and aluminium on the growth and feeding behaviour of smooth and palmate newt larvae. Ecotoxicol. 4(5): 299-306.

Bray, E.I. 2015. Aluminum. U.S. Geological Survey, Mineral Commodity Summary 2015, January 2015. 199 pp.

Bringmann, G. and R. Kuhn. 1959a.Water toxicological studies with protozoa as test organisms. TR-80-0058, Literature Research Company, 13 pp.

Bringmann, G. and R. Kuhn. 1959b. Comparative water-toxicological investigations on bacteria, algae, and *Daphnia*. Gesundheitsingenieur 80(4): 115-120.

Brix, K.V., D.K. DeForest, L. Tear, M. Grosell and W.J. Adams. 2017. Use of multiple linear regression models for setting water quality criteria for copper: A complimentary approach to the biotic ligand model. Environ. Toxicol. Chem. 51(9): 5182-5192.

Brodeur, J.C., T. Ytrestoyl, B. Finstad and R.S. McKinley. 1999. Increase of heart rate without elevation of cardiac output in adult Atlantic salmon (*Salmo salar*) exposed to acidic water and aluminium. Can. J. Fish. Aquat. Sci. 56(2): 184-190.

Brodeur, J.C., F. Okland, B. Finstad, D.G. Dixon and R.S. McKinley. 2001. Effects of subchronic exposure to aluminium in acidic water on bioenergetics of Atlantic salmon (*Salmo salar*). Ecotoxicol. Environ. Saf. 49(3): 226-234.

Brooke, L. 1985. Results of acute exposures to aluminum at pH >6.5 with planaria and daphnids. Memorandum to C. Stephan. Dated July 25th. U.S. EPA, Duluth, MN, 5 pp.

Brown, D.J.A. 1981a. The effects of various cations on the survival of brown trout, *Salmo trutta* at low pHs. J. Fish Biol. 18(1): 31-40.

Brown, D.J.A. 1981b. The effect of sodium and calcium concentrations on the hatching of eggs and the survival of the yolk sac fry of brown trout, *Salmo trutta* L. at low pH. Fish Biol. 19: 205-211.

Brown, D.J.A. 1983. Effect of calcium and aluminum concentrations on the survival of brown trout (*Salmo trutta*) at low pH. Bull. Environ. Contam. Toxicol. 30(5): 582-587.

Brown, M.T. and K.W. Bruland. 2009. Dissolved and particulate aluminum in the Columbia River and coastal waters of Oregon and Washington: behavior in near-field and far-field plumes. Estuar. Coast. Shelf Sci. 84(2): 171-185.

Brown, M.T., S.M. Lippiatt and K.W. Bruland. 2010. Dissolved Al, particulate Al, and silicic acid in northern Gulf of Alaska coastal waters – glacial–riverine inputs and extreme reactivity. Mar. Chem. 122: 160-175.

Brown, S.B., D.L. MacLatchy, T.J. Hara and J.G. Eales. 1990. Effects of low ambient pH and aluminum on plasma kinetics of cortisol, T_3, and T_4 in rainbow trout (*Oncorhynchus mykiss*). Can. J. Zool. 68: 1537-1543.

Brown, S.B., B.A. Adams, D.G. Cyr and J.G. Eales. 2004. Contaminant effects on the teleost fish thyroid. Environ. Toxicol. Chem. 23(7): 1680-1701.

Brown, T.E., A.W. Morley, N.T. Sanderson and R.D. Tait. 1983. Report of a large fish kill resulting from natural acid water conditions in Australia. J. Fish. Biol. 22(3): 335-350.

Brumbaugh, W.G. and D.A. Kane. 1985. Variability of aluminum concentrations in organs and whole bodies of smallmouth bass (*Micropterus dolomieui*). Environ. Sci. Technol. 19: 828-831.

Buckler, D.R., P.M. Mehrle, L. Cleveland and F.J. Dwyer. Manuscript. Influence of pH on the toxicity of aluminum and other inorganic contaminants to east coast striped bass. Columbia National Fisheries Research Laboratory, Columbia, MO.

Buckler, D.R., P.M. Mehrle, L. Cleveland and F.J. Dwyer. 1987. Influence of pH on the toxicity of aluminum and other inorganic contaminants to east coast striped bass. Water Air Soil Pollut. 35: 97-106.

Buckler, D.R., L. Cleveland, E.E. Little and W.G. Brumbaugh. 1995. Survival, sublethal responses, and tissue residues of Atlantic salmon exposed to acidic pH and aluminum. Aquat. Toxicol. 31(3): 203-216.

Budambula, N.L.M. and E.C. Mwachiro. 2006. Metal status of Nairobi River waters and their bioaccumulation in *Labeo cylindricus*. Water Air Soil Pollut. 169: 275-291.

Buergel, D.M. and R.A. Soltero. 1983. The distribution and accumulation of aluminum in rainbow trout following a whole-lake alum treatment. J. Fresh. Ecol. 2: 37-44.

Buhl, K.J. 2002. The relative toxicity of waterborne inorganic contaminants to the Rio Grande silvery minnow (*Hybognathus amarus*) and fathead minnow (*Pimephales promelas*) in a water quality simulating that in the Rio Grande, New Mexico. Final Rep. to U.S. Fish and Wildl. Serv., Study No. 2F33-9620003, U.S. Geol. Surv., Columbia Environ. Res. Ctr., Yankton Field Res. Stn., Yankton, SD, 75 pp.

Bukaveckas, P.A. 1989. Effects of calcite treatment on primary producers in acidified Adirondack lakes. II. Short-term response by phytoplankton communities. Can. J. Fish. Aquat. Sci. 46: 352-359.

Bulger, A.J., L. Lien, B.J. Cosby and A. Henriksen. 1993. Brown trout (*Salmo trutta*) status and chemistry from the Norwegian Thousand Lake Survey: Statistical analysis. Can. J. Fish. Aquat. Sci. 50: 575-585.

Burnham, K.P. and D.R. Anderson. 2004. Multimodel inference: Understanding AIC and BIC in model selection. Soc. Meth. Res. 33(2): 261-304.

Burnham, K.P., D.A. Anderson and K.P. Huyvaert. 2011. AIC model selection and multimodel inference in behavioral ecology: Some background, observations, and comparisons. Behav. Ecol. Sociobiol. 65: 23-35.

Burrows, W.D. 1977. Aquatic aluminium: chemistry, toxicology, and environmental prevalence. CRC Crit. Rev. Environ. Control 7: 167-216.

Burt, R., M.A. Wilson, M.D. Mays and C.W. Lee. 2003. Major and trace elements of selected pedons in the USA. J. Environ. Qual. 32(6): 2109-2121.

Burton, T.M. and J.W. Allan. 1986. Influence of pH, aluminum, and organic matter on stream invertebrates. Can. J. Fish. Aquat. Sci. 43: 1285-1289.

Cai, M., S. Zhang, C. Xing, F. Wang, N. Wang and L. Zhu. 2011. Developmental characteristics and aluminum resistance of root border cells in rice seedlings. Plant Sci. 180: 702-708.

Calabrese, A., R.S. Collier, D.A. Nelson and J.R. MacInnes. 1973. The toxicity of heavy metals to embryos of the American oyster *Crassostrea virginica*. Mar. Biol. 18(3): 162-166.

Calevro, F., C. Filippi, P. Deri, C. Albertosi and R. Batistoni. 1998a. Toxic effects of aluminium, chromium and cadmium in intact and regenerating freshwater planarians. Chemosphere 37(4): 651-659.

Calevro, F., S. Campani, M. Ragghianti, S. Bucci and G. Mancino. 1998b. Tests of toxicity in biphasic vertebrates treated with heavy metals (Cr^{3+}, Al^{3+}, Cd^{2+}). Chemosphere 37(14/15): 3011-3017.

Calevro, F., S. Campani, C. Filippi, R. Batistoni, P. Deri, S. Bucci, M. Ragghianti and G. Mancino. 1999. Bioassays for testing effects of Al, Cr and Cd using development in the amphibian *Pleurodeles waltl* and regeneration in the planarian *Dugesia etrusca*. Aquat. Ecosyst. Health Manag. 2(3): 281-288.

Call, D.J. 1984. University of Wisconsin-Superior, Superior, WI. Memorandum to C. Stephan. Dated November 27th. U.S. EPA, Duluth, MN.

Call, D.J., L.T. Brooke, C.A. Lindberg, T.P. Markee, D.J. McCauley and S.H. Poirier. 1984. Toxicity of aluminum to freshwater organisms in water of pH 6.5-8.5. Tech. Rep. Project No. 549-238-RT-WRD, Center for Lake Superior Environmental Studies, University of Wisconsin, Superior, WI.

Camargo, M.M.P., M.N. Fernandes and C.B.R. Martinez. 2007. Osmo-ionic alterations in a neotropical fish acutely exposed to aluminum. Comp. Biochem. Physiol. Part A: Molec. Integrat. Physiol. 148(Supplement 1): S78.

Camargo, M.M.P., M.N. Fernandes and C.B.R. Martinez. 2009. How aluminium exposure promotes osmoregulatory disturbances in the neotropical freshwater fish *Prochilus lineatus*. Aquat. Toxicol. 94(1): 40-46.

Camilleri, C., S.J. Markich, B.N. Noller, C.J. Turley, G. Parker and R.A. Van Dam. 2003. Silica reduces the toxicity of aluminium to a tropical freshwater fish (*Mogurnda mogurnda*). Chemosphere 50(3): 355-364.

Campbell, P.G.C., M. Bisson, R. Bougie, A. Tessier and J. Villeneuve. 1983. Speciation of aluminum in acidic freshwaters. Anal. Chem. 55: 2246-2252.

Campbell, M.M., K.N. White, R. Jugdaohsingh, J.J. Powell and C.R. McCrohan. 2000. Effect of aluminum and silicic acid on the behaviour of the freshwater snail *Lymnaea stagnalis*. Can. J. Fish. Aquat. Sci. 57(6): 1151-1159.

Capdevielle, M.C. and C.G. Scanes. 1995. Effect of dietary acid or aluminum on growth and growth-related hormones in mallard ducklings (*Anas platyrhynchos*). Arch. Environ. Contam. Toxicol. 29: 462-468.

Capdevielle, M.C., L.E. Hart, J. Goff and C.G. Scanes. 1998. Aluminum and acid effects on calcium and phosphorus metabolism in young growing chickens (*Gallus gallus domesticus*) and mallard ducks (*Anas platyrhynchos*). Arch. Environ. Contam. Toxicol. 35: 82-88.

Caplat, C., R. Oral, M.L. Mahaut, A. Mao, D. Barillier, M. Guida, C. Della Rocca and G. Pagano. 2010. Comparative toxicities of aluminum and zinc from sacrificial anodes or from sulfate salt in sea urchin embryos and sperm. Ecotoxicol. Environ. Saf. 73(6): 1138-1143.

Carballeira, A., M.D. Vazquez and J. Lopez. 2001. Biomonitoring of sporadic acidification of rivers on the basis of release of preloaded cadmium from the aquatic bryophyte *Fontinalis antipyretica* Hedw. Environ. Pollut. 111: 95-106.

Cardwell, R.D., C.E. Woelke, M.I. Carr and E.W. Sanborn. 1979. Toxic substance and water quality effects on larval marine organisms. Tech. Rep. No. 45, State of Washington, Dep. of Fish, Olympia, WA, 71 pp.

Cardwell, A.S., W.J. Adams, R.W. Gensemer, E. Nordheim, R.C. Santore, A.C. Ryan and W.A. Stubblefield. 2018. Chronic toxicity of aluminum, at a pH of 6, to freshwater organisms: Empirical data for the development of international regulatory standards/criteria. Environ. Toxicol. Chem. 37(1): 36-48.

Carroll, J.J., S.J. Ellis and W.S. Oliver. 1979. Influences of hardness constituents on the acute toxicity of cadmium to brook trout (*Salvelinus fontinalis*). Bull. Environ. Contam. Toxicol. 22:575-581.

Carter, L.F. and S.D. Porter. 1997. Trace-element accumulation by *Hygrohypnum ochraceum* in the Upper Rio Grande Basin, Colorado and New Mexico, USA. Environ. Toxicol. Chem. 16(12): 2521-2528.

Casas, A.M. and E.A. Crecelius. 1994. Relationship between acid volatile sulfide and toxicity of zinc, lead and copper in marine sediments. Environ. Toxicol. Chem. 13: 529-536.

CECM (Center for the Ecotoxicology and Chemistry of Metals). 2014. Studies on the effect of aluminium in the survival and reproduction of *Ceriodaphnia dubia* at different pHs and hardness. Final Report, December 2014, Santiago, Chile. (Data summarized in Gensemer et al. 2018).

Chakravorty, B., R. Dubey, M. Kumari and R. Naskar. 2012. Primary and secondary stress response of *Channa punctatus* to sublethal aluminium toxicity. J. Appl. Sci. Environ. Sanit. 7(2): 125-130.

Chamier, A.C. and E. Tipping. 1997. Effects of aluminium in acid streams on growth and sporulation of aquatic hyphomycetes. Environ. Pollut. 96(3): 289-298.

Chang, P.S.S., D.F. Malley and J.D. Hueber. 1988. Response of the mussel *Anadonta grandi* to acid and aluminum. Comparison of blood ions from laboratory and field results. Can. Tech. Rep. Fish. Aquat. Sci. 1607: 157-161.

Chapman, W.H., H.L. Fisher and M.W. Pratt. 1968. Concentration factors of chemical elements in edible aquatic organisms. Lawrence Radiat. Lab., Univ. of California, UCRL-50564, Livermore, CA, 32 pp.

Chapman, P.M., D.M. Leslie and J.G. Michaelson. 1987. Why fish mortality in bioassays with aluminum reduction plant wastes don't always indicate chemical toxicity. In: Light Metals, Warrendale, PA, 677-688.

Chen, C.S. 2005. Ecological risk assessment for aquatic species exposed to contaminants in Keelung River, Taiwan. Chemosphere 61(8): 1142-1158.

Chen, D., S.L. Gerstenberger, S.A. Mueting, W.H. Wong and D. Chen. 2011. Environmental factors affecting settlement of quagga mussel (*Dreissena rostriformis* Bugensis) veligers in Lake Mead, Nevada-Arizona, USA. Aquat. Invasions 6(2): 149-156.

Chevalier, G., A. Hontela and K. Lederis. 1987. Acidity and aluminium effects on osmo-iono-regulation in the brook trout. In: R. Perry, R.M. Harrison, J.N.B. Bell and J.N. Lester (*Eds*.), Acid Rain: Scientific and Technical Advances, Selper Ltd., London, 497-499.

Christensen, G.M. 1971/1972. Effects of metal cations and other chemicals upon the in vitro activity of two enzymes in the blood plasma of the white sucker, *Catostomus commersoni* (Lacepede). Chem. Biol. Interact. 4: 351-361.

Christensen, G.M. and J.H. Tucker. 1976. Effects of selected water toxicants on the in vitro activity of fish carbonic anhydrase. Chem. Biol. Interact. 13: 181-192.

Chu, K.W. and K.L. Chow. 2002. Synergistic toxicity of multiple heavy metals is revealed by a biological assay using a nematode and its transgenic derivative. Aquat. Toxicol. 61(1/2): 53-64.

CIMM (Chilean Mining and Metallurgy Research Center). 2009. Draft of the final report: Systematic characterization of the relationship between BLM parameters and aluminium toxicity in *Daphnia magna, Ceriodaphnia dubia* and *Pseudokirchneriella subcapitata*. Santiago, Chile.

CIMM (Chilean Mining and Metallurgy Research Center). 2016. Methods for compilation from aluminum project. Prepared by P. Rodriguez, CIMM for Rio Tinto and the Aluminum REACH Consortium. Draft November 2016.

Claesson, A. and L. Tornqvist. 1988. The toxicity of aluminum to two acido-tolerant green algae. Water Res. 22: 977-983.

Clark, K.L. and R.J. Hall. 1985. Effects of elevated hydrogen ion and aluminum concentrations on the survival of amphibian embryos and larvae. Can. J. Zool. 63: 116-123.

Clark, K.L. and B.D. LaZerte. 1985. A laboratory study of the effects of aluminum and pH on amphibian eggs and tadpoles. Can. J. Fish. Aquat. Sci. 42(9): 1544-1551.

Clark, K.L. and B.D. LaZerte. 1987. Intraspecific variation in hydrogen ion and aluminum toxicity in *Bufo americanus* and *Ambystoma maculatum*. Can. J. Fish. Aquat. Sci. 44: 1622-1628.

Clements, W.H. and P.M. Kiffney. 1996. Validation of whole effluent toxicity tests: Integrated studies using field assessments, microcosms, and mesocosms. In: D.L. Grothe, K.L. Dickson and D.K. Reed-Judkins (*Eds.*), Whole effluent toxicity testing: an evaluation of methods and prediction of receiving system impacts. Pensacola, FL., Society of Environmental Toxicology and Chemistry (SETAC), p. 229-244.

Clements, W.H., D.M. Carlisle, L.A. Courtney and E.A. Harrahy. 2002. Integrating observational and experimental approaches to demonstrate causation in stream biomonitoring studies. Environ. Toxicol. Chem. 21(6): 1138-1146.

Cleveland, L. E.E. Little, R.H. Wiedmeyer and D.R. Buckler. Manuscript. Chronic no-observed-effect concentrations of aluminum for brook trout exposed in dilute acidic water. National Fisheries Contaminant Research Center, Columbia, MO.

Cleveland, L., E.E. Little, S.J. Hamilton, D.R. Buckler and J.B. Hunn. 1986. Interactive toxicity of aluminum and acidity to early life stages of brook trout. Trans. Am. Fish. Soc. 115: 610-620.

Cleveland, L., E.E. Little, R.H. Wiedmeyer and D.R. Buckler. 1989. Chronic no-observed-effect concentrations of aluminum for brook trout exposed in low-calcium, dilute acidic water. In: T.E. Lewis (*Ed*.), Environmental Chemistry and Toxicology of Aluminum, Chapter 13, Lewis Publ., Chelsea, MI, 229-246.

Cleveland, L., D.R. Buckler and W.G. Brumbaugh. 1991a. Residue dynamics and effects of aluminum on growth and mortality in brook trout. Environ. Toxicol. Chem. 10(2): 243-248.

Cleveland, L., E.E. Little, C.G. Ingersoll, R.H. Wiedmeyer and J.B. Hunn. 1991b. Sensitivity of brook trout to low pH, low calcium and elevated aluminum concentrations during laboratory pulse exposures. Aquat. Toxicol. 19(4): 303-318.

Colman, J.A., A.J. Massey, S.L. Brandt and J.A. Colman. 2011. Determination of dilution factors for discharge of aluminum-containing wastes by public water-supply treatment facilities into lakes and reservoirs in Massachusetts. Scientific Investigations Report, U.S. Geological Survey.

Conklin, P.J., D. Drysdale, D.G. Doughtie, K.R. Rao, J.P. Kakareka, T.R. Gilbert and R.F. Shokes. 1983. Comparative toxicity of drilling muds: Role of chromium and petroleum hydrocarbons. Mar. Environ. Res. 10: 105-125.

Cook, W. and J. Haney. 1984. The acute effects of aluminum and acidity upon nine stream insects. In: Tech. Completion Rep., Project No. 373103, Water Resource Res. Center, Univ. of New Hampshire, Durham, NH, 33 p.

Cooper, J.A., J.G. Watson and J.J. Huntzicker. 1979. Summary of the Portland Aerosol Characterization Study (PACS). Presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 24-29, 1979. Air Pollution Control Association, Cincinnati, OH.

Correa, M., R.A. Coler and C.M. Yin. 1985. Changes in oxygen consumption and nitrogen metabolism in the dragonfly *Somatochlora cingulata* exposed to aluminum in acid waters. Hydrobiol. 121: 151-156.

Correa, M., R. Coler, C.M. Yin and E. Kaufman. 1986. Oxygen consumption and ammonia excretion in the detritivore caddisfly *Limnephillus sp*. exposed to low pH & aluminum. Hydrobiol. 140(3): 237-241.

Correia, T.G., A.M. Narcizo, A. Bianchini and R.G. Moreira. 2010. Aluminum as an endocrine disruptor in female Nile tilapia (*Oreochromis niloticus*). Comp. Biochem. Physiol. C Toxicol. Pharmacol. 151(4): 461-466.

Craig, G.R., W.P. Banas and W.J. Snodgrass. 1985. Development of provincial water quality objective criteria for aluminum. Water Qual. Object. Dev. Doc.: Aluminum, Prepared for Ontario Ministry of the Environ. Water Res. Branch, Beak Consultants Ltd., Mississauga, Ontario, Canada, 95 p.

Cravotta III, C.A., R.A. Brightbill, M.J. Langland and C.A. Cravotta III. 2010. Abandoned mine drainage in the Swatara Creek Basin, southern anthracite coalfield, Pennsylvania, USA: 1. Stream water quality trends coinciding with the return of fish. Mine Water Environ. 29(3): 176-199.

Crawford, K.D., J.E. Weinstein, R.E. Hemingway, T.R. Garner, G. Globensky and K.D. Crawford. 2010. A survey of metal and pesticide levels in stormwater retention pond sediments in coastal South Carolina. Arch. Environ. Contam. Toxicol. 58(1): 9-23.

CRC. 2000. CRC handbook of chemistry and physics. 81st Edition, D.R. Lide (*Ed*.). CRC Press LLC, Boca Raton, FL.

Crist, R.H., K. Oberholser, J. McGarrity, D.R. Crist, J.K. Johnson and J.M. Brittsan. 1992. Interaction of metals and protons with algae. 3. Marine algae, with emphasis on lead and aluminum. Environ. Sci. Technol. 26: 496-502.

Cummins, C.P. 1986. Effects of aluminium and low pH on growth and development in *Rana temporaria* tadpoles. Ecologia 69: 248-252.

Dalziel, T.R.K., R. Morris and D.J.A. Brown. 1986. The effects of low pH, low calcium concentrations and elevated aluminium concentrations on sodium fluxes in brown trout, *Salmo trutta* L. Water Air Soil Pollut. 30(3/4): 569-577.

Danilov, R.A. and N.G.A. Ekelund. 2002. Effects of short-term and long-term aluminium stress on photosynthesis, respiration, and reproductive capacity in a unicellular green flagellate (*Euglena gracilis*). Acta Hydrochim. Hydrobiol. 30(4): 190-196.

Dantzman, C.L. and H.L. Breland. 1970. Chemical status of some water sources in south central Florida. Soil Sci. Soc. Am. Proc. 29: 18-28.

Dave, G. 1985. The influence of pH on the toxicity of aluminum, cadmium, and iron to eggs and larvae of the zebrafish, *Brachydanio rerio*. Ecotoxicol. Environ. Saf. 10(2): 253-267.

Decker, C. and R. Menendez. 1974. Acute toxicity of iron and aluminum to brook trout. Proc. W. Va. Acad. Sci. 46(2): 159-167.

DeForest, D.K., K.V. Brix, L.M. Tear and W.J. Adams. 2018a. Multiple linear regression models for predicting chronic aluminum toxicity to freshwater aquatic organisms and developing water quality guidelines. Environ. Toxicol. Chem. 37(1): 80-90.

DeForest, D.K., K. Brix, L. Tear and B. Adams. 2018b. Updated aluminum multiple linear regression models for *Ceriodaphnia dubia* and *Pimephales promelas*. Memorandum to Diana Eignor and Kathryn Gallagher (EPA). Dated: August, 24, 2018.

De Jong, L.E.D.D. 1965. Tolerance of *Chlorella vulgaris* for metallic and non-metallic ions. Antonie Leeuwenhoek J. Microbiol. 31: 301-313.

Delaune, R.D., R.P. Gambrell, A. Jugsujinda, I. Devai, A. Hou and R.D. Delaune. 2008. Total Hg, methyl Hg and other toxic heavy metals in a northern Gulf of Mexico Estuary: Louisiana Pontchartrain Basin. J. Environ. Sci. Health Part A: Toxic/Hazard. Subst. Environ. Engin. 43(9): 1006-1015.

DeLonay, A.J. 1991. The effects of low pH and elevated aluminum on survival, growth, ionic composition, and behavior of early life stages of golden trout. M.S. Thesis, Univ. Missouri, Columbia, MO. 78 p.

DeLonay, A.J., E.E. Little, D.F. Woodward, W.G. Brumbaugh, A.M. Farag and C.F. Rabeni. 1993. Sensitivity of early-life-stage golden trout to low pH and elevated aluminum. Environ. Toxicol. Chem. 12: 1223-1232.

Desouky, M.M.A. 2006. Tissue distribution and subcellular localization of trace metals in the pond snail *Lymnaea stagnalis* with special reference to the role of lysosomal granules in metal sequestration. Aquat. Toxicol. 77(2): 143-152.

Desouky, M.M.A. 2012. Metallothionein is up-regulated in molluscan responses to cadmium, but not aluminum, exposure. J. Basic Appl. Zool. 65: 139-143.

Desouky, M.M., J.J. Powell, R. Jugdaohsingh, K.N. White and C.R. McCrohan. 2002. Influence of oligomeric silicic and humic acids on aluminum accumulation in a freshwater grazing invertebrate. Ecotoxicol. Environ. Saf. 53(3): 382-387.

Desouky, M.M., C.R. McCrohan, R. Jugdaohsingh, J.J. Powell and K.N. White. 2003. Effect of orthosilicic acid on the accumulation of trace metals by the pond snail *Lymnaea stagnalis*. Aquat. Toxicol. 64(1): 63-71.

DeWalle, D.R., B.R. Swistock and W.E. Sharpe. 1995. Episodic flow-duration analysis: a method of assessing toxic exposure of brook trout (*Salvelinus fontinalis*) to episodic increases in aluminum. Can. J. Fish. Aquat. Sci. 52(4): 816-827.

Dhawan, R., D.B. Dusenbery and P.L. Williams. 2000. A comparison of metal-induced lethality and behavioral responses in the nematode *Caenorhabditis elegans*. Environ. Toxicol. Chem. 19(12): 3061-3067.

Dickson, W. 1983. Liming toxicity of aluminium to fish. Vatten 39: 400-404.

Dietrich, D.R. 1988. Aluminium toxicity to salmonids at low pH. Ph.D. Thesis No. 8715. Swiss Federal Institute of Technology, Institute of Toxicology, Zürich, Switzerland. 210 pp.

Dietrich, D. and C. Schlatter. 1989a. Aluminium toxicity to rainbow trout at low pH. Aquat. Toxicol. 15(3): 197-212.

Dietrich, D. and C. Schlatter. 1989b. Low levels of aluminium causing death of brown trout (*Salmo trutta fario*, L.) in a Swiss alpine lake. Aquat. Sci. 51(4): 279-295.

Dietrich, D., C. Schlatter, N. Blau and M. Fischer. 1989. Aluminium and acid rain: mitigating effects of NaCl on aluminium toxicity to brown trout (*Salmo trutta fario*) in acid water. Toxicol. Environ. Chem. 19: 17-23.

Dixon, W.J. and M.B. Brown (*Eds*). 1979. BMDP Biomedical Computer Programs, P-series. University of California, Berkeley, California. p. 521.

Dobranskyte, A., R. Jugdaohsingh, E. Stuchlik, J.J. Powell, K.N. White and C.R. McCrohan. 2004. Role of exogenous and endogenous silicon in ameliorating behavioural responses to aluminium in a freshwater snail. Environ. Pollut. 132: 427-433.

DOI (Department of the Interior). 1971. Geochemical cycles involving flora, lake water, and bottom sediments. United States Department of the Interior, Office of Water Resources Research, Washington, DC. PB206197.

Doke, J.L., W.H. Funk, S.T.J. Juul and B.C. Moore. 1995. Habitat availability and benthic invertebrate population changes following alum treatment and hypolimnetic oxygenation in Newman Lake, Washington. J. Fresh. Ecol. 10(2): 87-102.

Doudoroff, P. and M. Katz. 1953. Critical review of literature on the toxicity of industrial wastes and their components to fish. II. The metals, as salts. Sewage Ind. Wastes 25(7): 802-839.

Driscoll, C.T. 1984. A procedure for the fractionation of aqueous aluminum in dilute acidic waters. Intern. J. Environ. Anal. Chem. 16: 267-283.

Driscoll, C.T. 1985. Aluminum in acidic surface waters: chemistry, transport, and effects. Environ. Health Perspect. 63: 93-104.

Driscoll, C.T. and K.M. Postek. 1996. The chemistry of aluminum in surface waters. In: G. Sposito (*Ed.*), The Environmental Chemistry of Aluminum (2nd Ed.). Lewis Publishers, NY, 363-418.

Driscoll, C.T. and W.D. Schecher. 1988. Aluminum in the environment. In: H.H. Sigel and A. Sigel (*Eds.*), Metal Ions in Biological Systems, Vol. 24. Aluminum and its Role in Biology. Marcel Dekker, NY, 59-122.

Driscoll, C.T.J., J.P. Baker, J.J. Bisogni Jr. and C.L. Schofield. 1980. Effect of aluminium speciation on fish in dilute acidified waters. Nature 284(5752): 161-164.

Duis, K. and A. Oberemm. 2001. Aluminium and calcium - key factors determining the survival of vendace embryos and larvae in post-mining lakes? Limnol. 31(1): 3-10.

Durrett, T.P., W. Gassmann and E.E. Rogers. 2007. The FRD3-mediated efflux of citrate into the root vasculature is necessary for efficient iron translocation. Plant Physiol. 144: 197-205.

Dussault, E.B., R.C. Playle, D.G. Dixon and R.S. McKinley. 2001. Effects of sublethal, acidic aluminum exposure on blood ions and metabolites, cardiac output, heart rate, and stroke volume of rainbow trout, *Oncorhynchus mykiss*. Fish Physiol. Biochem. 25(4): 347-357.

Dussault, E.B., R.C. Playle, D.G. Dixon and R.S. McKinley. 2004. Effects of chronic aluminum exposure on swimming and cardiac performance in rainbow trout, *Oncorhynchus mykiss*. Fish Physiol. Biochem. 30(2): 137-148.

Dwyer, F.J., L.C. Sappington, D.R. Buckler and S.B. Jones. 1995. Use of surrogate species in assessing contaminant risk to endangered and threatened fishes. EPA/600/R-96/029, U.S. EPA, Washington, DC, 78 p.

Dwyer, F.J., D.K. Hardesty, C.E. Henke, C.G. Ingersoll, D.W. Whites, T. Augspurger, T.J. Canfield, D.R. Mount and F.L. Mayer. 2005. Assessing contaminant sensitivity of endangered and threatened aquatic species: Part III. Effluent toxicity tests. Arch. Environ. Contam. Toxicol. 48(2): 174-183.

Dzubay, T.G. 1980. Chemical element balance method applied to dichotomous sampler data. Ann. NY Acad. Sci. 338: 126-144.

Eaton, J.G., W.A. Swenson, J.H. McCormick, T.D. Simonson and K.M. Jensen. 1992. A field and laboratory investigation of acid effects on largemouth bass, rock bass, black crappie, and yellow perch. Trans. Am. Fish. Soc. 121: 644-658.

ECB (European Chemicals Bureau). 2003. Technical guidance document on risk assessment. European Commission Joint Research Centre, EUR 20418 EN/2.

Ecological Analysts, Inc. 1984. Study on metals in food fish near the abandoned Vienna fly ash disposal area. PB84-178441. National Technical Information Service, Springfield, VA.

Eddy, F.B. and C. Talbot. 1983. Formation of the perivitelline fluid in Atlantic salmon eggs (*Salmo salar*) in fresh water and in solutions of metal ions. Comp. Biochem. Physiol. C 75(1): 1-4.

Eddy, F.B. and C. Talbot. 1985. Sodium balance in eggs and dechorionated embryos of the Atlantic salmon *Salmo salar* L. exposed to zinc, aluminium and acid waters. Comp. Biochem. Physiol. C Comp. Pharmacol. 81(2): 259-266.

Eichenberger, E. 1986. The interrelation between essentiality and toxicity of metals in the aquatic ecosystem. In: H. Sigel (*Ed*.), Metal Ions in Biological Systems, Vol. 20. Concepts on Metal Ion Toxicity. Marcel Dekker, NY, 67-100.

Eisenreich, S.J. 1980. Atmospheric input of trace metals to Lake Michigan (USA). Water Air Soil Pollut. 13(3): 287-301.

Eisentraeger, A., W. Dott, J. Klein and S. Hahn. 2003. Comparative studies on algal toxicity testing using fluorometric microplate and Erlenmeyer flask growth-inhibition assays. Ecotoxicol. Environ. Saf. 54(3): 346-354.

Eisler, R., R.M. Rossoll and G.A. Gaboury. 1979. Fourth annotated bibliography on biological effects of metals in aquatic environments (No. 2247-3132). EPA-600/3-79-084, U.S. EPA, Narragansett, RI, 592 pp.

Elangovan, R., K.N. White and C.R. McCrohan. 1997. Bioaccumulation of aluminium in the freshwater snail *Lymnaea stagnalis* at neutral pH. Environ. Pollut. 96(1): 29-33.

Elangovan, R., S. Ballance, K.N. White, C.R. McCrohan and J.J. Powell. 1999. Accumulation of aluminium by the freshwater crustacean *Asellus aquaticus* in neutral water. Environ. Pollut. 106(3): 257-263.

Elangovan, R., C.R. McCrohan, S. Ballance, J.J. Powell and K.N. White. 2000. Localization and fate of aluminium in the digestive gland of the freshwater snail *Lymnaea stagnalis*. Tissue Cell 32(1): 79-87.

Ellis, M.M. 1937. Detection and measurement of stream pollution. Bull. Bur. Fish. 48: 365-437.

Elsebae, A.A. 1994. Comparative susceptibility of the Alareesh Marine Culture Center shrimp *Penaeus japonicus* and the brine shrimp *Artemia salina* to different insecticides and heavy metals. Alexandria Sci. Exch. J. 15(3): 425-435.

Elwood, J.W., S.G. Hildebrand and J.J. Beauchamp. 1976. Contribution of gut contents to the concentration and body burden of elements in *Tipula spp.* from a spring-fed stream. J. Fish. Res. Board Can. 33: 1930-1938.

ENSR Consulting and Engineering. 1992a. Short-term chronic toxicity of aluminum to the fathead minnow (*Pimephales promelas*) under static renewal test conditions at four levels of water hardness. Doc. No. 8505-092-047, Prepared for Climax Metals Company, Golden, CO by ENSR Consulting and Engineering, Ft. Collins, CO, 120 pp.

ENSR Consulting and Engineering. 1992b. Chronic toxicity of aluminum to *Ceriodaphnia dubia* under static renewal test conditions at four levels of water hardness. Doc. No. 8505-092-047, Prepared for Climax Metals Company, Golden, CO by ENSR Consulting and Engineering, Ft. Collins, CO, 122 pp.

ENSR Consulting and Engineering. 1992c. Acute toxicity of aluminum to *Pimephales promelas* under static renewal test conditions at four levels of water hardness. Climax Metals Company, Golden, CO.

ENSR Consulting and Engineering. 1992d. Acute toxicity of aluminum to *Ceriodaphnia dubia* under static renewal test conditions at four levels of water hardness. Climax Metals Company, Golden, CO.

Eriksen, T.E., J.V. Arnekleiv and G. Kjaerstad. 2009. Short-term effects on riverine Ephemeroptera, Plecoptera, and Trichoptera of rotenone and aluminum sulfate treatment to eradicate *Gyrodactylus salaris*. J. Fresh. Ecol. 24(4): 597-607.

Ernst, A.G., B.P. Baldigo, G.E. Schuler, C.D. Apse, J.L. Carter, G.T. Lester and A.G. Ernst. 2008. Effects of habitat characteristics and water quality on macroinvertebrate communities along the Neversink River in southeastern New York, 1991-2001. Scientific Investigations Report. U.S. Geological Survey.

European Al Association. 2009. Systematic characterization of the relationship between BLM parameters and aluminum toxicity in *Daphnia magna*, *Ceriodaphnia dubia* and *Pseudokirchneriella subcapitata*. Draft of the Final Report, Chilean Mining and Metalurgy Research Center, Vitacura, Santiago, Chile. (Algae data summarized in Gensemer et al. 2018)

European Al Association. 2010. Effect of different test media composition in Al acute and chronic toxicity. Draft Report, Chilean Mining and Metalurgy Research Center, Vitacura, Santiago, Chile. (Chronic and algae data summarized in Gensemer et al. 2018).

Evans, D.H. 1987. The fish gill: site of action and model for toxic effects of environmental pollutants. Environ. Health Perspect. 71: 47-58.

Evans, R.E., S.B. Brown and T.J. Hara. 1988. The effects of aluminum and acid on the gill morphology in rainbow trout, *Salmo gairdneri*. Environ. Biol. Fishes 22(4): 299-311.

Everhart, W.H. and R.A. Freeman. 1973. Effects of chemical variations in aquatic environments. Volume II. Toxic effects of aqueous aluminum to rainbow trout. EPA-R3-73-011b. National Technical Information Service, Springfield, VA.

Exley, C. 2000. Avoidance of aluminum by rainbow trout. Environ. Toxicol. Chem. 19(4): 933-939.

Exley, C. 2003. A biogeochemical cycle for aluminium. J. Inorg. Biochem. 97: 1-7.

Exley, C., J.S. Chappell and J.D. Birchall. 1991. A mechanism for acute aluminium toxicity in fish. J. Theor. Biol. 151(3): 417-428.

Exley, C., A. Tollervey, G. Gray, S. Roberts and J.D. Birchall. 1993. Silicon, aluminium and the biological availability of phosphorus in algae. Proc. R. Soc. Lond. Ser. B Biol. Sci. 253: 93-99.

Exley, C., A.J. Wicks, R.B. Hubert and J.D. Birchall. 1994. Polynuclear aluminum and acute toxicity in the fish. J. Theor. Biol. 167: 415-416.

Exley, C., A.J. Wicks, R.B. Hubert and J.D. Birchall. 1996. Kinetic constraints in acute aluminium toxicity in the rainbow trout (*Oncorhynchus mykiss*). J. Theor. Biol. 179: 25-31.

Exley, C., J.K. Pinnegar and H. Taylor. 1997. Hydroxyaluminosilicates and acute aluminium toxicity in fish. J. Theor. Biol. 189(2): 133-139.

Fageria, N.K. 1985. Influence of aluminum in nutrient solutions on chemical composition in two rice cultivars at different growth stages. Plant Soil 85: 423-429.

Famoso, A.N., R.T. Clark, J.E. Shaff, E. Craft, S.R. McCouch and L.V. Kochian. 2010. Development of a novel aluminum tolerance phenotyping platform used for comparisons of cereal aluminum tolerance and investigations into rice aluminum tolerance mechanisms. Plant Physiol. 153: 1678-1691.

Farag, A.M., D.F. Woodward, E.E. Little, B.L. Steadman and F.A. Vertucci. 1993. The effects of low pH and elevated aluminum on Yellowstone cutthroat trout (*Oncorhynchus clarki* Bouvieri). Environ. Toxicol. Chem. 12: 719-731.

Fargasova, A. 2001. Winter third- to fourth-instar larvae of *Chironomus plumosus* as bioassay tools for assessment of acute toxicity of metals and their binary combinations. Ecotoxicol. Environ. Saf. 48(1): 1-5.

Fargasova, A. 2003. Cd, Cu, Zn, Al and their binary combinations acute toxicity for *Chironomus plumosus* larvae. Fresenius Environ. Bull. 12: 830-834.

Farringer, J.E. 1972. The determination of the acute toxicity of rotenone and bayer 73 to selected aquatic organisms. M.S. Thesis, University of Wisconsin, La Crosse, WI.

Fernandez-Davila, M.L., A.C. Razo-Estrada., S. Garcia-Medina, L.M. Gomez-Olivan, M.J. Pinon-Lopez, R.G. Ibarra and M. Galar-Martinez. 2012. Aluminum-induced oxidative stress and neurotoxicity in grass carp (Cyprinidae-*Ctenopharingodon idella*). Ecotoxicol. Environ. Saf. 76(1): 87-92.

Finn, R.N. 2007. The physiology and toxicology of salmonid eggs and larvae in relation to water quality criteria. Aquat. Toxicol. 81(4): 337-354.

Fischer, W.K. and P. Gode. 1977. Toxicological studies on natural aluminum silicates as additives to detergents using freshwater organisms. Vom Wasser 49: 11-26.

Fisher, D.W., A.W. Gambell, G.E. Likens and F.H. Bormann. 1968. Atmospheric contributions to water quality of streams in the Hubbard Brook Experimental Forest, New Hampshire. Water Resour. Res. 4: 1115-1126.

Fivelstad, S. and H. Leivestad. 1984. Aluminium toxicity to Atlantic salmon (*Salmo salar* L.) and brown trout (*Salmo trutta* L.): mortality and physiological response. Rep. No. 61, Inst. Fresh. Res., Nat. Swed. Board Fish., Drottningholm, Sweden, 70-77.

Fjellheim, A., G.G. Raddum and T. Sagen. 1985. Effect of aluminium at low pH on the mortality of elvers (*Anguilla anguilla* L.), a laboratory experiment. Verh. Int. Ver. Theor. Angew. Limnol. 22: 2544-2547.

Fok, P., J.G. Eales and S.B. Brown. 1990. Determination of 3,5,3"-triiodo-L-thyronine (T3) levels in tissues of rainbow trout (*Salmo gairdneri*) and the effects of low ambient pH and aluminum. Fish Physiol. Biochem. 8: 281-290.

Folsom, B.R., N.A. Popescu and J.M. Wood. 1986. Comparative study of aluminum and copper transport and toxicity in an acid-tolerant freshwater green alga. Environ. Sci. Technol. 20(6): 616-620.

Fort, D.J. and E.L. Stover. 1995. Impact of toxicities and potential interactions of flocculants and coagulant aids on whole effluent toxicity testing. Water Environ. Res. 67(6): 921-925.

Foy, C.D. and G.C. Gerloff. 1972. Response of *Chlorella pyrenoidosa* to aluminum and low pH. J. Phycol. 8: 268-271.

France, R.L. and P.M. Stokes. 1987. Influence of manganese, calcium, and aluminum on hydrogen ion toxicity to the amphipod *Hyalella azteca*. Can. J. Zool. 65(12): 3071-3078.

Freda, J. 1991. The effects of aluminum and other metals on amphibians. Environ. Pollut. 71(2-4): 305-328.

Freda, J. and D.G. McDonald. 1990. Effects of aluminum on the leopard frog, *Rana pipiens*: life stage comparisons and aluminum uptake. Can. J. Fish. Aquat. Sci. 47: 210-216.

Freda, J., V. Cavdek and D.G. McDonald. 1990. Role of organic complexation in the toxicity of aluminum to *Rana pipiens* embryos and *Bufo americanus* tadpoles. Can. J. Fish. Aquat. Sci. 47: 217-224.

Freeman, R.A. 1973. Recovery of rainbow trout from aluminum poisoning. Trans. Am. Fish. Soc. 102(1): 152-154.

Freeman, R.A. and W.H. Everhart. 1971. Toxicity of aluminum hydroxide complexes in neutral and basic media to rainbow trout. Trans. Am. Fish. Soc. 100(4): 644-658.

Frick, K.G. and J. Herrmann. 1990. Aluminum accumulation in a lotic mayfly at low pH - a laboratory study. Ecotoxicol. Environ. Saf. 19(1): 81-88.

Frink, C.R. 1996. A perspective on metals in soils. J. Soil Contam. 5(4): 329-359.

Fuma, S., N. Ishii, H. Takeda, K. Miyamoto, K. Yanagisawa, Y. Ichimasa, M. Saito, Z. Kawabata and G.G. Polikarpov. 2003. Ecological effects of various toxic agents on the aquatic microcosm in comparison with acute ionizing radiation. J. Environ. Radioact. 67(1): 1-14.

Gagen, C.J. 1986. Aluminum toxicity and sodium loss in three salmonid species along a pH gradient in a mountain stream. M.S. Thesis, PA State Univ., University Park, PA, 87 pp.

Gagen, C.J., W.E. Sharpe and R.F. Carline. 1993. Mortality of brook trout, mottled sculpins, and slimy sculpins during acidic episodes. Trans. Am. Fish. Soc. 122(4): 616-628.

Galindo, B.A., G. Troilo, I.M.S. Colus, C.B.R. Martinez and S.H. Sofia. 2010. Genotoxic effects of aluminum on the neotropical fish *Prochilodus lineatus*. Water Air Soil Pollut. 212(1-4): 419-428.

Gallon, C., C. Munger, S. Premont and P.G.C. Campbell. 2004. Hydroponic study of aluminum accumulation by aquatic plants: effects of fluoride and pH. Water Air Soil Pollut. 153(1-4): 135-155.

Galloway, J.M., J.C. Petersen, E.L. Shelby, J.A. Wise and J.M. Galloway. 2008. Water quality and biological characteristics of the middle fork of the Saline River, Arkansas, 2003-06. Scientific Investigations Report. U.S. Geological Survey.

Garcia, R., R. Belmont, H. Padilla, M.C. Torres and A. Baez. 2009. Trace metals and inorganic ion measurements in rain from Mexico City and a nearby rural area. Chem. Ecol. 25(2): 71-86.

Garcia-Garcia, G., S. Nandini, S.S.S. Sarma, F. Martinez-Jeronimo, J. Jimenez-Contreras and G. Garcia-Garcia. 2012. Impact of chromium and aluminium pollution on the diversity of zooplankton: a case study in the Chimaliapan wetland (ramsar site) (Lerma Basin, Mexico). J. Environ. Sci. Health Part A: Toxic/Hazard. Subst. Environ. Engin. 47(4): 534-547.

Garcia-Medina, S., A.C. Razo-Estrada, L.M. Gomez-Olivan, A. Amaya-Chavez, E. Madrigal-Bujaidar and M. Galar-Martinez. 2010. Aluminum-induced oxidative stress in lymphocytes of common carp (*Cyprinus carpio*). Fish Physiol. Biochem. 36(4): 875-882.

Garcia-Medina, S., C. Razo-Estrada, M. Galar-Martinez, E. Cortez-Barberena, L.M. Gomez-Olivan, I. Alvarez-Gonzalez and E. Madrigal-Bujaidar. 2011. Genotoxic and cytotoxic effects induced by aluminum in the lymphocytes of the common carp (*Cyprinus carpio*). Comp. Biochem. Physiol. C Toxicol. Pharmacol. 153(1): 113-118.

Garcia-Medina, S., J.A. Nunez-Betancourt, A.L. Garcia-Medina, M. Galar-Martinez, N. Neri-Cruz, H. Islas-Flores and L.M. Gomez-Olivan. 2013. The relationship of cytotoxic and genotoxic damage with blood aluminum levels and oxidative stress induced by this metal in common carp (*Cyprinus carpio*) erythrocytes. Ecotoxicol. Environ. Saf. 96: 191-197.

Gardner, J.L. and S.H. Al-Hamdani. 1997. Interactive effects of aluminum and humic substances on salvinia. J. Aquat. Plant Manag. 35: 30-34.

Gardner, M.J., E. Dixon, I. Sims and P. Whitehouse. 2002. Importance of speciation in aquatic toxicity tests with aluminum. Bull. Environ. Contam. Toxicol. 68(2): 195-200.

Gardner, M.J., B. Brown, P. Whitehouse and M. Birch. 2008. Towards the establishment of an environmental quality standard for aluminium in surface waters. J. Environ. Monit. 10(7): 877.

Gascon, C., D. Planas and G. Moreau. 1987. The interaction of pH, calcium and aluminum concentrations on the survival and development of wood frog (*Rana sylvatica*) eggs and tadpoles. Ann. R. Zool. Soc. Belgium 117: 189-199.

Gayer, K.H., C.L. Thompson and O.T. Zajacik. 1958. The solubility of aluminum hydroxide in acidic and basic media at 25°C. Can. J. Chem. 36: 1268-1271.

GEI Consultants, Inc. 2010. Ambient water quality standards for aluminum - review and update. Submitted to Colorado Mining Association. GEI Consultants, Inc., Ecological Division, Denver, CO.

Geiger, D.L., L.T. Brooke and D.J. Call. 1990. Acute toxicities of organic chemicals to fathead minnows (*Pimephales promelas*), Volume 5. Ctr. Lake Superior Environ. Stud., Univ. Wisconsin-Superior, Superior, WI, 332 pp.

Gensemer, R.W. 1989. Influence of aluminum and pH on the physiological ecology and cellular morphology of the acidophilic diatom *Asterionella ralfsii* var. *americana*. Ph.D. Thesis, Univ. Michigan, Ann Arbor, MI, 170 pp.

Gensemer, R.W. 1990. Role of aluminum and growth rate on changes in cell size and silica content of silica-limited populations of *Asterionella ralfsii* var. *americana* (Bacillariophyceae). J. Phycol. 26: 250-258.

Gensemer, R.W. 1991a. The effects of pH and aluminum on the growth of the acidophilic diatom *Asterionella ralfsii* var. *americana*. Limnol. Oceanogr. 36(1): 123-131.

Gensemer, R.W. 1991b. The effects of aluminum on phosphorus and silica-limited growth in *Asterionella ralfsii* var. *americana*. Verh. Internat. Verein. Limnol. 24: 2635-2639.

Gensemer, R.W. and R.C. Playle. 1999. The bioavailability and toxicity of aluminum in aquatic environments. Crit. Rev. Environ. Sci. Technol. 29(4): 315-450.

Gensemer, R.W., R.E.H. Smith and H.C. Duthie. 1993. Comparative effects of pH and aluminum on silica-limited growth and nutrient uptake in *Asterionella ralfsii* var. *americana* (Bacillariophyceae). J. Phycol. 29: 36-44.

Gensemer, R.W., R.E.H. Smith and H.C. Duthie. 1994. Interactions of pH and aluminum on cell length reduction in *Asterionella ralfsii* var. *americana* Korn. In: Proc.13th Int. Diatom Symp., 39-46.

Gensemer, R., J. Gondek, P. Rodriquez, J.J. Arbildua, W. Stubblefield, A. Cardwell, R. Santore, A. Ryan, W. Adams and E. Nordheim. 2018. Evaluating the effects of pH, hardness, and dissolved organic carbon on the toxicity of aluminum to freshwater aquatic organisms under circumneutral conditions. Environ. Toxicol. Chem. 37(1): 49-60.

Genter, R.B. 1995. Benthic algal populations respond to aluminum, acid, and aluminum-acid mixtures in artificial streams. Hydrobiol. 306(1): 7-19.

Genter, R.B. and D.J. Amyot. 1994. Freshwater benthic algal populations and community changes due to acidity and aluminum-acid mixtures in artificial streams. Environ. Toxicol. 13: 369-380.

Gibbons, M.V., F.D. Woodwick, W.H. Funk and H.L. Gibbons. 1984. Effects of multiphase restoration, particularly aluminum sulfate application, on the zooplankton community of a eutrophic lake in eastern Washington. J. Fresh. Ecol. 2: 393-404.

Gidde, M.R., A.R. Bhalerao and H. Tariq. 2012. Occurrence of aluminium concentration in surface water samples from different areas of Pune city. Intern. J. Emerg. Tech. Advan. Eng. 2(7): 215-219.

Gill, A.C., J.A. Robinson, J.E. Redmond, M.W. Bradley and A.C. Gill. 2008. Assessment of water-quality conditions in Fivemile Creek in the vicinity of the Fivemile Creek Greenway, Jefferson County, Alabama, 2003-2005. Scientific Investigations Report. U.S. Geological Survey.

Gilmore, R.L. 2009. Laboratory studies in chemically mediated phosphorus removal. M.S. Thesis. Wilfrid Laurier University, Waterloo, Ontario, Canada. 144 pp.

Gimmler, H., B. Treffny, M. Kowalski and U. Zimmermann. 1991. The resistance of *Dunaliella acidophila* against heavy metals: The importance of the zeta potential. J. Plant Physiol. 138(6): 708-716.

Gladden, B. 1987. The effect of aluminum on cortisol levels in goldfish (*Carassius auratus*). M.S. Thesis, Northwestern State University, Evanston, IL, 35 p.

Golomb, D., D. Ryan, N. Eby, J. Underhill and S. Zemba. 1997. Atmospheric deposition of toxics onto Massassachuted Bay – I. Metals. Atmos. Environ. 31: 1349-1359.

Goncharuk, V.V., V.B. Lapshin, M.A. Chichaeva, I.S. Matveeva, A.O. Samsoni-Todorov, V.V. Taranov and A.V. Syroezhkin. 2012. Heavy metals, aluminum, and arsenic in aerosols of the world ocean. J. Water Chem. Technol. 34(1): 1-10.

Goossenaerts, C., R. Van Grieken, W. Jacob, H. Witters and O. Vanderborght. 1988. A microanalytical study of the gills of aluminium-exposed rainbow trout (*Salmo gairdneri*). Int. J. Environ. Anal. Chem. 34: 227-237.

Gopalakrishnan, S., H. Thilagam and P.V. Raja. 2007. Toxicity of heavy metals on embryogenesis and larvae of the marine sedentary polychaete *Hydroides elegans*. Arch. Environ. Contam. Toxicol. 52(2): 171-178.

Goss, G.G. and C.M. Wood. 1988. The effects of acid and acid/aluminum exposure on circulating plasma cortisol levels and other blood parameters in the rainbow trout, *Salmo gairdneri*. J. Fish Biol. 32(1): 63-76.

Gostomski, F. 1990.The toxicity of aluminum to aquatic species in the US. Environ. Geochem. Health. 12: 51-54.

Government of Canada. 1998. Aluminum. Available online at: http://healthycanadians.gc.ca/publications/healthy-living-vie-saine/water-aluminum-eau/alt/water-aluminum-eau-eng.pdf.

Graham, J.M., P. Arancibia-Avila and L.E. Graham. 1996. Effects of pH and selected metals on growth of the filamentous green alga mougeotia under acidic conditions. Limnol. Oceanogr. 41(2): 263-270.

Greenwood, N.N. and A. Earnshaw. 1997. Chemistry of the Elements (2nd Edition). Elsevier Butterworth–Heinemann, Burlington, MA. 217 pp.
Greger, M., J.E. Tillberg and M. Johansson. 1992a. Aluminium effects on *Scenedesmus obtusiusculus* with different phosphorus status. I. Mineral uptake. Physiol. Plant. 84: 193-201.

Greger, M., J.E. Tillberg and M. Johansson. 1992b. Aluminium effects on *Scenedesmus obtusiusculus* with different phosphorus status. II. Growth, photosynthesis and pH. Physiol. Plant. 84: 202-208.

Gregor, J., D. Jancula and B. Marsalek. 2008. Growth assays with mixed cultures of cyanobacteria and algae assessed by in vivo fluorescence: One step closer to real ecosystems? Chemosphere 70: 1873-1878.

Griffitt, R.J., J. Luo, J. Gao, J.C. Bonzongo and D.S. Barber. 2008. Effects of particle composition and species on toxicity of metallic nanomaterials in aquatic organisms. Environ. Toxicol. Chem. 27(9): 1972-1978.

Griffitt, R.J., A. Feswick, R. Weil, K. Hyndman, P. Carpinone, K. Powers, N.D. Denslow, D.S. Barber and R.J. Griffitt. 2011. Investigation of acute nanoparticulate aluminum toxicity in zebrafish. Environ. Toxicol. 26(5): 541-551.

Guerold, F., L. Giamberini, J.L. Tourmann, J.C. Pihan and R. Kaufmann. 1995. Occurrence of aluminium in chloride cells of *Perla marginata* (Plecoptera) after exposure to low pH and elevated aluminum concentration. Bull. Environ. Contam. Toxicol. 54(4): 620-625.

Gundersen, D.T., S. Bustaman, W.K. Seim and L.R. Curtis. 1994. pH, hardness, and humic acid influence aluminum toxicity to rainbow trout (*Oncorhynchus mykiss*) in weakly alkaline waters. Can. J. Fish. Aquat. Sci. 51: 1345-1355.

Gunn, J.M. and W. Keller. 1984. Spawning site water chemistry and lake trout (*Salvelinus namaycush*) sac fry survival during spring snow melt. Can. J. Fish. Aquat. Sci. 41: 319-329.

Gunn, J.M. and D.L.G. Noakes. 1986. Avoidance of low pH and elevated Al concentrations by brook charr (*Salvelinus fontinalis*) alevins in laboratory tests. Water Air Soil Pollut. 30: 497-503.

Gunn, J.M. and D.L.G. Noakes. 1987. Latent effects of pulse exposure to aluminum and low pH on size, ionic composition, and feeding efficiency of lake trout (*Salvelinus namaycush*) alevins. Can. J. Fish. Aquat. Sci. 44: 1418-1424.

Guo, T.R., P.C. Yao, Z.D. Zhang, J.J. Wang and M. Wang. 2012. Involvement of antioxidative defense system in rice seedlings exposed to aluminum toxicity and phosphorus deficiency. Rice Sci. 19(3): 207-212.

Guthrie, R.K., F.L. Singleton and D.S. Cherry. 1977. Aquatic bacterial populations and heavy metals - II. Influence of chemical content of aquatic environments on bacterial uptake of chemical elements. Water Res. 11: 643-646.

Guzman, F.T., F.J.A. Gonzalez and R.R. Martinez. 2010. Implementing *Lecane quadridentata* acute toxicity tests to assess the toxic effects of selected metals (Al, Fe and Zn). Ecotoxicol. Environ. Saf. 73: 287-295.

Hackett, C. 1967. Ecological aspects of the nutrition of *Deschampsia flexuosa* (L.) Trin. III. Investigation of phosphorus requirement and response to aluminium in water culture, and a study of growth in soil. J. Ecol. 55: 831-840.

Hall Jr., L.W., A.E. Pinkney, L.O. Horseman and S.E. Finger. 1985. Mortality of striped bass larvae in relation to contaminants and water quality in a Chesapeake Bay tributary. Trans. Am. Fish. Soc. 114(6): 861-868.

Hall, R.J., C.T. Driscoll and G.E. Likens. 1987. Importance of hydrogen ions and aluminium in regulating the structure and function of stream ecosystems: an experimental test. Fresh. Biol. 18: 17-43.

Hamilton, S.J. and T.A. Haines. 1995. Influence of fluoride on aluminum toxicity to Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 52(11): 2432-2444.

Hamilton-Taylor, J., M. Willis and C.S. Reynolds. 1984. Depositional fluxes of metals and phytoplankton in Windermere as measured by sediment traps. Limnol. Oceanogr. 29: 695-710.

Handy, R.D. 1993. The accumulation of dietary aluminium by rainbow trout, *Oncorhynchus mykiss*, at high exposure concentrations. J. Fish Biol. 42: 603-606.

Handy, R.D. and F.B. Eddy. 1989. Surface absorption of aluminium by gill tissue and body mucus of rainbow trout, *Salmo gairdneri*, at the onset of episodic exposure. J. Fish. Biol. 34(6): 865-874.

Hanks, R.W. 1965. Effect of metallic aluminum particles on oysters and clams. Chesapeake Sci. 6(3): 146-149.

Harford, A.J., A.C. Hogan, J.J. Tsang, D.L. Parry, A.P. Negri, M.S. Adams, J.L. Stauber and R.A. Van Dam. 2011. Effects of alumina refinery wastewater and signature metal constituents at the upper thermal tolerance of: 1. The tropical diatom *Nitzschia closterium*. Mar. Pollut. Bull.62: 466-473.

Harper, S., C. Usenko, J.E. Hutchinson, B.L.S. Maddux and R.L. Tanguay. 2008. In vivo biodistribution and toxicity depends on nanomaterial composition, size, surface functionalisation and route of exposure. J. Exp. Nanosci. 3(3): 195-206.

Harry, H.W. and D.V. Aldrich. 1963. The distress syndrome in *Taphius glabratus* (Say) as a reaction to toxic concentrations of inorganic ions. Malacol. 1(2): 283-289.

Havas, M. 1985. Aluminum bioconcentration and toxicity to *Daphnia magna* in soft water at low pH. Can. J. Fish. Aquat. Sci. 42: 1741-1748.

Havas, M. 1986a. Effects of aluminum on aquatic biota. In: M. Havas and J.F. Jaworski (*Eds*.), Publ. No. 24759, Aluminum in the Canadian Environment. Natl. Res. Counc. Can., Ottawa, Ontario, 79-127.

Havas, M. 1986b. Aluminum chemistry of inland waters. In: M. Havas and J.F. Jaworski (*Eds.*), Publ. No 24759, Aluminum in the Canadian Environment. Natl. Res. Counc. Can., Ottawa, Ontario, 51-77.

Havas, M. and T.C. Hutchinson. 1982. Aquatic invertebrates from the Smoking Hills, N.W.T.: effect of pH and metals on mortality. Can. J. Fish. Aquat. Sci. 39: 890-903.

Havas, M. and T.C. Hutchinson. 1983. Effect of low pH on the chemical composition of aquatic invertebrates from tundra ponds at the Smoking Hills, N.W.T., Canada. Can. J. Zool. 61(1): 241-249.

Havas, M., and J.F. Jaworski. 1986. Aluminum in the Canadian Environment. Natl. Res. Counc. Can., Ottawa, Ontario, Publication No. 24759.

Havas, M. and G.E. Likens. 1985a. Changes in ^{22}Na influx and outflux in *Daphnia magna* (Straus) as a function of elevated A1 concentrations in soft water at low pH. Proc. Natl. Acad. Sci. U.S.A. 82, 7345-7349.

Havas, M. and G.E. Likens. 1985b. Toxicity of aluminum and hydrogen ions to *Daphnia catawba*, *Holopedium gibberum*, *Chaoborus punctipennis*, and *Chironomus anthrocinus* from Mirror Lake, N.H. Can. J. Zool. 63: 1114-1119.

Havens, K.E. 1990. Aluminum binding to ion exchange sites in acid-sensitive versus acid-tolerant cladocerans. Environ. Pollut. 64: 133-141.

Havens, K.E. 1991. Littoral zooplankton responses to acid and aluminum stress during short-term laboratory bioassays. Environ. Pollut. 73(1): 71-84.

Havens, K. 1992. Acid and aluminum effects on sodium homeostasis and survival of acid-sensitive and acid-tolerant cladoceran. Can. J. Fish. Aquat. Sci. 49: 2392-2398.

Havens, K.E. 1993a. Acid and aluminum effects on the survival of littoral macro-invertebrates during acute bioassays. Environ. Pollut. 80: 95-100.

Havens, K.E. 1993b. Acid and aluminum effects on osmoregulation and survival of the freshwater copepod *Skistodiaptomus oregonensis*. J. Plankton Res. 15: 683-691.

Havens, K.E. and J. DeCosta. 1987. The role of aluminium contamination in determining phytoplankton and zooplankton responses to acidification. Water Air Soil Pollut. 33(3-4): 277-293.

Havens, K.E. and R.T. Heath. 1989. Acid and aluminum effects on freshwater zooplankton: an in situ mesocosm study. Environ. Pollut. 62(2/3): 195-211.

Havens, K.E. and R.T. Heath. 1990. Phytoplankton succession during acidification with and without increasing aluminum levels. Environ. Pollut. 68(1/2): 129-145.

Heier, L.S., H.C. Teien, D. Oughton, K.E. Tollefsen, P.A. Olsvik, B.O. Rosseland, O.C. Lind, E. Farmen, L. Skipperud and B. Salbu. 2012. Sublethal effects in Atlantic salmon (*Salmo salar*) exposed to mixtures of copper, aluminium and gamma radiation. J. Environ. Radioact. (0).

Helliwell, S., G.E. Batley, T.M. Florence and B.G. Lumsden. 1983. Speciation and toxicity of aluminum in a model fresh water. Environ. Technol. Lett. 4: 141-144.

Hem, J.D. 1986a. Aluminum species in water. In: Trace inorganics in water. R.A. Baker. (*Ed.*) Advances in Chemistry Series 73. American Chemical Society, Washington, DC, 98-114.

Hem, J.D. 1968b. Graphical methods for studies of aqueous aluminum hydroxide, fluoride, and sulfate complexes. Water Supply Paper 1827-B. U.S. Geological Survey, U.S. Government Printing Office, Washington, DC.

Hem, J.D. and C.E. Roberson. 1967. Form and stability of aluminum hydroxide complexes in dilute solution. Water Supply Paper 1827-A. U.S. Geological Survey, U.S. Government Printing Office, Washington, DC.

Heming, T.A. and K.A. Blumhagen. 1988. Plasma acid-base and electrolyte states of rainbow trout exposed to alum (aluminum sulphate) in acidic and alkaline environments. Aquat. Toxicol. 12(2): 125-140.

Herkovits, J., F.D. Herkovits and C.S. Perez-Coll. 1997. Identification of aluminum toxicity and aluminum-zinc interaction in amphibian *Bufo arenarum* embryos. Environ. Sci. 5(1): 57-64.

Herrmann, J. and K.G. Andersson. 1986. Aluminium impact on respiration of lotic mayflies at low pH. Water Air Soil Pollut. 30: 703-709.

Herrmann, J. and K. Frick. 1995. Do stream invertebrates accumulate aluminium at low pH conditions? Water Air Soil Pollut. 85: 407-412.

Hesse, P.R. 1963. Phosphorus relationships in a mangrove-swamp mud with particular reference to aluminium toxicity. Plant Soil 19(2): 205-218.

Hickie, B.E., N.J. Hutchinson, D.G. Dixon and P.V. Hodson. 1993. Toxicity of trace metal mixtures to alevin rainbow trout (*Oncorhynchus mykiss*) and larval fathead minnow (*Pimephales promelas*) in soft, acidic water. Can. J. Fish. Aquat. Sci. 50: 1348-1355.

Hill, A.J., H. Teraoka, W. Heideman and R.E. Peterson. 2005. Zebrafish as a model vertebrate for investigating chemical toxicity. Toxicol. Sci. 86(1): 6-19.

Hockett, J.R. and D.R. Mount. 1996. Use of metal chelating agents to differentiate among sources of acute aquatic toxicity. Environ. Toxicol. Chem. 15(10): 1687-1693.

Hoffman, G.L., R.A. Duce and W.H. Zoller. 1969. Vanadium, copper, and aluminum in the lower atmosphere between California and Hawaii. Environ. Sci. Technol. 3: 1207-1210.

Hofler, K. 1958. Action of aluminum salts on *Spirogyra* and *Zygnema*. Protoplasma 49: 248.

Holtze, K.E. 1983. Effects of pH and ionic strength on aluminum toxicity to early developmental stages of rainbow trout (*Salmo gairdneri* Richardson). Res. Rep., Ontario Ministry of the Environment, Rexdale, Ontario, Canada, 39 pp.

Holtze, K.E. and N.J. Hutchinson. 1989. Lethality of low pH and Al to early life stages of six fish species inhabiting Precambrian shield waters in Ontario. Can. J. Fish. Aquat. Sci. 46(1): 1188-1202.

Horne, M.T. and W.A. Dunson. 1994. Exclusion of the Jefferson salamander, *Ambystoma jeffersonianum,* from some potential breeding ponds in Pennsylvania: effects of pH, temperature, and metals on embryonic development. Arch. Environ. Contam. Toxicol. 27(3): 323-330.

Horne, M.T. and W.A. Dunson. 1995a. Toxicity of metals and low pH to embryos and larvae of the Jefferson salamander, *Ambystoma jeffersonianum*. Arch. Environ. Contam. Toxicol. 29(1): 110-114.

Horne, M.T. and W.A. Dunson. 1995b. Effects of low pH, metals, and water hardness on larval amphibians. Arch. Environ. Contam. Toxicol. 29(4): 500-505.

Hornstrom, E., C. Ekstrom and M.O. Duraini. 1984. Effects of pH and different levels of aluminium on lake plankton in the Swedish west coast area. Rep. No. 61, Natl. Swed. Board Fish., Drottningholm, Sweden, 115-127.

Hornstrom, E., A. Harbom, F. Edberg and C. Andren. 1995. The influence of pH on aluminium toxicity in the phytoplankton species *Monoraphidium dybowskii* and *M. griffithii*. Water Air Soil Pollut. 85(2): 817-822.

Howells, G.D., D.J.A. Brown and K. Sadler. 1983. Effects of acidity, calcium, and aluminium on fish survival and productivity - a review. J. Sci. Food Agric. 34: 559-570.

Howells, G., T.R.K. Dalziel, J.P. Reader and J.F. Solbe. 1990. EIFAC water quality criteria for European freshwater fish: report on aluminium. Chem. Ecol. 4: 117-173.

HSDB (Hazardous Substances Data Bank). 2008. Aluminum and compounds. National Library of Medicine, Bethesda, MD.

Hsu, P.H. 1968. Interaction between aluminum and phosphate in aqueous solution. In: Trace inorganics in water. R.A. Baker (*Ed.*). Advances in Chemistry Series 73. American Chemical Society, Washington, DC, 115-127.

Huebner, J.D. and K.S. Pynnonen. 1992. Viability of glochidia of two species exposed to low pH and selected metals. Can. J. Zool. 70: 2348-2355.

Hunn, J.B., L. Cleveland and E.E. Little. 1987. Influence of pH and aluminum on developing brook trout in a low calcium water. Environ. Pollut. 43(1): 63-73.

Hunter, J.B., S.L. Ross and J. Tannahill. 1980. Aluminum pollution and fish toxicity. Water Pollut. Control 79(3): 413-420.

Husaini, Y. and L.C. Rai. 1992. pH dependent aluminium toxicity to *Nostoc linckia*: studies on phosphate uptake, alkaline and acid phosphatase activity, ATP content, and photosynthesis and carbon fixation. J. Plant Physiol. 139: 703-707.

Husaini, Y., L.C. Rai and N. Mallick. 1996. Impact of aluminium, fluoride and fluoroaluminate complex on ATPase activity of *Nostoc linckia* and *Chlorella vulgaris*. Biometals 9(3): 277-283.

Hutchinson, N.J. and J.B. Sprague. 1986. Toxicity of trace metal mixtures to American flagfish (*Jordanella floridae*) in soft, acidic water and implications for cultural acidification. Can. J. Fish. Aquat. Sci. 43: 647-655.

Hutchinson, N.J., K.E. Holtze, J.R. Munro and T.W. Pawson. 1987. Lethal responses of salmonid early life stages to H+ and Al in dilute waters. Ann. R. Zool. Soc. Belgium 117(Suppl.): 201-217.

Hwang, H.M. 2001. Lysosomal responses to environmental contaminants in bivalves. Ph.D. Thesis, Texas A&M, College Station, TX, 179 p.

Hydes, D.J. and P.S. Liss. 1977. Behavior of dissolved aluminum in estuarine and coastal waters. Estuar. Coast. Mar. Sci. 5: 755-769.

Hyne, R.V. and S.P. Wilson. 1997. Toxicity of acid-sulphate soil leachate and aluminium to the embryos and larvae of Australian bass (*Macquaria novemaculeata*) in estuarine water. Environ. Pollut. 97(3): 221-227.

Ingersoll, C.G. 1986. The effects of pH, aluminum, and calcium on survival and growth of brook trout (*Salvelinus fontinalis*) early life stages. Ph.D Thesis, Univ. Wyoming, Laramie, WY.

Ingersoll, C.G., D.D. Gulley, D.R. Mount, M.E. Mueller, J.D. Fernandez, J.R. Hockett and H.L. Bergman. 1990a. Aluminum and acid toxicity to two strains of brook trout (*Salvelinus fontinalis*). Can. J. Fish. Aquat. Sci. 47: 1641-1648.

Ingersoll, C.G., D.A. Sanchez, J.S. Meyer, D.D. Gulley and J.E. Tietge. 1990b. Epidermal response to pH, aluminum, and calcium exposure in brook trout (*Salvelinus fontinalis*) fry. Can. J. Fish. Aquat. Sci. 47: 1616-1622.

Ingersoll, C.G., D.R. Mount, D.D. Gulley, T.W. LaPoint and H.L. Bergman. 1990c. Effects of pH, aluminum, and calcium on survival and growth of eggs and fry of brook trout (*Salvelinus fontinalis*). Can. J. Fish. Aquat. Sci. 47: 1580-1592.

Ivey, C., N. Wang, W. Brumbaugh and C. Ingersoll. 2014. Columbia Environmental Research Center (CERC) preliminary summary for acute aluminum toxicity tests with freshwater mussels. Memorandum to Ed Hammer. Dated August 3, 2014. U.S. Geological Survey, CERC, Columbia, MO.

Jagoe, C.H. and T.A. Haines. 1997. Changes in gill morphology of Atlantic salmon (*Salmo salar*) smolts due to addition of acid and aluminum to stream water. Environ. Pollut. 97(1/2): 137-146.

Jain, S., S. Sharma, A. Rajawat, N. Upreti, S. Sharma and K.P. Sharma. 2012. Acute and chronic toxicity of aluminium fluoride to flora and fauna in a microcosm. Nat. Environ. Pollut. Technol.11(1): 7-15.

Jan, F. and H. Matsumoto. 1999. Early effects of aluminium on nutrient (K, Ca, and Mg) status of different root zones of two rice cultivars. Toxicol. Environ. Chem. 69: 43-48.

Jan, F. and S. Pettersson. 1993. Effects of low aluminium levels on growth and nutrient relations in three rice cultivars with different tolerances to aluminium. J. Plant Nutr. 16(2): 359-372.

Jancula, D., P. Mikula and B. Marsalek. 2011. Effects of polyaluminium chloride on the freshwater invertebrate *Daphnia magna*. Chem. Ecol. 27(4): 351-357.

Jaworska, M. and P. Tomasik. 1999. Metal-metal interactions in biological systems. Part VI. Effect of some metal ions on mortality, pathogenicity and reproductivity of *Steinernema carpocapsae* and *Heterorhabditis bacteriophora* entomopathogenic nematodes under laboratory conditions. Water Air Soil Pollut. 110(1-2): 181-194.

Jaworska, M., J. Sepiol and P. Tomasik. 1996. Effect of metal ions under laboratory conditions on the entomopathogenic *Steinernema carpocapsae* (Rhabditida: Steinernematidae). Water Air Soil Pollut. 88(3/4): 331-341.

Jaworska, M., A. Gorczyca, J. Sepiol and P. Tomasik. 1997. Effect of metal ions on the entomopathogenic nematode *Heterorhabditis bacteriophora* Poinar (Nematode: Heterohabditidae) under laboratory conditions. Water Air Soil Pollut. 93: 157-166.

Jay, F.B. and R.J. Muncy. 1979. Toxicity to channel catfish of wastewater from an Iowa coal beneficiation plant. Iowa State J. Res. 54: 45-50.

Jensen, F.B. and H. Malte. 1990. Acid-base and electrolyte regulation, and haemolymph gas transport in crayfish, *Astacus astacus*, exposed to soft, acid water with and without aluminium. J. Comp. Physiol. B Biochem. Syst. Environ. Physiol. 160: 483-490.

Jensen, F.B. and R.E. Weber. 1987. Internal hypoxia-hypercapnia in tench exposed to aluminium in acid water: effects on blood gas transport, acid-base status and electrolyte composition in arterial blood. J. Exp. Biol. 127: 427-442.

Ji, J., Z. Long and D. Lin. 2011. Toxicity of oxide nanoparticles to the green algae *Chlorella* sp. Chem. Eng. J. 170: 525-530.

Jones, J.R.E. 1939. The relation between the electrolytic solution pressures of the metals and their toxicity to the stickleback (*Gasterosteus aculeatus* L.). J. Exp. Biol. 16(4): 425-437.

Jones, J.R.E. 1940. A further study of the relation between toxicity and solution pressure, with *Polycelis nigra* as test animal. J. Exp. Biol. 17: 408-415.

Jones, B.F., V.C. Kennedy and G.W. Zellweger. 1974. Comparison of observed and calculated concentrations of dissolved Al and Fe in stream water. Water Res. 10(4): 791-793.

Jonsson, C.M., L.C. Paraiba and H. Aoyama. 2009. Metals and linear alkylbenzene sulphonate as inhibitors of the algae *Pseudokirchneriella subcapitata* acid phosphatase activity. Ecotoxicol.18: 610-619.

Juhel, G., E. Batisse, Q. Hugues, D. Daly, F.N. Van Pelt, J. O'halloran, M.A. Jansen and G. Juhel. 2011. Alumina nanoparticles enhance growth of *Lemna minor*. Aquat. Toxicol. 105(3-4): 328-336.

Jung, R.E. and C.H. Jagoe. 1995. Effects of low pH and aluminum on body size, swimming performance, and susceptibility to predation of green tree frog (*Hyla cinerea*) tadpoles. Can. J. Zool. 73(12): 2171-2183.

Kadar, E., J. Salanki, R. Jugdaohsingh, J.J. Powell, C.R. McCrohan and K.N. White. 2001. Avoidance responses to aluminium in the freshwater bivalve *Anodonta cygnea*. Aquat. Toxicol. 55(3/4): 137-148.

Kadar, E., J. Salanki and J. Powell. 2002. Effect of sub-lethal concentrations of aluminium on the filtration activity of the freshwater mussel *Anodonta cygnea* L. at neutral pH. Acta Biol. Hung. 53(4): 485-494.

Kaiser, K.L.E. 1980. Correlation and prediction of metal toxicity to aquatic biota. Can. J. Fish. Aquat. Sci. 37: 211-218.

Kane, D.A. 1984. Effects of low pH and aluminum on early life stages of smallmouth bass (*Micropterus dolomieui*). M.S. Thesis, Univ. Missouri, Columbia, MO. 70 p.

Kane, D.A. and C.F. Rabeni. 1987. Effects of aluminum and pH on the early life stages of smallmouth bass (*Micropterus dolomieui*). Water Res. 21(6): 633-639.

Karlsson-Norrgren, L., I. Bjorklund, O. Ljungberg and P. Runn. 1986a. Acid water and aluminium exposure: experimentally induced gill lesions in brown trout, *Salmo trutta* L. J. Fish Dis. 9(1): 11-25.

Karlsson-Norrgren, L., W. Dickson, O. Ljungberg and P. Runn. 1986b. Acid water and aluminium exposure: gill lesions and aluminium accumulation in farmed brown trout, *Salmo trutta* L. J. Fish Dis. 9(1): 1-9.

Keinanen, M., S. Peuranen., C. Tigerstedt and P.J. Vuorinen. 1998. Ion regulation in whitefish (*Coregonus lavaretus* L.) yolk-sac fry exposed to low pH and aluminum at low and moderate ionic strength. Ecotoxicol. Environ. Saf. 40(1/2): 166-172.

Keinanen, M., S. Peuranen, M. Nikinmaa, C. Tigerstedt and P.J. Vuorinen. 2000. Comparison of the responses of the yolk-sac fry of pike (*Esox lucius*) and roach (*Rutilus rutilus*) to low pH and aluminium: sodium influx, development and activity. Aquat. Toxicol. 47(3-4): 161-179.

Keinanen, M., C. Tigerstedt, P. Kalax and P.J. Vuorinen. 2003. Fertilization and embryonic development of whitefish (*Coregonus lavaretus lavaretus*) in acidic low-ionic-strength water with aluminum. Ecotoxicol. Environ. Saf. 55(3): 314-329.

Keinanen, M., C. Tigerstedt, S. Peuranen and P.J. Vuorinen. 2004. The susceptibility of early developmental phases of an acid-tolerant and acid-sensitive fish species to acidity and aluminum. Ecotoxicol. Environ. Saf. 58(2): 160-172.

Khangarot, B.S. 1991. Toxicity of metals to a freshwater tubificid worm, *Tubifex tubifex* (Muller). Bull Environ. Contam. Toxicol. 46: 906-912.

Khangarot, B.S. and S. Das. 2009. Acute toxicity of metals and reference toxicants to a freshwater ostracod, *Cypris subglobosa* Sowerby, 1840 and correlation to EC_{50} values of other test models. J. Hazard. Mater. 172: 641-649.

Khangarot, B.S. and P.K. Ray. 1989. Investigation of correlation between physicochemical properties of metals and their toxicity to the water flea *Daphnia magna* Straus. Ecotoxicol. Environ. Saf. 18(2): 109-120.

Kimball, G. 1978. The effects of lesser known metals and one organic to fathead minnows (*Pimephales promelas*) and *Daphnia magna*. Dept. Entomol. Fish. Wild., Univ. Minnesota, Minneapolis, MN, 88 pp.

King, S.O., C.E. Mach and P.L. Brezonik. 1992. Changes in trace metal concentrations in lake water and biota during experimental acidification of Little Rock Lake, Wisconsin, USA. Environ. Pollut. 78: 9-18.

Kinross, J.H., P.A. Read and N. Christofi. 2000. The influence of pH and aluminium on the growth of filamentous algae in artificial streams. Arch. Hydrobiol. 149(1): 67-86.

Kitamura, H. 1990. Relation between the toxicity of some toxicants to the aquatic animals (*Tanichthys albonubes* and *Neocaridina denticulata*) and the hardness of the test solution. Bull. Fac. Fish. Nagasaki Univ. (Chodai Sui Kempo) 67: 13-19.

Klaprat, D.A., S.B. Brown and T.J. Hara. 1988. The effect of low pH and aluminum on the olfactory organ of rainbow trout, *Salmo gairdneri*. Environ. Biol. Fish. 22(1): 69-77.

Klauda, R.J. and R.E. Palmer. 1987. Responses of blueback herring eggs and larvae to pulses of acid and aluminum. Trans. Am. Fish. Soc. 116(4): 561-569.

Klauda, R.J., R.E. Palmer and M.J. Lenkevich. 1987. Sensitivity of early life stages of blueback herring to moderate acidity and aluminum in soft freshwater. Estuaries 10(1): 44-53.

Klimek, B., E. Fialkowska, J. Fyda, W. Kocerba-Soroka, A. Pajdak-Stos and L. Sobczyk. 2013. The toxicity of aluminium salts to *Lecane inermis* rotifers: Are chemical and biological methods used to overcome activated sludge bulking mutually exclusive? Arch. Environ. Prot. 39(3): 127-138.

Kline, E. 1992. The effects of organic complexation on aluminum toxicity to rainbow trout (*Oncorhynchus mykiss*). M.S. Thesis, Univ. Wyoming, WY, 68 p.

Klusek, C.S., M. Heit and S. Hodgkiss. 1993. Trace element concentrations in the soft tissue of transplanted freshwater mussels near a coal-fired power plant. In: R.F. Keefer and K.S. Sajwan (*Eds.*), Trace elements in coal and coal combustion residues. Boca Raton, FL.

Knapp, S.M. and R.A. Soltero. 1983. Trout-zooplankton relationships in Medical Lake, WA following restoration by aluminum sulfate treatment. J. Fresh. Ecol. 2: 1-12.

Kobbia, I.A., A.E. Dowidar, E.F. Shabana and S.A. El-Attar. 1986. Studies on the effects of some heavy metals on the biological activities of some phytoplankton species I. Differential tolerance of some Nile phytoplanktonic populations in cultures to the effects of some heavy metals. Egypt. J. Physiol. Sci. 13(1/2): 29-54.

Kong, F.X. and Y. Chen. 1995. Effect of aluminum and zinc on enzyme activities in the green alga *Selenastrum capricornutum*. Bull. Environ. Contam. Toxicol. 55(5): 759-765.

Kovacevic, G., D. Zeljezic, K. Horvatin and M. Kalafatic. 2007. Morphological features and comet assay of green and brown hydra treated with aluminium. Symbiosis 44(1-3): 145-152.

Kovacevic, G., G. Gregorovic, M. Kalafatic and I. Jaklinovic. 2009a. The effect of aluminium on the planarian *Polycelis felina* (Daly.). Water Air Soil Pollut. 196(1-4): 333-344.

Kovacevic, G, M. Kalafatic, K. Horvatin and G. Kovacevic. 2009b. Aluminium deposition in hydras. Folia Biologica 57(3-4): 139-142.

Kowalczyk, G.S., G.E. Gordon and S.W. Rheingrover. 1982. Identification of atmospheric particulate sources in Washington, DC, using chemical element balances. Environ. Sci. Technol. 16: 79-90.

Krishnasamy, V. and D.V. Seshu. 1990. Phosphine fumigation influence on rice seed germination and vigor. Crop Sci. 30: 82-85.

Kroglund, F., B. Finstad, S.O. Stefansson, T.O. Nilsen, T. Kristensen, B.O. Rosseland, H.C. Teien and B. Salbu. 2007. Exposure to moderate acid water and aluminum reduces Atlantic salmon post-smolt survival. Aquacult. 273(2-3): 360-373.

Kroglund, F., B.O. Rosseland, H.C. Teien, B. Salbu, T. Kristensen and B. Finstad. 2008. Water quality limits for Atlantic salmon (*Salmo salar* L.) exposed to short term reductions in pH and increased aluminum simulating episodes. Hydrol. Earth Syst. Sci. 12(2): 491-507.

Kroglund, F., B. Finstad, K. Pettersen, H.C. Teien, B. Salbu, B.O. Rosseland, T.O. Nilsen, S. Stefansson, L.O.E. Ebbesson, R. Nilsen, P.A. Bjorn and T. Kristensen. 2012. Recovery of Atlantic salmon smolts following aluminum exposure defined by changes in blood physiology and seawater tolerance. Aquacult. 362-363: 232-240.

Kudlak, B., L. Wolska and J. Namiesnik. 2011. Determination of EC_{50} in toxicity data of selected heavy metals toward *Heterocypris incongruens* and their comparison to "direct-contact" and microbiotests. Environ. Monit. Assess. 174: 509-516.

Kumar, K.S., K.S. Sajwan, J.P. Richardson and K. Kannan. 2008. Contamination profiles of heavy metals, organochlorine pesticides, polycyclic aromatic hydrocarbons and alkylphenols in sediment and oyster collected from marsh/estuarine Savannah GA, USA. Mar. Pollut. Bull. 56: 136-162.

Kure, E.H., M. Saebo, A.M. Stangeland, J. Hamfjord, S. Hytterod, J. Heggenes and E. Lydersen. 2013. Molecular responses to toxicological stressors: Profiling microRNAs in wild Atlantic salmon (*Salmo salar*) exposed to acidic aluminum-rich water. Aquat. Toxicol. 138-139: 98-104.

Lacroix, G.L., R.H. Peterson, C.S. Belfry and D.J. Martin-Robichaud. 1993. Aluminum dynamics on gills of Atlantic salmon fry in the presence of citrate and effects on integrity of gill structures. Aquat. Toxicol. 27(3/4): 373-402.

Laitinen, M. and T. Valtonen. 1995. Cardiovascular, ventilatory and haematological responses of brown trout (*Salmo trutta* L.), to the combined effects of acidity and aluminium in humic. Aquat. Toxicol. 31(2): 99-112.

Lamb, D.S. and G.C. Bailey. 1981. Acute and chronic effects of alum to midge larvae (Diptera: Chironomidae). Bull. Environ. Contam. Toxicol. 27: 59-67.

Lamb, D.S. and G.C. Bailey. 1983. Effects of aluminum sulfate to midge larvae (Diptera: Chironomidae) and rainbow trout (*Salmo gairdneri*). EPA 440/5-83-001, Lake Restoration, Protection and Management, 307-312.

Landis, M. and G.J. Keeler. 1997. Critical evaluation of a modified automatic wet-only precipitation collector for mercury and trace element determinations. Environ. Sci. Technol. 31: 2610-2615.

Lange, J.E. 1985. Toxicity of aluminum to selected freshwater invertebrates in water of pH 7.5. Prepared for D.J. Call and L.T. Brooke, 20 pp.

Lantzy, R.J. and F.T. MacKenzie. 1979. Atmospheric trace metals: global cycles and assessment of man's impact. Geochim. Cosmochim. Acta 43(4): 511-525.

Lee, H.C., P.N. Lu, H.L. Huang, C. Chu, H.P. Li and H.J. Tsai. 2014. Zebrafish transgenic line *huORFZ* is an effective living bioindicator for detecting environmental toxicants. PLoS One 9(3): e90160.

Lee, P.F. and P. Hughes. 1998. A plant bioassay protocol for sediment heavy metal toxicity studies using wild rice as an indicator species. In: R. Clement and B. Burk (*Eds.*), Enviroanalysis Proceedings. Biennial International Conference on Chemical Measurement and Monitoring of the Environment, Carleton Univ., Ottawa, Ontario. pp. 363-368.

Lee, R.E. Jr. and D.J. Von Lehmden. 1973. Trace metal pollution in the environment. J. Air Pollut. Control Assoc. 23(1): 853-857.

Leino, R.L. and J.H. McCormick. 1993. Response of juvenile largemouth bass to different pH and aluminium levels at overwintering temperatures: effects on gill morphology, electrolyte balance, scale calcium, liver glycogen, and depot fat. Can. J. Zool. 71(3): 531-543.

Leino, R.L., J.H. McCormick and K.M. Jensen. 1988. Effects of acid and aluminum on swim bladder development and yolk absorption in the fathead minnow, *Pimephales promelas*. Can. Tech. Rep. Fish. Aquat. Sci. 1607: 37-41.

Leino, R.L., J.H. McCormick and K.M. Jensen. 1990. Multiple effects of acid and aluminum on brood stock and progeny of fathead minnows, with emphasis on histopathology. Can. J. Zool. 68: 234-244.

Leivestad, H., P. Muniz and B. O. Rosseland. 1980. Acid stress in trout from a dilute mountain stream. Proc. Int. Conf. Ecol. Impact Acid Precip., Norway. SNSF-Project, p. 318-319.

Leonard, A. and G.B Gerber. 1988. Mutagenicity, carcinogenicity and teratogenicity of aluminium. Mutat. Res. 196(3): 247-57.

Lewis, C. and E.S. Macias. 1980. Composition of size-fractionated aerosol in Charleston, West Virginia. Atmos. Environ. 14: 185-194.

Lewis, T.E. 1989. Environmental Chemistry and Toxicology of Aluminum. Lewis Publishers, Chelsea, MI.

Li, K., Y. Chen, W. Zhang, Z. Pu, L. Jiang and Y. Chen. 2012. Surface interactions affect the toxicity of engineered metal oxide nanoparticles toward *Paramecium*. Chem. Res. Toxicol. 25: 1675-1681.

Li, M., K.J. Czymmek and C.P. Huang. 2011. Responses of *Ceriodaphnia dubia* to TiO_2 and Al_2O_3 nanoparticles: A dynamic nano-toxicity assessment of energy budget distribution. J. Hazard. Mater. 187: 502-508.

Li, X. and F. Zhang. 1992 Toxic effects of low pH and elevated Al concentration on early life stages of several species of freshwater fishes. Huanjing Kexue Xuebao 12(1): 97-104.

Lim, B. and T.D. Jickells. 1990. Dissolved, particulate and acid-leachable trace metal concentrations in North Atlantic precipitation collected on the Global Change expedition. Global Biogeochem. Cycles 4: 445-458.

Lincoln, T.A., D.A. Horan-Ross, M.R. McHale, G.B. Lawrence and T.A. Lincoln. 2009. Quality-assurance data for routine water analyses by the U.S. Geological Survey Laboratory in Troy, New York - July 2005 through June 2007. Open-File Report. U.S. Geological Survey.

Lindemann, J., E. Holtkamp and R. Herrmann. 1990. The impact of aluminium on green algae isolated from two hydrochemically different headwater streams, Bavaria, Germany. Environ. Pollut. 67: 61-77.

Linnik, P.N. 2007. Aluminum in natural waters: content, forms of migration, toxicity. Hydrobiol. J./Gidrobiol. Zh. 43(4): 76-95.

Lithner, G., K. Holm and H. Borg. 1995. Bioconcentration factors for metals in humic waters at different pH in the Ronnskar area (N. Sweden). Water Air Soil Pollut. 85(2): 785-790.

Lockard, R.G. and A.R. McWalter. 1956. Effects of toxic levels of sodium, arsenic, iron and aluminium on the rice plant. Malay. Agric. J. 539: 256-267.

Lydersen, E. 1990. The solubility and hydrolysis of aqueous aluminium hydroxides in dilute fresh waters at different temperatures. Nord. Hydrol. 21: 195-204.

Lydersen, E. and S. Lofgren. 2002. Potential effects of metals in reacidified limed water bodies in Norway and Sweden. Environ. Monit. Assess. 73: 155-178.

Ma, L.Q., F. Tan and W.G. Harris. 1997. Concentrations and distributions of eleven metals in Florida soils. J. Environ. Qual. 26: 769-775.

MacDonald, J.M., J.D. Shields and R.K. Zimmer-Faust. 1988. Acute toxicities of eleven metals to early life-history stages of the yellow crab *Cancer anthonyi*. Mar. Biol. 98(2): 201-207.

Mackie, G.L. 1989. Tolerances of five benthic invertebrates to hydrogen ions and metals (Cd, Pb, Al). Arch. Environ. Contam. Toxicol. 18(1/2): 215-223.

Mackie, G.L. and B.W. Kilgour. 1995. Efficacy and role of alum in removal of zebra mussel veliger larvae from raw water supplies. Water Res. 29(2): 731-744.

Macova, S., J. Machova, M. Prokes, L. Plhalova, Z. Siroka, K. Dleskova, P. Dolezelova and Z. Svobodova. 2009. Polyaluminium chloride (PAX-18) - acute toxicity and toxicity for early development stages of common carp (*Cyprinus carpio*). Neuroendocrinol. Lett. 30(Suppl. 1): 192-198.

Macova, S., L. Plhalova, Z. Siroka, P. Dolezelova, V. Pistekova and Z. Svobodova. 2010. Acute toxicity of the preparation PAX-18 for juvenile and embryonic stages of zebrafish (*Danio rerio*). Acta Vet. Brno 79(4): 587-592.

Madigosky, S.R., X. Alvarez-Hernandez and J. Glass. 1992. Concentrations of aluminum in gut tissue of crayfish (*Procambarus clarkii*), purged in sodium chloride. Bull. Environ. Contam. Toxicol. 49(4): 626-632.

Maessen, M., J.G.M. Roelofs, M.J.S. Bellemakers and G.M. Verheggen. 1992. The effects of aluminium, aluminium/calcium and pH on aquatic plants from poorly buffered environments. Aquat. Bot. 43: 115-127.

Malcolm, I.A., P.J. Bacon, S.J. Middlemas, R.J. Fryer, E.M. Shilland and P. Collen. 2012. Relationships between hydrochemistry and the presence of juvenile brown trout (*Salmo trutta*) in headwater streams recovering from acidification. Ecol. Indicat. (0).

Malea, P. and S. Haritonidis. 1996. Toxicity and uptake of aluminium by the seagrass *Halophila stipulacea* (Forsk.) aschers., in response to aluminium exposure. Fres. Environ. Bull. 5(5-6): 345-350.

Malecki-Brown, L.M., J.R. White and H. Brix. 2010. Alum application to improve water quality in a municipal wastewater treatment wetland: Effects on macrophyte growth and nutrient uptake. Chemosphere 79: 186-192.

Mallatt, J. 1985. Fish gill structural changes induced by toxicants and other irritants: A statistical review. Can. J. Fish. Aquat. Sci. 42: 630-648.

Malley, D.F. and P.S.S. Chang. 1985. Effects of aluminum and acid on calcium uptake by the crayfish *Orconectes virilis*. Arch. Environ. Contam. Toxicol. 14(6): 739-747.

Malley, D.F., P.S.S. Chang and C.M. Moore. 1986. Change in the aluminum content of tissues of crayfish held in the laboratory and in experimental field enclosures. In: G.H. Geen and K.L. Woodward (*Eds*.), Proc. 11th Annual Aquatic Toxicity Workshop, Nov.13-15, 1984, Vancouver, B.C., Can. Tech. Rep. Fish. Aquat. Sci. No. 1480: 54-68.

Malley, D.F., J.D. Huebner and K. Donkersloot. 1988. Effects on ionic composition of blood and tissues of *Anodonta grandis grandis* (Bivalvia) of an addition of aluminum and acid to a lake. Arch. Environ. Contam. Toxicol. 17(4): 479-491.

Malte, H. 1986. Effects of aluminium in hard, acid water on metabolic rate, blood gas tensions and ionic status in the rainbow trout. J. Fish Biol. 29(2): 187-198.

Malte, H. and R.E. Weber. 1988. Respiratory stress in rainbow trout dying from aluminium exposure in soft acid water, with or without added sodium chloride. Fish Physiol. Biochem. 5: 249-256.

Mao, A., M.L. Mahaut, S. Pineau, D. Barillier and C. Caplat. 2011. Assessment of sacrificial anode impact by aluminum accumulation in mussel *Mytilus edulis*: a large-scale laboratory test. Mar. Pollut. Bull. 62(12): 2707-2713.

Markarian, R.K., M.C. Matthews and L.T. Connor. 1980. Toxicity of nickel, copper, zinc and aluminum mixtures to the white sucker (*Catostomus commersoni*). Bull. Environ. Contam. Toxicol. 25: 790-796.

Marquis, J.K. 1982. Aluminum neurotoxicity: An experimental perspective. Bull. Environ. Contam. Toxicol. 29: 43-49.

Martin, T.R. and D.M. Holdich. 1986. The acute lethal toxicity of heavy metals to peracarid crustaceans (with particular reference to fresh-water asellids and gammarids). Water Res. 20(9): 1137-1147.

Martin, M., G. Ichikawa, J. Goetzl, M. De los Reyes and M.D. Stephenson. 1984. Relationships between physiological stress and trace toxic substances in the bay mussel, *Mytilus edulis*, from San Francisco Bay, California. Mar. Environ. Res. 11: 91-110.

Matheson III, J.C. 1975. Availability of aluminum phosphate complexes to a green alga in various culture media. PB-268510. National Technical Information Services, Springfield, VA.

Mayer Jr., F.L and M.R. Ellersieck. 1986. Manual of acute toxicity: interpretation and data base for 410 chemicals and 66 species of freshwater animals. Resour. Publ. No. 160, U.S. Dep. Interior, Fish Wildl. Serv., Washington, DC, 505 pp.

Mazerolle, M.J. 2015. AICcmodavg: Model selection and multimodel inference based on (Q)AIC(c). R package version 2.0-3. Available online at: http://CRAN.R-project.org/package=AICcmodavg.

McCahon, C.P. and D. Pascoe. 1989. Short-term experimental acidification of a Welsh stream: toxicity of different forms of aluminium at low pH to fish and invertebrates. Arch. Environ. Contam. Toxicol. 18: 233-242.

McCauley, D.J., L.T. Brooke, D.J. Call and C.A. Lindberg. 1986. Acute and chronic toxicity of aluminum to *Ceriodaphnia dubia* at various pH's. Center for Lake Superior Environmental Stud., Univ. Wisconsin-Superior, Superior, WI.

McCormick, J.H. and K.M. Jensen. 1992. Osmoregulatory failure and death of first-year largemouth bass (*Micropterus salmoides*) exposed to low pH and elevated aluminum, at low temperature in. Can. J. Fish. Aquat. Sci. 49(6): 1189-1197.

McCormick, J.H., K.M. Jensen and L.E. Anderson. 1989. Chronic effects of low pH and elevated aluminum on survival, maturation, spawning and embryo-larval development of the fathead minnow in soft water. Water Air Soil Pollut. 43(3/4): 293-307.

McCormick, S.D., D.T. Lerner, A.M. Regish, M.F. O'Dea and M.Y. Monette. 2012. Thresholds for short-term acid and aluminum impacts on Atlantic salmon smolts. Aquacult. 362-363: 224-231.

McCrohan, C.R., M.M. Campbell, R. Jugdaohsingh, S. Balance, J.J. Powell and K.N. White. 2000. Bioaccumulation and toxicity of aluminium in the pond snail at neutral pH+. Acta Biol. Hung. 51(2-4): 309-316.

McDonald, D.G. and C.L. Milligan. 1988. Sodium transport in the brook trout, *Salvelinus fontinalis*: effects of prolonged low pH exposure in the presence and absence of aluminum. Can. J. Fish. Aquat. Sci. 45(9): 1606-1613.

McDonald, D.G., C.M. Wood, R.G. Rhem, M.E. Mueller, D.R. Mount and H.L. Bergman. 1991. Nature and time course of acclimation to aluminum in juvenile brook trout (*Salvelinus fontinalis*). I. Physiology. Can. J. Fish. Aquat. Sci. 48(10): 2006-2015.

McGarry, M.G. 1970. Algal flocculation with aluminum sulfate and polyelectrolytes. J. Water Pollut. Control Fed. 42: R191-R201.

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.

McGeer, J.C., K.V. Brix, J.M. Skeaff, D.K. DeForest, S.I. Brigham, W.J. Adams and A.S. Green. 2003. The inverse relationship between bioconcentration factor and exposure concentration for metals: Implications for hazard assessment of metals in the aquatic environment. Environ. Toxicol. Chem. 22(5): 1017-1037.

McKee, J.E. and H.W. Wolf. 1963. Water quality criteria. 2nd Edition. State Water Quality Control Board, Sacramento, CA. p. 129-132.

McKee, M.J., C.O. Knowles and D.R. Buckler. 1989. Effects of aluminum on the biochemical composition of Atlantic salmon. Arch. Environ. Contam. Toxicol. 18(1/2): 243-248.

McLeish, J.A., T.J.A. Chico, H.B. Taylor, C. Tucker, K. Donaldson and S.B. Brown. 2010. Skin exposure to micro- and nano-particles can cause haemostasis in zebrafish larvae. Thromb. Haemostasis 103: 797-807.

Mebane, C.A. 2006. Cadmium risks to freshwater life: Derivation and validation of low-effect criteria values using laboratory and field studies. U.S. Geological Survey Scientific Investigation Report 2006-5245 (2010 rev.). Available online at: http://pubs.usgs.gov/sir/2006/5245/.

Mehta, S., R.C. Srivastava and A.N. Gupta. 1982. Relative toxicity of some non-insecticidal chemicals to the free living larvae guinea-worm (*Dracunculus medinensis*). Acta Hydrochim. Hydrobiol. 10(4): 397-400.

Meili, M. and D. Wills. 1985. Seasonal concentration changes of mercury, cadmium, copper, and aluminum in a population of roach. In: T.D. Lekkas (*Ed*.), Heavy Metal Environ., 5th Int. Conf., Volume 1, CEP Consult., Edinburgh, UK, 709-711.

Meland, S., L.S. Heier, B. Salbu, K.E. Tollefsen, E. Farmen, B.O. Rosseland and S. Meland. 2010. Exposure of brown trout (*Salmo trutta* L.) to tunnel wash-water runoff -- chemical characterization and biological impact. Sci. Total Environ. 408(13): 2646-2656.

Mendez, G.O. 2010. Water-quality data from storm runoff after the 2007 fires, San Diego County, California. Open-File Report. U.S. Geological Survey.

Merrett, W.J., G.P. Rutt, N.S. Weatherley, S.P. Thomas and S.J. Ormerod. 1991. The response of macroinvertebrates to low pH and increased aluminium concentrations in Welsh streams: multiple episodes and chronic exposure. Arch. Hydrobiol. 121(1): 115-125.

Mersch, J., F. Guerold, P. Rousselle and J.C. Pihan. 1993. Transplanted aquatic mosses for monitoring trace metal mobilization in acidified streams of the Vosges Mountains, France. Bull. Environ. Contam. Toxicol. 51: 255-259.

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. DiToro. 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.

Michailova, P., J. Ilkova and K.N. White. 2003. Functional and structural rearrangements of salivary gland polytene chromosomes of *Chironomus riparius* Mg. (Diptera, Chironomidae) in response to freshly neutralized aluminium. Environ. Pollut. 123(2): 193-207.

Minzoni, F. 1984. Effects of aluminum on different forms of phosphorus and freshwater plankton. Environ. Technol. Lett. 5: 425-432.

Mitchell, M.A. 1982. The effects of aluminum and acidity on algal productivity: A study of an effect of acid deposition. Bull. S.C. Acad. Sci. 44: 76.

Mo, S.C., D.S. Choi and J.W. Robinson. 1988. A study of the uptake by duckweed of aluminum, copper, and lead from aqueous solution. J. Environ. Sci. Health Part A 23(2): 139-156.

Mohanty, S., A.B. Das, P. Das and P. Mohanty. 2004. Effect of a low dose of aluminum on mitotic and meiotic activity, 4C DNA content, and pollen sterility in rice, *Oryza sativa* L. cv. Lalat. Ecotoxicol. Environ. Saf. 59: 70-75.

Monette, M.Y. 2007. Impacts of episodic acid and aluminum exposure on the physiology of Atlantic salmon, *Salmo salar*, smolt development. Ph.D. Thesis, Univ. Massachusetts Amherst, MA, 158 pp.

Monette, M.Y. and S.D. McCormick. 2008. Impacts of short-term acid and aluminum exposure on Atlantic salmon (*Salmo salar*) physiology: a direct comparison of parr and smolts. Aquat. Toxicol. 86(2): 216-226.

Monette, M.Y., B.T. Bjornsson and S.D. McCormick. 2008. Effects of short-term acid and aluminum exposure on the parr-smolt transformation in Atlantic salmon (*Salmo salar*): Disruption of seawater tolerance and endocrine status. Gen. Comp. Endocrinol. 158(1): 122-130.

Monette, M.Y., T. Yada, V. Matey and S.D. McCormick. 2010. Physiological, molecular, and cellular mechanisms of impaired seawater tolerance following exposure of Atlantic salmon, *Salmo salar*, smolts to acid and aluminum. Aquat. Toxicol. 99(1): 17-32.

Moomaw, J.C., M.T. Nakamura and G.D. Sherman. 1959. Aluminum in some Hawaiian plants. Pac. Sci. 13: 335-341.

Morel, F.M.M. and J.G. Hering. 1993. Principals and applications of aquatic chemistry. J. Wiley, New York. 588 pp.

Morgan, E.L., Y.C.A. Wu and R.C. Young. 1990. A plant toxicity test with the moss *Physcomitrella patens* (Hedw.) B.S.G. In: W. Wang, J.W. Gorsuch and W.R. Lower (*Eds*.), Plants for Toxicity Assessment, ASTM STP 1091, Philadelphia, PA, 267-279.

Morgan, E.L., Y.C.A. Wu and J.P. Swigert. 1993. An aquatic toxicity test using the moss *Physcomitrella patens* (Hedw) B.S.G. In: W.G. Landis, J.S. Hughes and M.A. Lewis (*Eds*.), Environmental Toxicology and Risk Assessment, ASTM STP 1179, Philadelphia, PA, 340-352.

Mothersill, C., B. Salbu, L.S. Heier, H.C. Teien, J. Denbeigh, D. Oughton, B.O. Rosseland and C.B. Seymour. 2007. Multiple stressor effects of radiation and metals in salmon (*Salmo salar*). J. Environ. Radioact. 96: 20-31.

Mount, D.R. 1987. Physiological and toxicological effects of long-term exposure to acid, aluminum and low calcium on adult brook trout (*Salvelinus fontinalis*) and rainbow trout (*Salmo gairdneri*). Ph.D. Thesis, University of Wyoming, Laramie, WY, 171 pp.

Mount, D.R. and J.R. Hockett. 2015. Issue summary regarding test conditions and methods for water only toxicity testing with *Hyalella azteca*. Memorandum to K. Gallagher. Date August 6th. U.S. Environmental Protection Agency, Office of Research and Development, Duluth, MN, 10 pp. Available online at: https://www.epa.gov/sites/production/files/2016-03/documents/cadmium-final-report-2016.pdf, Appendix K.

Mount, D.R., C.G. Ingersoll, D.D. Gulley, J.D. Fernandez, T.W. LaPoint and H.L. Bergman. 1988a. Effect of long-term exposure to acid, aluminum, and low calcium on adult brook trout (*Salvelinus fontinalis*). 1. Survival, growth, fecundity, and progeny survival. Can. J. Fish. Aquat. Sci. 45(9): 1623-1632.

Mount, D.R., J.R. Hockett and W.A. Gern. 1988b. Effect of long-term exposure to acid, aluminum, and low calcium on adult brook trout (*Salvelinus fontinalis*). 2. Vitellogenesis and osmoregulation. Can. J. Fish. Aquat. Sci. 45(9): 1633-1642.

Mount, D.R., M.J. Swanson, J.E. Breck, A.M. Farag and H.L. Bergman. 1990. Responses of brook trout (*Salvelinus fontinalis*) fry to fluctuating acid, aluminum and low calcium exposure. Can. J. Fish. Aquat. Sci. 47: 1623-1630.

Moyers, J.L., L.E. Ranweiler, S.B. Hopf and N.E. Korte. 1977. Evaluation of particulate trace species in Southwest desert atmosphere. Environ. Sci. Technol. 11(8): 789-795.

Mueller, M.E., D.A. Sanchez, H.L. Bergman, D.G. McDonald, R.G. Rhem and C.M. Wood. 1991. Nature and time course of acclimation to aluminum in juvenile brook trout (*Salvelinus fontinalis*). II. Gill histology. Can. J. Fish. Aquat. Sci. 48: 2016-2027.

Mukai, H. 1977. Effects of chemical pretreatment on the germination of statoblasts of the freshwater bryozoan, *Pectinatella gelatinosa*. Biol. Zentralbl. 96: 19-31.

Mulvey, B., M.L. Landolt and R.A. Busch. 1995. Effects of potassium aluminium sulphate (alum) used in an *Aeromonas salmonicida* bacterin on Atlantic salmon, *Salmo salar* L. J. Fish Dis. 18(6): 495-506.

Muniz, I.P. and H. Leivestad. 1980a. Acidification - effects on freshwater fish. Proc. Int. Conf. Ecol. Impact Acid Precip, Norway, SNSF-project, 84-92.

Muniz, I.P. and H. Leivestad. 1980b. Toxic effects of aluminium on the brown trout, *Salmo trutta* L. In: D. Drablos and A. Tollan (*Eds*.), Ecological Impact of Acid Precipitation, SNSF Project, Oslo, Norway, 320-321.

Muniz, I.P., R. Andersen and T.J. Sullivan. 1987. Physiological response of brown trout (*Salmo trutta*) spawners and postspawners to acidic alminum-rich stream water. Water Air Soil Pollut. 36: 371-379.

Muramoto, S. 1981. Influence of complexans (NTA, EDTA) on the toxicity of aluminum chloride and sulfate to fish at high concentrations. Bull. Environ. Contam. Toxicol. 27(2): 221-225.

Murungi, J.I. and J.W. Robinson. 1987. Synergistic effects of pH and aluminum concentrations on the life expectancy of tilapia (mozambica) fingerlings. J. Environ. Sci. Health Part A 2(5): 391-395.

Murungi, J.I. and J.W. Robinson. 1992. Uptake and accumulation of aluminum by fish-the modifying effect of added ions. J. Environ. Sci. Health Part A 27(3): 713-719.

Musibono, D.E. and J.A. Day. 2000. Active uptake of aluminium, copper and manganese by the freshwater amphipod *Paramelita nigroculus* in acidic waters. Hydrobiol. 437(1-3): 213-219.

Nagasaka, S., N.K. Nishizawa, T. Negishi, K. Satake, S. Mori and E. Yoshimura. 2002. Novel iron-storage particles may play a role in aluminum tolerance of *Cyanidium caldarium*. Planta 215: 399-404.

Naskar, R., N.S. Sen and M.F. Ahmad. 2006. Aluminium toxicity induced poikilocytosis in an air-breathing teleost, *Clarias batrachus* (Linn.). Indian J. Exp. Biol. 44(1): 83-85.

Nalewajko, C. and B. Paul. 1985. Effects of manipulation of aluminum concentrations and pH on phosphate uptake and photosynthesis of planktonic communities in two Precambrian Shield lakes. Can. J. Fish. Aquat. Sci. 42: 1946-1953.

Neave, M.J., C. Streten-Joyce, A.S. Nouwens, C.J. Glasby, K.A. McGuinness, D.L. Parry and K.S. Gibb. 2012. The transcriptome and proteome are altered in marine polychaetes (Annelida) exposed to elevated metal levels. J. Proteom. 75(9): 2721-2735.

Negri, A.P., A.J. Harford, D.L. Parry and R.A. Van Dam. 2011. Effects of alumina refinery wastewater and signature metal constituents at the upper thermal tolerance of: 2. The early life stages of the coral *Acropora tenuis*. Mar. Pollut. Bull. 62: 474-482.

Neter, J. and W. Wasserman. 1974. Applied linear statistical models. Irwin, Inc., Homewood, Illinois.

Neville, C.M. 1985. Physiological response of juvenile rainbow trout, *Salmo gairdneri*, to acid and aluminum - prediction of field responses from laboratory data. Can. J. Fish. Aquat. Sci. 42: 2004-2019.

Neville, C.M. and P.G.C. Campbell. 1988. Possible mechanisms of aluminum toxicity in a dilute, acidic environment to fingerlings and older life stages of salmonids. Water Air Soil Pollut. 42: 311-327.

Nilsen, T.O., L.O.E. Ebbesson, O.G. Kverneland, F. Kroglund, B. Finstad and S.O. Stefansson. 2010. Effects of acidic water and aluminum exposure on gill Na^+, K^+ -ATPase α-subunit isoforms, enzyme activity, physiology and return rates in Atlantic salmon (*Salmo salar* L.). Aquat. Toxicol. 97: 250-259.

Nilsen, T.O., L.O.E. Ebbesson, S.O. Handeland, F. Kroglund, B. Finstad, A.R. Angotzi and S.O. Stefansson. 2013. Atlantic salmon (*Salmo salar* L.) smolts require more than two weeks to recover from acidic water and aluminium exposure. Aquat. Toxicol. 142-143: 33-44.

Norberg-King, T. and D. Mount. 1986. Validity of effluent and ambient toxicity tests for predicting biological impact, Skeleton Creek, Enid, Oklahoma. Environmental Research Laboratory, Office of Research and Development, U.S. EPA. Duluth, MN. EPA/600/8-86/002.

Norrgren, L. and E. Degerman. 1993. Effects of different water qualities on the early development of Atlantic salmon and brown trout exposed in situ. Ambio 22(4): 213-218.

Norrgren, L., A. Wicklund Glynn and O. Malmborg. 1991. Accumulation and effects of aluminium in the minnow (*Phoxinus phoxinus* L.) at different pH levels. J. Fish Biol. 39: 833-847.

Nyberg, P., P. Andersson, E. Degerman, H. Borg and E. Olofsson. 1995. Labile inorganic manganese - An overlooked reason for fish mortality in acidified streams? Water Air Soil Pollut. 85: 333-340.

Odonnell, A.R., G. Mance and R. Norton. 1984. A review of the toxicity of aluminium in fresh water. Tech. Rep. TR 197, WRC Environment, Medmenham, 1-27.

Ogilvie, D.M. and D.M. Stechey. 1983. Effects of aluminum on respiratory responses and spontaneous activity of rainbow trout, *Salmo gairdneri*. Environ. Toxicol. Chem. 2: 43-48.

Olaveson, M.M.and C. Nalewajko. 2000. Effects of acidity on the growth of two *Euglena* species. Hydrobiol. 433: 39-56.

Olson, D.L. and G.M. Christensen. 1980. Effects of water pollutants and other chemicals on fish acetylcholinesterase (in vitro). Environ. Res. 21: 327-335.

Ondov, J.M., W.H. Zoller and G.E. Gordon. 1982. Trace element emissions of aerosols from motor vehicles. Environ. Sci. Technol. 16(6): 318-328.

Ormerod, S.J., P. Boole, C.P.M. Weatherley, D. Pascoe and R.W. Edwards. 1987. Short-term experimental acidification of Welsh stream: Comparing the biological effects of hydrogen ions and aluminium. Fresh. Biol. 17(2): 341-356.

Orr, P.L., R.W. Bradley, J.B. Sprague and N.J. Hutchinson. 1986. Acclimation-induced change in toxicity of aluminum to rainbow trout (*Salmo gairdneri*). Can. J. Fish. Aquat. Sci. 43: 243-246.

OSU (Oregon State University Aquatic Toxicology Laboratory). 2012a. Toxicity of aluminum, at pH 6, to the fathead minnow, *Pimephales promelas*, under varying hardness and dissolved organic carbon (DOC) conditions. Prepared by Oregon State University Aquatic Toxicology Laboratory, Albany, Oregon, USA. Owner Company: European Aluminum Association. May 2012. (Data are summarized in Gensemer et al. 2018).

OSU (Oregon State University Aquatic Toxicology Laboratory). 2012b. Chronic toxicity of aluminum, at pH 6, to the great pond snail, *Lymnaea stagnalis*. Prepared by Oregon State Univeristy Aquatic Toxicology Laboratory, Albany, Oregon, USA. Owner Company: European Aluminum Association. June 2012. (Data are summarized in Cardwell et al. 2018).

OSU (Oregon State University Aquatic Toxicology Laboratory). 2012c. Chronic toxicity of aluminum, at pH 6, to the rotifer, *Brachionus calyciflorus*. Prepared by Oregon State University Aquatic Toxicology Laboratory, Albany, Oregon, USA. Owner Company: European Aluminum Association. June 2012. (Data are summarized in Cardwell et al. 2018).

OSU (Oregon State University Aquatic Toxicology Laboratory). 2012d. Chronic toxicity of aluminum, at pH 6, to the freshwater duckweed, *Lemna minor*. Prepared by Oregon State University Aquatic Toxicology Laboratory, Albany, Oregon, USA. Owner Company: European Aluminum Association. September 2012. (Data are summarized in Cardwell et al. 2018).

OSU (Oregon State University Aquatic Toxicology Laboratory). 2012e. Chronic toxicity of aluminum, at pH 6, to the aquatic oligochaete, *Aeolosoma sp*. Prepared by Oregon State University Aquatic Toxicology Laboratory, Albany, Oregon, USA. Owner Company: European Aluminum Association. September 2012. (Data are summarized in Cardwell et al. 2018).

OSU (Oregon State University Aquatic Toxicology Laboratory). 2012f. Life-cycle toxicity of aluminum, at pH 6, to the midge, *Chironomus riparius*, under flow-through conditions. Prepared by Oregon State University Aquatic Toxicology Laboratory, Albany, Oregon, USA. Owner Company: European Aluminum Association. October 2012. (Data are summarized in Cardwell et al. 2018).

OSU (Oregon State University Aquatic Toxicology Laboratory). 2012g. Early life-stage toxicity of aluminum, at pH 6, to the fathead minnow, *Pimephales promelas*, under flow-through conditions. Prepared by Oregon State University Aquatic Toxicology Laboratory, Albany, Oregon, USA. Owner Company: European Aluminum Association. October 2012. (Data are summarized in Cardwell et al. 2018).

OSU (Oregon State University Aquatic Toxicology Laboratory). 2012h. Life-cycle toxicity of aluminum, at pH 6, to the amphipod, *Hyalella azteca*, under flow through conditions. Prepared by Oregon State University Aquatic Toxicology Laboratory, Albany, Oregon, USA. Owner Company: European Aluminum Association. October 2012. (Data are summarized in Cardwell et al. 2018).

OSU (Oregon State University Aquatic Toxicology Laboratory). 2013. Early life-stage toxicity of aluminum, at pH 6, to the zebrafish, *Danio rerio*, under flow-through conditions. Prepared by Oregon State University Aquatic Toxicology Laboratory, Albany, Oregon, USA. Owner Company: European Aluminum Association. March 2013. (Data are summarized in Cardwell et al. 2018).

OSU (Oregon State University Aquatic Toxicology Laboratory). 2018a. Chronic toxicity of aluminum to the cladoceran, *Ceriodaphnia dubia*: Expansion of the empirical database for bioavailability modeling. Prepared by Oregon State University Aquatic Toxicology Laboratory, Corvallis, OR, USA. Prepared for Aluminum Reach Consortium, Brussels, Belgium.

OSU (Oregon State University Aquatic Toxicology Laboratory). 2018b. Short-term chronic toxicyt of aluminum to the fathead minnow, *Pimephales promelas*: Expansion of the empirical database for bioavailability modeling. Prepared by Oregon State University Aquatic Toxicology Laboratory, Corvallis, OR, USA. Prepared for Aluminum Reach Consortium, Brussels, Belgium.

OSU (Oregon State University Aquatic Toxicology Laboratory). 2018c. Analytical method validation for determining bioavailable aluminum in freshwater. Prepared by Oregon State University Aquatic Toxicology Laboratory, Corvallis, OR, USA. Prepared for Aluminum Reach Consortium, Brussels, Belgium.

OSU (Oregon State University Aquatic Toxicology Laboratory). 2018d. Short-term chronic toxicity of aluminum to the fathead minnow, *Pimephales promelas*: Validation of aluminum bioavailability models (confirmatory studies). Prepared by Oregon State University Aquatic Toxicology Laboratory, Corvallis, OR, USA. Prepared for Aluminum Reach Consortium, Brussels, Belgium.

OSU (Oregon State University Aquatic Toxicology Laboratory). 2018e. Chronic toxicity of aluminum to the rotifer, *Brachionus calyciflorus*: Validation of aluminum bioavailability models. Prepared by Oregon State University Aquatic Toxicology Laboratory, Corvallis, OR, USA. Prepared for Aluminum Reach Consortium, Brussels, Belgium.

OSU (Oregon State University Aquatic Toxicology Laboratory). 2018f. Chronic toxicity of aluminum to the great pond snail, *Lymnaea stagnalis*: Validation of aluminum bioavailability models. Prepared by Oregon State University Aquatic Toxicology Laboratory, Corvallis, OR, USA. Prepared for Aluminum Reach Consortium, Brussels, Belgium.

Otto, C. and B.S. Svensson. 1983. Properties of acid brown water streams in south Sweden. Arch. Hydrobiol. 99: 15-36.

Pagano, G., G. Corsale, A. Esposito, P.A. Dinnel and L.A. Romana. 1989. Use of sea urchin sperm and embryo bioassay in testing the sublethal toxicity of realistic pollutant levels. In: Carcinogenic, Mutagenic, and Teratogenic Marine Pollutants: Impact on Human Health and the Environment, Adv. Appl. Biotechnol. Ser. Vol. 5, W.H.O. and U.N. Environment Programme, Gulf Publ. Co., Houston, TX, p. 153-163.

Pagano, G., E. His, R. Beiras, A. De Biase, L.G. Korkina, M. Iaccarino, R. Oral, F. Quiniou and M. Warnau. 1996. Cytogenetic, developmental, and biochemical effects of aluminum, iron, and their mixture in sea urchins and mussels. Arch. Environ. Contam. Toxicol. 31(4): 466-474.

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.

Pakrashi, S., S. Dalai, T.C. Prathna, S. Trivedi, R. Myneni, A.M. Raichur, N. Chandrasekaran and A. Mukherjee. 2013a. Cytotoxicity of aluminium oxide nanoparticles towards fresh water algal isolate at low exposure concentrations. Aquat. Toxicol. 132-133: 34-45.

Pakrashi, S., S. Dalai, A. Humayun, S. Chakravarty, N. Chandrasekaran and A. Mukherjee. 2013b. *Ceriodaphnia dubia* as a potential bio-indicator for assessing acute aluminum oxide nanoparticle toxicity in fresh water environment. PLoS One 8(9): e74003.

Paladino, F.V. and D. Swartz. 1984. Interactive and synergistic effects of temperature, acid and aluminum toxicity on fish critical thermal tolerance. In: Conf. Fed. Am. Soc. Exp. Biol., 68th Annu. Meet., Apr. 1-6, 1984, St. Louis, MO.

Palawski, D.U., J.B. Hunn, D.N. Chester and R.H. Wiedmeyer. 1989. Interactive effects of acidity and aluminum exposure on the life cycle of the midge *Chironomus riparius* (Diptera). J. Fresh. Ecol. 5: 155.

Palmer, R.E., R.J. Klauda and T.E. Lewis. 1988. Comparative sensitivities of bluegill, channel catfish and fathead minnow to pH and aluminum. Environ. Toxicol. Chem. 7(6): 505-516.

Palmer, R.E., R.J. Klauda, M.A. Jepson and E.S. Perry. 1989. Acute sensitivity of early life stages of fathead minnow (*Pimephales promelas*) to acid and aluminum. Water Res. 23(8): 1039-1047.

Panda, S.K. and M.H. Khan. 2004. Lipid peroxidation and oxidative damage in aquatic duckweed (*Lemna minor* L.) in response to aluminium toxicity. Indian J. Plant Physiol. 9(2): 176-180.

Pandey, P., R.K. Srivastava and R.S. Dubey. 2013. Salicylic acid alleviates aluminum toxicity in rice seedlings better than magnesium and calcium by reducing aluminum uptake, suppressing oxidative damage and increasing antioxidative defense. Ecotoxicol. 22: 656-670.

Papathanasiou, G., K.N. White, R. Walton and S. Boult. 2011. Toxicity of aluminium in natural waters controlled by type rather than quantity of natural organic matter. Sci. Total Environ. 409: 5277-5283.

Paquin, P., D. DiToro, R.C. Santore, B. Trivedi and B. Wu. 1999. A biotic ligand model of the acute toxicity of metals III: Application to fish and daphnia exposure to silver. U.S. Government Printing Office: Washington, D.C. EPA-E-99-001.

Parametrix. 2009. Chronic toxicity of aluminium to the fathead minnow (*Pimephales promelas*) in filtered and unfiltered test solutions. Report No. 598-6012-001. Albany, Oregon, USA.

Parent, L. and P.G.C. Campbell. 1994. Aluminum bioavailability to the green alga *Chlorella pyrenoidosa* in acidified synthetic soft water. Environ. Toxicol. Chem. 13(4): 587-598.

Parent, L., M.R. Twiss and P.G.C. Campbell. 1996. Influences of natural dissolved organic matter on the interaction of aluminum with the microalga *Chlorella*: a test of the free-ion model of trace metal toxicity. Environ. Sci. Technol. 30(5): 1713-1720.

Parkhurst, B.R., H.L. Bergman, J.D. Fernandez, D.D. Gulley, J.R. Hockett and D.A. Sanchez. 1990. Inorganic monomeric aluminum and pH as predictors of acidic water toxicity to brook trout (*Salvelinus fontinalis*). Can. J. Fish. Aquat. Sci. 47: 1631-1640.

Parsons Engineering Science Inc. 1997. Aluminum water-effect ratio study for the calculation of a site-specific water quality standard in Welsh reservoir. Parsons Engineering Science, Inc., 152 pp.

Pauwels, S.J. 1990. Some effects of exposure to acid and aluminum on several lifestages of the Atlantic salmon (*Salmo salar*). Ph.D. Thesis, The University of Maine, ME.

Payton, J.M. and R.W. Greene. 1980. A comparison of the effect of aluminum on a single species algal assay and indigenous community algal toxicity bioassay. Proc. Indiana Acad. Sci. 90: 193-194.

Peles, J.D. 2013. Effects of chronic aluminum and copper exposure on growth and development of wood frog (*Rana sylvatica*) larvae. Aquat. Toxicol. 140-141: 242-248.

Peterson, H.G., S.E. Hrudey, I.A. Cantin, T.R. Perley and S.L. Kenefick. 1995. Physiological toxicity, cell membrane damage and the release of dissolved organic carbon and geosmin by *Aphanizomenon flos-aquae* after exposure to water treatment chemicals. Water Res. 29(6): 1515-1523.

Peterson, R.H., R.A. Bourbonniere, G.L. Lacroix, D.J. Martin-Robichaud, P. Takats and G. Brun. 1989. Responses of Atlantic salmon (*Salmo salar*) alevins to dissolved organic carbon and dissolved aluminum at low pH. Water Air Soil Pollut. 46: 399-413.

Peterson, S.A., W.D. Sanville, F.S. Stay and C.F. Powers. 1974. Nutrient inactivation as a lake restoration procedure. Laboratory investigations. EPA-660/3-74-032. National Technical Information Services, Springfield, VA.

Petrich, S.M. and D.J. Reish. 1979. Effects of aluminum and nickel on survival and reproduction in polychaetous annelids. Bull. Environ. Contam. Toxicol. 23(4/5): 698-702.

Pettersson, A., L. Hallbom and B. Bergman. 1985a. Physiological and structural responses of the cyanobacterium *Anabaena cylindrica* to aluminum. Physiol. Plant. 63(2): 153-158.

Pettersson, A., L. Kunst, B. Bergman and G.M. Roomans. 1985b. Accumulation of aluminium by *Anabaena cylindrica* into polyphosphate granules and cell walls: an X-ray energy-dispersive microanalysis study. J. Gen. Microbiol. 131: 2545-2548.

Pettersson, A., L. Hallbom and B. Bergman. 1986. Aluminium uptake by *Anabaena cylindrica*. J. Gen. Microbiol. 132: 1771-1774.

Pettersson, A., L. Hallbom and B. Bergman. 1988. Aluminium effects on uptake and metabolism of phosphorus by the cyanobacterium *Anabaena cylindrica*. Plant Physiol. 86: 112-116.

Peuranen, S., P.J. Vuorinen, M. Vuorinen and H. Tuurala. 1993. Effects of acidity and aluminium on fish gills in laboratory experiments and in the field. Sci. Total Environ. Pt. 2: 979-988.

Phillips, G.R. and R.C. Russo. 1978. Metal bioaccumulation in fishes and aquatic invertebrates: A literature review. EPA-600/3-78-103. National Technical Information Service, Springfield, VA.

Piasecki, W.G. and D. Zacharzewski. 2010. Influence of coagulants used for lake restoration on *Daphnia magna* Straus (Crustacea, Cladocera). Baltic Coast. Zone 14: 49-56.

Pilgrim, K.M. and P.L. Brezonik. 2005. Treatment of lake inflows with alum for phosphorus removal. Lake Res. Manag. 21(1): 1-9.

Pillay, K.K.S. and C.C. Thomas Jr. 1971. Determination of the trace element levels in atmospheric pollutants by neutron activation analysis. J. Radioanal. Chem. 7: 107-118.

Pillsbury, R.W. and J.C. Kingston. 1990. The pH-independent effect of aluminum on cultures of phytoplankton from an acidic Wisconsin Lake. Hydrobiol. 194(3): 225-233.

Playle, R.C. 1989. Physiological effects of aluminum on rainbow trout in acidic soft water, with emphasis on the gill micro-environment. Ph.D. Thesis, McMaster University, Hamilton, Ontario, Canada, 249 pp.

Playle, R.S. and C.M. Wood. 1989. Water pH and aluminum chemistry in the gill micro-environment of rainbow trout during acid and aluminum exposures. J. Comp. Physiol. Part B Biochem. Syst. Environ. Physiol. 159: 539-550.

Playle, R.C. and C.M. Wood. 1991. Mechanisms of aluminium extraction and accumulation at the gills of rainbow trout, *Oncorhynchus mykiss* (Walbaum), in acidic soft water. J. Fish Biol. 38: 791-805.

Playle, R.C., G.G. Goss and C.M. Wood. 1988. Physiological disturbances in rainbow trout during acid and aluminum exposures. Can. Tech. Rep. Fish. Aquat. Sci. 1607: 36.

Playle, R.C., G.G. Goss and C.M. Wood. 1989. Physiological disturbances in rainbow trout (*Salmo gairdneri*) during acid and aluminum exposures in soft water of two calcium concentrations. Can. J. Zool. 67(2): 314-324.

Poleo, A.B.S. 1992. Temperature as a major factor concerning fish mortality in acidic aluminum-rich waters: experiments with young Atlantic salmon (*Salmo salar* L.). Fauna 45(2): 90-99.

Poleo, A.B.S. 1995. Aluminium polymerization: a mechanism of acute toxicity of aqueous aluminium to fish. Aquat. Toxicol. 31: 347-356.

Poleo, A.B.S. and I.P. Muniz. 1993. The effect of aluminium in soft water at low pH and different temperatures on mortality, ventilation frequency and water balance in smoltifying Atlantic salmon, *Salmo salar*. Environ. Biol. Fishes 36(2): 193-203.

Poleo, A.B.S., E. Lydersen and I.P. Muniz. 1991. The influence of temperature on aqueous aluminium chemistry and survival of Atlantic salmon (*Salmo salar* L.) fingerlings. Aquat. Toxicol. 21: 267-278.

Poleo, A.B.S., S.A. Oxneyad, K. Ostbye, R.A. Andersen, D.H. Oughton and L.A. Vollestad. 1995. Survival of crucian carp, *Carassius carassius*, exposed to a high low-molecular weight inorganic aluminium challenge. Aquat. Sci. 57(4): 350-359.

Poleo, A.B.S., K. Ostbye, S.A. Oxnevad, R.A. Andersen, E. Heibo and L.A. Vollestad. 1997. Toxicity of acid aluminium-rich water to seven freshwater fish species: a comparative laboratory study. Environ. Pollut. 96(2): 129-139.

Poleo, A.B.S., J. Schjolden, H. Hansen, T.A. Bakke, T.A. Mo, B.O. Rosseland and E. Lydersen. 2004. The effect of various metals on *Gyrodactylus salaris* (Platyhelminthes, Monogenea) infections in Atlantic salmon (*Salmo salar*). Parasitol. 128(2): 169-177.

Pond, G.J., M.E. Passmore, F.A. Borsuk, L. Reynolds and C.J. Rose. 2008. Downstream effects of mountaintop coal mining: comparing biological conditions using family- and genus-level macroinvertebrate bioassessment tools. J. North Amer. Benthol. Soc. 27(3): 717-737.

Poor, N.D. 2010. Effect of lake management efforts on the trophic state of a subtropical shallow lake in Lakeland, Florida, USA. Water Air Soil Pollut. 207(1-4): 333-347.

Poston, H.A. 1991. Effect of dietary aluminum on growth and composition of young Atlantic salmon. Prog. Fish-Cult. 53(1): 7-10.

Potzl, K. 1970. Inorganic chemical analyses of nonpolluted aerosols sample at 1800 meters altitude. J. Geophys. Res. 75: 2347-2352.

Prange, J.A. and W.C. Dennison. 2000. Physiological responses of five seagrass species to trace metals. Mar. Pollut. Bull. 41(7-12): 327-336.

Pribyl, P., V. Cepak and V. Zachleder. 2005. Cytoskeletal alterations in interphase cells of the green alga *Spirogyra decimina* in response to heavy metals exposure: I. The effect of cadmium. Protoplasm 226: 231-240.

Pynnonen, K. 1990. Aluminium accumulation and distribution in the freshwater clams (Unionidae). Comp. Biochem. Physiol. C Comp. Pharmacol. 97(1): 111-117.

Que Hee, S.S., V.N. Finelli, F.L. Fricke and K.A. Wolnik. 1982. Metal content of stack emissions, coal and fly ash from some eastern and western power plants in the U.S.A. as obtained by ICP-AES. Int. J. Environ. Anal. Chem. 13: 1-18.

Quiroz-Vazquez, P., D.C. Sigee and K.N. White. 2010. Bioavailability and toxicity of aluminium in a model planktonic food chain (*Chlamydomonas-Daphnia*) at neutral pH. Limnol. 40(3): 269-277.

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available online at: https://www.R-project.org/.

Radic, S., M. Babic, D. Skobic, V. Roje and B. Pevalek-Kozlina. 2010. Ecotoxicological effects of aluminum and zinc on growth and antioxidants in *Lemna minor* L. Ecotoxicol. Environ. Saf. 73(3): 336-342.

Rahman, M.T., K. Kawamura, H. Koyama and T. Hara. 1998. Varietal differences in the growth of rice plants in response to aluminum and silicon. Soil Sci. Plant Nutr. 44(3): 423-431.

Rai, L.C., Y. Husaini and N. Mallick. 1996. Physiological and biochemical responses of *Nostoc linckia* to combined effects of aluminium, fluoride and acidification. Environ. Exp. Bot. 36(1): 1-12.

Rai, L.C., Y. Husaini and N. Mallick. 1998. pH-altered interaction of aluminium and fluoride on nutrient uptake, photosynthesis and other variables of *Chlorella vulgaris*. Aquat. Toxicol. 42(1): 67-84.

Rajesh, M. 2010. Toxic effect of aluminium in *Oreochromis mossambicus* (Peters). J. Pure Appl. Microbiol. 4(1): 279-284.

Ramamoorthy, S. 1988. Effect of pH on speciation and toxicity of aluminum to rainbow trout (*Salmo gairdneri*). Can. J. Fish. Aquat. Sci. 45(4): 634-642.

Rao, V.N.R. and S.K. Subramanian. 1982. Metal toxicity tests on growth of some diatoms. Acta Bot. Indica 10: 274-281.

Rayburn, J.R. and R.K. Aladdin. 2003. Developmental toxicity of copper, chromium, and aluminum using the shrimp embryo teratogenesis assay: Palaemonid with artificial seawater. Bull. Environ. Contam. Toxicol. 71(3): 481-488.

Razo-Estrada, A.C., S. Garcia-Medina, E. Madrigal-Bujaidar, L.M. Gomez-Olivan and M. Galar-Martinez. 2013. Aluminum-induced oxidative stress and apoptosis in liver of the common carp, *Cyprinus carpio*. Water Air Soil Pollut. 224:1510.

Reader, J.P. and R. Morris. 1988. Effects of aluminium and pH on calcium fluxes, and effects of cadmium and manganese on calcium and sodium fluxes in brown trout (*Salmo trutta* L.). Comp. Biochem. Physiol. Part C Comp. Pharmacol. 91(2): 449-457.

Reader, J.P., T.R.K. Dalziel and R. Morris. 1988. Growth, mineral uptake and skeletal calcium deposition in brown trout, *Salmo trutta* L., yolk-sac fry exposed to aluminium and manganese in soft acid water. J. Fish Biol. 32(4): 607-624.

Reader, J.P., N.C. Everall, M.D.J. Sayer and R. Morris. 1989. The effects of eight trace metals in acid soft water on survival, mineral uptake and skeletal calcium deposition in yolk-sac fry of brown trout, *Salmo trutta* L. J. Fish Biol. 35: 187-198.

Reader, J.P., T.R.K. Dalziel, R. Morris, M.D.J. Sayer and C.H. Dempsey. 1991. Episodic exposure to acid and aluminium in soft water: survival and recovery of brown trout, *Salmo trutta* L. J. Fish Biol. 39(2): 181-196.

Reid, S.D., D.G. McDonald and R.R. Rhem. 1991. Acclimation to sublethal aluminum: modifications of metal - gill surface interactions of juvenile rainbow trout (*Oncorhynchus mykiss*). Can. J. Fish. Aquat. Sci. 48(10): 1996-2005.

Reitzel, K., J. Hansen, F. Andersen, K.S. Hansen and H.S. Jensen. 2005. Lake restoration by dosing aluminum relative to mobile phosphorus in the sediment. Environ. Sci. Technol. 39(11): 4134-4140.

Reznikoff, P. 1926. Micrurgical studies in cell physiology. II. The action of chlorides of lead, mercury, copper, iron, and aluminum on the protoplasm of *Amoeba proteus*. J. Gen. Physiol. 10: 9.

Rice, K.C. 1999. Trace-element concentrations in streambed sediment across the conterminous United States. Environ. Sci. Technol. 33(15): 2499-2504.

Riseng, C.M., R.W. Gensemer and S.S. Kilham. 1991. The effect of pH, aluminum, and chelator manipulations on the growth of acidic and circumneutral species of *Asterionella*. Water Air Soil Pollut. 60: 249-261.

Rizzo, L., V. Belgiorno, M. Gallo and S. Meric. 2005. Removal of THM precursors from a high-alkaline surface water by enhanced coagulation and behaviour of THMFP toxicity on *D. magna*. Desalination 176(1-3): 177-188.

Roberson, C.E. and J.D. Hem. 1969. Solubility of aluminum in the presence of hydroxides, fluoride, and sulfate. Water Supply Paper 1827-C. U.S. Geological Survey, U.S. Government Printing Office, Washington, DC.

Robertson, E.L. and K. Liber. 2007. Bioassays with caged *Hyalella azteca* to determine in situ toxicity downstream of two Saskatchewan, Canada, uranium operations. Environ. Toxicol. Chem. 26(11): 2345-2355.

Robertson, L.J., A.T. Campbell and H.V. Smith. 1992. Survival of *Cryptosporidium parvum* oocysts under various environmental pressures. Appl. Environ. Microbiol. 58(11): 3494-3500.

Robinson, J.W. and P.M. Deano. 1985. The synergistic effects of acidity and aluminum on fish (golden shiners) in Louisiana. J. Environ. Sci. Health A 20(2): 193-204.

Robinson, J.W. and P.M. Deano. 1986. Acid rain: the effects of pH, aluminum, and leaf decomposition products on fish survival. Am. Lab. (Fairfield Conn.) 18(7): 17-26.

Robinson, D.J.S. and E.J. Perkins. 1977. The toxicity of some wood pulp effluent constituents. Sci. Rep. No. 74/1, Cumbria Sea Fish. Comm., The Courts, Carlisle, England, 22 pp.

Rockwood, J.P., D.S. Jones and R.A. Coler. 1990. The effect of aluminum in soft water at low pH on oxygen consumption by the dragonfly *Libellula julia* Uhler. Hydrobiol. 190: 55-59.

Rosemond, S.D., D.C. Duro, M. Dube and M. Dube. 2009. Comparative analysis of regional water quality in Canada using the water quality index. Environ. Monit. Assess. 156(1-4): 223-240.

Rosseland, B.O. and O.K. Skogheim. 1984. A comparative study on salmonid fish species in acid aluminium-rich water II. Physiological stress and mortality of one- and two-year-old fish. In: Rep. No. 61, National Swedish Board of Fisheries, Drottningholm, Sweden, 186-194.

Rosseland, B.O. and O. K. Skogheim, 1987. Differences in sensitivity to acidic soft water among strains of brown trout (*Salmo trutta*). Annls. Soc. R. Zool. Belg. 11711: 255-26.

Rosseland, B.O., O.K. Skogheim, F. Kroglund and E. Hoell. 1986. Mortality and physiological stress of year-classes of land-locked and migratory Atlantic salmon, brown trout and brook trout in acidic aluminium rich soft water. Water Air Soil Pollut. 30: 751-756.

Rosseland, B.O., T.D. Eldhuset and M. Staurnes. 1990. Environmental effects of aluminum. Environ. Geochem. Health 12: 17-27.

Rosseland, B.O., I.A. Blakar, A. Bulger, F. Kroglund, A. Kvellstad, E. Lydersen, D.H. Oughton, B. Salbu, M. Staurnes and R. Vogt. 1992. The mixing zone between limed and acidic river waters: complex aluminium and extreme toxicity for salmonids. Environ. Pollut. 78: 3-8.

Rosseland, B.O., B. Salbu, F. Kroglund, T. Hansen, H.C. Teien and J. Havardstun. 1998. Changes in metal speciation in the interface between freshwater and seawater (estuaries), and the effects on Atlantic salmon and marine organisms. Final Report to the Norwegian Research Council, Contract No. 108102/122.

Roy, B. and S. Bhadra. 2013. Hematoxylin staining of seedling roots is a potential phenotypic index for screening of aluminium tolerance in rice (*Oryza sativa* L.). Indian J. Genet. Plant Breed. 73(2): 194-198.

Roy, R. and P.G.C. Campbell. 1995. Survival time modeling of exposure of juvenile Atlantic salmon (*Salmo salar*) to mixture of aluminum and zinc in soft water at low pH. Aquat. Toxicol. 33(2): 155-176.

Roy, R.L. and P.G.C. Campbell. 1997. Decreased toxicity of Al to juvenile Atlantic salmon (*Salmo salar*) in acidic soft water containing natural organic matter: a test of the free-ion model. Environ. Toxicol. Chem. 16(9): 1962-1969.

Royset, O., B.O. Rosseland, T. Kristensen, F. Kroglund, O.A. Garmo and E. Steinnes. 2005. Diffusive gradients in thin films sampler predicts stress in brown trout (*Salmo trutta* L.) exposed to aluminum in acid fresh waters. Environ. Sci. Technol. 39(4): 1167-1174.

Rueter, J.G.Jr., K.T. O'Reilly and R.R. Petersen. 1987. Indirect aluminum toxicity to the green alga *Scenedesmus* through increased cupric ion activity. Environ. Sci. Technol. 21(5): 435-438.

Ruthven, J.A. and J. Cairns Jr. 1973. The response of fresh-water protozoan artificial communities to metals. J. Protozool. 20(1): 127-135.

Sacan, M.T. and I.A. Balcioglu. 2001. Bioaccumulation of aluminium in *Dunaliella tertiolecta* in natural seawater: aluminium-metal (Cu, Pb, Se) interactions and influence of pH. Bull. Environ. Contam. Toxicol. 66(2): 214-221.

Sacan, M.T., F. Oztay and S. Bolkent. 2007. Exposure of *Dunaliella tertiolecta* to lead and aluminum: toxicity and effects on ultrastructure. Biol. Trace Elem. Res. 120(1/3): 264-272.

Sadler, K. and S. Lynam. 1987. Some effects on the growth of brown trout from exposure to aluminium at different pH levels. J. Fish Biol. 31: 209-219.

Sadler, K. and S. Lynam. 1988. The influence of calcium on aluminium-induced changes in the growth rate and mortality of brown trout, *Salmo trutta* L. J. Fish Biol. 33(2): 171-179.

Salbu, B., J. Denbeigh, R.W. Smith, L.S. Heier, H.C. Teien, B.O. Rosseland, D. Oughton, C.B. Seymour and C. Mothersill. 2008. Environmentally relevant mixed exposures to radiation and heavy metals induce measurable stress responses in Atlantic salmon. Environ. Sci. Technol. 42: 3441-3446.

Sanborn, N.H. 1945. The lethal effect of certain chemicals on fresh water fish. The Canning Trade 16(27): 13-15.

Santore, R.C., A.C. Ryan, F. Kroglund, P. Rodriguez, W. Stubblefield, A. Cardwell, W. Adams and E. Nordheim. 2018. Development and application of a biotic ligand model for predicting the chronic toxicity of dissolved and precipitated aluminum to aquatic organisms. Environ. Toxicol. Chem. 37(1): 70-79.

Sauer, G.R. 1986. Heavy metals in fish scales: accumulation and effects of calcium regulation in the mummichog, *Fundulus heteroclitus* L. Ph.D. Thesis, University of South Carolina.

Sauvant, M.P., D. Pepin, J. Bohatier and C.A. Groliere. 2000. Effects of chelators on the acute toxicity and bioavailability of aluminium to *Tetrahymena pyriformis*. Aquat. Toxicol. 47(3-4): 259-275.

Sayer, M.D.J. 1991. Survival and subsequent development of brown trout, *Salmo trutta* L., subjected to episodic exposures of acid, aluminium and copper in soft water during embryonic and larval stages. J. Fish Biol. 38: 969-972.

Sayer, M.D.J., J.P. Reader and R. Morris. 1991a. Embryonic and larval development of brown trout, *Salmo trutta* L.: exposure to aluminium, copper, lead or zinc in soft, acid water. J. Fish Biol. 38: 431-455.

Sayer, M.D.J., J.P. Reader and R. Morris. 1991b. Embryonic and larval development of brown trout, *Salmo trutta* L.: exposure to trace metal mixtures in soft water. J. Fish Biol. 38: 773-787.

Sayer, M.D.J., J.P. Reader and R. Morris. 1991c. Effects of six trace metals on calcium fluxes in brown trout (*Salmo trutta* L.) in soft water. J. Comp. Physiol. B.: 537-542.

Sayer, M.D.J., J.P. Reader, T.R.K. Dalziel and R. Morris. 1991d. Mineral content and blood parameters of dying brown trout (*Salmo trutta* L.) exposed to acid and aluminium in soft water. Comp. Biochem. Physiol. C Comp. Pharmacol. 99: 345-348.

Scheuhammer, A.M. 1991. Acidification-related changes in the biogeochemistry and ecotoxicology of mercury, cadmium, lead and aluminum – overview. Environ. Pollut. 71: 87-90.

Schindler, D.W. and M.A. Turner. 1982. Biological, chemical and physical responses of lakes to experimental acidification. Water Air Soil Pollut. 18: 259-271.

Scholfield, C.L. 1977. Acid snow-melt effects on water quality and fish survival in the Adirondack Mountains of New York State. Research Project Technical Completion Report. Office of Water Research and Technology, US Department of the Interior. Washington, DC, 22 pp.

Schofield, C.L. and J.R. Trojnar. 1980. Aluminum toxicity to brook trout (*Salvelinus fontinalis*) in acidified waters. Environ. Sci. Res. 17: 341-366.

Schumaker, R.J., W.H. Funk and B.C. Moore. 1993. Zooplankton responses to aluminum sulfate treatment of Newman Lake, Washington. J. Fresh. Ecol. 8(4): 375-387.

Segner, H., R. Marthaler and M. Linnenbach. 1988. Growth, aluminium uptake and mucous cell morphometrics of early life stages of brown trout, *Salmo trutta*, in low pH water. Environ. Biol. Fishes 21(2): 153-159.

Seip, H.M., L. Muller and A. Naas. 1984. Aluminum speciation: Comparison of two spectrophotometric analytical methods and observed concentrations in some acidic aquatic systems in southern Norway. Water Air Soil Pollut. 23: 81-95.

Senger, M.R., K.J. Seibt, G.C. Ghisleni, R.D. Dias, M.R. Bogo and C.D. Bonan. 2011. Aluminum exposure alters behavioral parameters and increases acetylcholinesterase activity in zebrafish (*Danio rerio*) brain. Cell Biol. Toxicol. 27(3): 199-205.

Shabana, E.F., A.F. Dowidar, I.A. Kobbia and S.A. El Attar. 1986a. Studies on the effects of some heavy metals on the biological activities of some phytoplankton species. II. The effects of some metallic ions on. Egypt. J. Physiol. Sci. 13(1/2): 55-71.

Shabana, E.F., I.A. Kobbia, A.E. Dowidar and S.A. El Attar. 1986b. Studies on the effects of some heavy metals on the biological activities of some phytoplankton species. III. Effects of Al^{3+}, Cr^{3+}, Pb^{2+} and Zn^{2+} on heterocyst frequency, nitrogen and phosphorus metabolism of *Anabaena oryzae* and *Aulosira fertilissima*. Egypt. J. Physiol. Sci. 13(1/2): 73-94.

Shacklette, H.T. and J.G. Boerngen. 1984. Element concentrations in soils and other surficial materials of the conterminous United States. United States Geological Survey Professional Paper, 1270. USGS, Alexandria, VA. Available online at http://pubs.usgs.gov/pp/1270/pdf/PP1270_508.pdf.

Sharma, K.P., N. Upreti, S. Sharma and S. Sharma. 2012. Protective effect of *Spirulina* and tamarind fruit pulp diet supplement in fish (*Gambusia affinis* Baird & Girard) exposed to sublethal concentration of fluoride, aluminum and aluminum fluoride. Indian J. Exp. Biol. 50: 897-903.

Shephard, B. 1983. The effect of reduced pH and elevated aluminum concentrations on three species of zooplankton: *Ceriodaphnia reticulata*, *Daphnia magna* and *Daphnia pulex*. U.S. EPA, Duluth, MN, 14 pp.

Shuhaimi-Othman, M., N. Yakub, N.A. Ramle and A. Abas. 2011a. Toxicity of metals to a freshwater ostracod: *Stenocypris major*. J. Toxicol. Article ID 136104, 8 pp.

Shuhaimi-Othman, M., N. Yakub, N.S. Umirah, A. Abas and M. Shuhaimi-Othman. 2011b. Toxicity of eight metals to Malaysian freshwater midge larvae *Chironomus javanus* (Diptera, Chironomidae). Toxicol. Indust. Health 27(10): 879-886.

Shuhaimi-Othman, M., Y. Nadzifah, N.S. Umirah and A.K. Ahmad. 2012a. Toxicity of metals to an aquatic worm, *Nais elinguis* (Oligochaeta, Naididae). Res. J. Environ. Toxicol. 6(4): 122-132.

Shuhaimi-Othman, M., R. Nur-Amalina and Y. Nadzifah. 2012b. Toxicity of metals to a freshwater snail, *Melanoides tuberculata*. Sci. World J. 125785, 10 p.

Shuhaimi-Othman, M., Y. Nadzifah, N.S. Umirah and A.K. Ahmad. 2012c. Toxicity of metals to tadpoles of the common Sunda toad, *Duttaphrynus melanostictus*. Toxicol. Environ. Chem. 94(2): 364-376.

Shuhaimi-Othman, M., Y. Nadzifah, R. Nur-Amalina and N.S. Umirah. 2013. Deriving freshwater quality criteria for copper, cadmium, aluminum and manganese for protection of aquatic life in Malaysia. Chemosphere 90: 2631-2636.

Siddens, L.K., W.K. Seim, L.R. Curtis and G.A. Chapman. 1986. Comparison of continuous and episodic exposure to acidic, aluminum-contaminated waters of brook trout (*Salvelinus fontinalis*). Can. J. Fish. Aquat. Sci. 43(10): 2036-2040.

Siebers, D. and U. Ehlers. 1979. Heavy metal action on transintegumentary absorption of glycine in two annelid species. Mar. Biol. 50(2): 175-179.

Sigel, H. and A. Sigel. 1988. Metal Ions in Biological Systems, Vol. 24. Aluminum and its Role in Biology. Marcel Dekker, NY.

Simon, M.L. 2005. Sediment and interstitial water toxicity to freshwater mussels and the ecotoxicological recovery of remediated acid mine drainage streams. Master of Science Thesis, Virginia Polytechnic Institute and State University. 113 pp.

Sivakumar, S. and J. Sivasubramanian. 2011. FT-IR study of the effect of aluminium on the muscle tissue of *Cirrhinus mrigala*. J. Pharm. Res. 4(12): 4734-4735.

Skogheim, O.K. and B.O. Rosseland. 1984. A comparative study on salmonid fish species in acid aluminium-rich water I. Mortality of eggs and alevins. In: Rep. No. 61, Institute of Freshwater Swedish Board of Fisheries, Drottningholm, Sweden, 177-185.

Skogheim, O.K. and B.O. Rosseland. 1986. Mortality of smolt of Atlantic salmon, *Salmo salar* L., at low levels of aluminium in acidic softwater. Bull. Environ. Contam. Toxicol. 37(2): 258-265.

Skogheim, O.K., B.O. Rosseland, F. Kroglund and G. Hagenlund. 1987. Addition of NaOH, limestone slurry and finegrained limestone to acidified lake water and the effects on smolts of Atlantic salmon (*Salmo salar* L.). Water Res. 21(4): 435-443.

Skrabal, S.A., J.R. Donat and D.J. Burdige. 2000. Pore water distributions of dissolved copper and copper-complexing ligands in estuarine and coastal marine sediments. Geochim. Cosmoch. Acta 64(11): 1843-1857.

Smith, L.L., Jr., D.M. Oseid, G.L. Kimball and S.M. El-Kandelgy. 1976. Toxicity of hydrogen sulfide to various life history stages of bluegill (*Lepomis macrochirus*). Trans. Amer. Fish. Soc. 105: 442-449.

Smith, R.W. and J.D. Hem. 1972. Chemistry of aluminum in natural water: Effect of aging on aluminum hydroxide complexes in dilute aqueous solutions. Water Supply Paper 1827-D. U.S. Geological Survey, U.S. Government Printing Office, Washington, DC.

Snell, T.W. 1991. New rotifer bioassays for aquatic toxicology - final report. U.S. Army Med. Res. Dev. Command, Ft. Detrick, Frederick, MD, 29 pp. U.S. NTIS AD-A258002.

Snell, T.W., B.D. Moffat, C. Janssen and G. Persoone. 1991. Acute toxicity tests using rotifers IV. Effects of cyst age, temperature, and salinity on the sensitivity of *Brachionus calyciflorus*. Ecotoxicol. Environ. Saf. 21(3): 308-317.

Snodgrass, W.J., M.M. Clark and C.R. O'Melia. 1984. Particle formation and growth in dilute aluminum(III) solutions. Water Res. 18: 479-488.

Soleng, A., A.B.S. Poleo and T.A. Bakke. 2005. Toxicity of aqueous aluminium to the ectoparasitic *Monogenean gyrodactylus salaris*. Aquacult. 250(3/4): 616-620.

Sonnichsen, T. 1978. Toxicity of a phosphate-reducing agent (aluminium sulphate) on the zooplankton in the Lake Lyngby So. Int. Assoc. Theor. Appl. Limnol. Proc./Int. Ver. Theor. Angew. Limnol. Verh. 20(1): 709-713.

Sorenson, J.R.J., I.R. Campbell, L.B. Tepper and R.D. Lingg. 1974. Aluminum in the environment and human health. Environ. Health Perspect. 8: 3-95. Available online at http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1474938/pdf/envhper00498-0010.pdf.

Soucek, D.J., D.S. Cherry and C.E. Zipper. 2001. Aluminum-dominated acute toxicity to the cladoceran *Ceriodaphnia dubia* in neutral waters downstream of an acid mine drainage discharge. Can. J. Fish. Aquat. Sci. 58(12): 2396-2404.

Sparling, D.W. 1990. Conditioned aversion of aluminum sulfate in black ducks. Environ. Toxicol. Chem. 9: 479-483.

Sparling, D.W. and T.P. Lowe. 1996a. Environmental hazards of aluminum to plants, invertebrates, fish, and wildlife. Rev. Environ. Contam. Toxicol. 145: 1-127.

Sparling, D.W. and T.P. Lowe. 1996b. Metal concentrations of tadpoles in experimental ponds. Environ. Pollut. 91(2): 149-159.

Sparling, D.W. and T.P. Lowe. 1998. Metal concentrations in aquatic macrophytes as influenced by soil and acidification. Water Air Soil Pollut. 108: 203-221.

Sparling, D.W., T.P. Lowe, D. Day and K. Dolan. 1995. Responses of amphibian populations to water and soil factors in experimentally-treated aquatic macrocosms. Arch. Environ. Contam. Toxicol. 29(4): 455-461.

Sparling, D.W., T.P. Lowe and P.G.C. Campbell. 1997. Ecotoxicology of aluminum to fish and wildlife. In: R.A. Yokel and M.S. Golub (*Eds*.), Research Issues in Aluminum Toxicity, Taylor and Francis, Washington, DC, 47-68.

Sposito, G. 1989. The Environmental Chemistry of Aluminum. CRC Press, Boca Raton, FL.

Sposito, G. 1996. The Environmental Chemistry of Aluminum (2nd Ed.). Lewis Publishers, Boca Raton, FL.

Sprague, J.B. 1985. Factors that modify toxicity. In: G.M. Rand and S.R. Petrocelli (*Eds.*), Fundamentals of aquatic toxicology. Hemisphere Publishing Company, New York, NY, 124-163.

Staley, J.T. and W. Haupin. 1992. Aluminum and aluminum alloys. In: J.I. Kroschwitz and M. Howe-Grant (*Eds.*), Kirk-Othmer encyclopedia of chemical technology. Vol. 2: Alkanolamines to antibiotics (glycopeptides). John Wiley & Sons, Inc., NY, 248-249.

Stanley, R.A. 1974. Toxicity of heavy metals and salts to Eurasian watermilfoil (*Myriophyllum spicatum* L.). Arch. Environ. Contam. Toxicol. 2(4): 331-341.

Staurnes, M., T. Sigholt and O.B. Reite. 1984. Reduced carbonic anhydrase and Na-K-ATPase activity in gills of salmonids exposed to aluminium-containing acid water. Experientia 40: 226-227.

Staurnes, M., P. Blix and O.B. Reite. 1993. Effects of acid water and aluminum on parr-smolt transformation and seawater tolerance in Atlantic salmon, *Salmo salar*. Can. J. Fish. Aquat. Sci. 50: 1816-1827.

Stearns, F.M., R.A. DeMaio and H.J. Eichel. 1978. Occurrence of cyanide-resistant respiration and of increased concentrations of cytochromes in *Tetrahymena* cells grown with various metals. Fed. Proc. 37: 1516.

Stephan, C.E. 1978. Chronic screening toxicity test with *Daphnia magna*. Memorandum to Dr. David Friedman, Sept. 29th, U.S. EPA, Washington, DC, 3 p.

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. PB85-227040. National Technical Information Service, Springfield, WA. Available online at: https://www.epa.gov/sites/production/files/2016-02/documents/guidelines-water-quality-criteria.pdf.

Stevens, R.K., T.G. Dzubay, G. Russwurm and D. Rickel. 1978. Sampling and analysis of atmospheric sulfates and related species. Atmos. Environ. 12(1-3): 55-68.

Storey, D.M., F.B. Pyatt and L.E. Broadley. 1992. An appraisal of some effects of simulated acid rain and aluminum ions on *Cyclops viridis* (Crustacea, Copepoda) and *Gammarus pulex* (Crustacea, Amphipoda). Int. J. Environ. Stud. 42: 159-176.

Strigul, N., L. Vaccari, C. Galdun, M. Wazne, X. Liu, C. Christodoulatos and K. Jasinkiewicz. 2009. Acute toxicity of boron, titanium dioxide, and aluminum nanoparticles to *Daphnia magna* and *Vibrio fischeri*. Desalination 248(1-3): 771-782.

Stumm, W. and J.J. Morgan. 1981. Aquatic chemistry. Wiley, New York, NY. p. 176-177.

Sudo, R. and S. Aiba. 1975. Effect of some metals on the specific growth rate of ciliata isolated from activated sludge. In: 1st Proc. Int. Congr. Int. Assoc. Microbiol. Soc. 2: 512-521.

Suedel, B.C., J.A. Boraczek, R.K. Peddicord, P.A. Clifford and T.M. Dillon. 1994. Trophic transfer and biomagnification potential of contaminants in aquatic ecosystems. Rev. Environ. Contam. Toxicol. 136: 22-89.

Sugiura, K. 2001. Effects of Al^{3+} ions and Cu^{2+} ions on microcosms with three different biological complexities. Aquat. Toxicol. 51(4): 405-417.

Tabak, L.M. and K.E. Gibbs. 1991. Effects of aluminum, calcium and low pH on egg hatching and nymphal survival of *Cloeon triangulifer* McDunnough (Ephemeroptera: Baetidae). Hydrobiol. 218(2): 157-166.

Takano, M. and T. Shimmen. 1999. Effects of aluminum on plasma membrane as revealed by analysis of alkaline band formation in internodal cells of *Chara corallina*. Cell Struct. Funct. 24: 131-137.

Takeda, K., K. Marumoto, T. Minamikawa, H. Sakugawa and K. Fujiwara. 2000. Three-year determination of trace metals and the lead isotope ratio in rain and snow depositions collected in Higashi-Hiroshima, Japan. Atmos. Environ. 34: 4525–4535.

Tanaka, A. and S.A. Navasero. 1966. Aluminum toxicity of the rice plant under water culture conditions. Soil Sci. Plant Nutr. 12(2): 9-14.

Tandjung, S.D. 1982. The acute toxicity and histopathology of brook trout (*Salvelinus fontinalis*, Mitchill) exposed to aluminum in acid water. Ph.D. Thesis, Fordham University, New York, NY, 330 pp.

Taneeva, A.I. 1973. Toxicity of some heavy metals for hydrobionts. In: V.N. Greze (*Ed*.), Proc. Mater. Vses. Simp. Izuch. Chern. Sredizemnogo Morei, Ispol'Z Okhr. Ikh. Resur. Kiev, USSR Ser. 4, 114-117.

Taskinen, J., P. Berg, M. Saarinen-Valta, S. Valila, E. Maenpaa, K. Myllynen, J. Pakkala and P. Berg. 2011. Effect of pH, iron and aluminum on survival of early life history stages of the endangered freshwater pearl mussel, *Margaritifera margaritifera*. Toxicol. Environ. Chem. 93(9): 1764-1777.

Tchobanoglous, G., F.L. Burton and H.D. Stensel. 2003. Meltcalf & Eddy, Inc.'s Wastewater Engineering: Treatment, Disposal, and Reuse, 4th Edition. McGraw-Hill, Inc. NY, 1,819 pp.

Tchounwou, T.B., C.G. Yedjou, A.K. Patlolla and D.J. Sutton. 2012. Heavy metals toxicity and the environment. EXS. 101: 133-164.

Tease, B. and R.A. Coler. 1984. The effect of mineral acids and aluminum from coal leachate on substrate periphyton composition and productivity. J. Fresh. Ecol. 2: 459-467.

Teien, H.C., W.J.F. Standring and B. Salbu. 2006a. Mobilization of river transported colloidal aluminium upon mixing with seawater and subsequent deposition in fish gills. Sci. Total Environ. 364: 149-164.

Teien, H.C., F. Kroglund, A. Atland, B.O. Rosseland and B. Salbu. 2006b. Sodium silicate as alternative to liming-reduced aluminium toxicity for Atlantic salmon (*Salmo salar* L.) in unstable mixing zones. Sci. Total Environ. 358: 151-163.

Terhaar, C.J., W.S. Ewell., S.P. Dziuba and D.W. Fassett. 1972. Toxicity of photographic processing chemicals to fish. Photogr. Sci. Eng. 16(5): 370-377.

Thawornwong, N. and A. Van Diest. 1974. Influences of high acidity and aluminum on the growth of lowland rice. Plant Soil 41: 141-159.

Thomas, A. 1915. Effects of certain metallic salts upon fishes. Trans. Am. Fish. Soc. 44: 120-124.

Thompson, S.E., C.A. Burton, D.J. Quinn and Y.C. Ng. 1972. Concentration factors of chemical elements in edible aquatic organisms. UCRL-50564. Rev. 1. National Technical Information Service, Springfield, VA.

Thomsen, A., B. Korsgaard and J. Joensen. 1988. Effect of aluminum and calcium ions on survival and physiology of rainbow trout *Salmo gairdneri* (Richardson) eggs and larvae exposed to acid stress. Aquat. Toxicol. 12: 291-300.

Thorstad, E.B., I. Uglem, B. Finstad, F. Kroglund, I.E. Einarsdottir, T. Kristensen, O. Diserud, P. Arechavala-Lopez, I. Mayer, A. Moore, R. Nilsen, B.T. Bjornsson and F. Okland. 2013. Reduced marine survival of hatchery-reared Atlantic salmon post-smolts exposed to aluminium and moderate acidification in freshwater. Estuar. Coast. Shelf Sci. 124: 34-43.

Tietge, J.E., R.D. Johnson and H.L. Bergman. 1988. Morphometric changes in gill secondary lamellae of brook trout (*Salvelinus fontinalis*) after long-term exposure to acid and aluminum. Can. J. Fish. Aquat. Sci. 45: 1643-1648.

Tipping, C., C.D. Vincent, A.J. Lawlor and S. Lofts. 2008. Metal accumulation by stream bryophytes, related to chemical speciation. Environ. Pollut. 156: 936-943.

Tomasik, P., C.H.D. Magadza, S. Mhizha and A. Chirume. 1995a. The metal-metal interactions in biological systems. Part III. *Daphnia magna*. Water Air Soil Pollut. 82: 695-711.

Tomasik, P., C.M. Magadza, S. Mhizha, A. Chirume, M.F. Zaranyika and S. Muchiriri. 1995b. Metal-metal interactions in biological systems. Part IV. Freshwater snail *Bulinus globosus*. Water Air Soil Pollut. 83(1/2): 123-145.

Tornqvist, L. and A. Claesson. 1987. The influence of aluminum on the cell-size distribution of two green algae. Environ. Exp. Bot. 27: 481-488.

Trenfield, M.A., S.J. Markich, J.C. Ng, B. Noller and R.A. Van Damy. 2012. Dissolved organic carbon reduces the toxicity of aluminum to three tropical freshwater organisms. Environ. Toxicol. Chem. 31(2): 427-436.

Tria, J., E.C.V. Butler, P.R. Haddad and A.R. Bowie. 2007. Determination of aluminium in natural water samples. Anal. Chim. Acta. 588: 153-165.

Troilo, G., M.M.P. Camargo, M.N. Fernandes and C.B.R. Martinez. 2007. Biochemical responses of *Prochilodus lineatus* after 24-h exposure to aluminum. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 148: S78.

Truscott, R., C.R. McCrohan, S.E.R. Bailey and K.N. White. 1995. Effect of aluminium and lead on activity in the freshwater pond snail *Lymnaea stagnalis*. Can. J. Fish. Aquat. Sci. 52(8): 1623-1629.

Tunca, E., E. Ucuncu, A.D. Ozkan, Z.E. Ulger and T. Tekinay. 2013. Tissue distribution and correlation profiles of heavy-metal accumulation in the freshwater crayfish *Astacus leptodactylus*. Arch. Environ. Contam. Toxicol. 64: 676-691.

Tyler-Jones, R., R.C. Beattie and R.J. Aston. 1989. The effects of acid water and aluminium on the embryonic development of the common frog, *Rana temporaria*. J. Zool. (Lond.) 219: 355-372.

Umebese, C.E. and A.F. Motajo. 2008. Accumulation, tolerance and impact of aluminium, copper and zinc on growth and nitrate reductase activity of *Ceratophyllum demersum* (Hornwort). J. Environ. Biol. 29(2): 197-200.

Unz, R.F. and J.A. Davis. 1975. Microbiology of combined chemical-biological treatment. J. Water Pollut. Control Fed. 47: 185-194.

Upreti, N., S. Sharma, S. Sharma and K.P. Sharma. 2013. Toxic effects of aluminium and fluoride on planktonic community of the microcosms. Nat. Environ. Pollut. Technol. 12(3): 523-528.

Ura, K., T. Kai, S. Sakata, T. Iguchi, and K. Arizono. 2002. Aquatic acute toxicity testing using the nematode Caenorhabditis elegans. Journal of Health Science 48: 583-586.

U.S. EPA (United States Environmental Protection Agency). 1976. Quality criteria for water. PB-263943 or EPA-440/9-76-023. National Technical Information Service, Springfield, VA.

U.S. EPA (United States Environmental Protection Agency). 1980. Water quality criteria documents. Federal Register 45: 79318-79379.

U.S. EPA (United States Environmental Protection Agency). 1983a. Methods for chemical analysis of water and wastes. EPA-600/4-79-020 (Revised March 1983). National Technical Information Service, Springfield, VA.

U.S. EPA (United States Environmental Protection Agency). 1983b. Water quality standards regulation. Federal Register 48: 51400-51413.

U.S. EPA (United States Environmental Protection Agency). 1983c. Water quality standards handbook. Office of Water Regulations and Standards, Washington, DC.

U.S. EPA (United States Environmental Protection Agency). 1985a. Appendix B - Response to public comments on "Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses." Federal Register 50: 30793-30796.

U.S. EPA (United States Environmental Protection Agency). 1985b. Water quality criteria. Federal Register. 50: 30784-30792.

U.S. EPA (United States Environmental Protection Agency). 1985c. Technical support document for water quality-based toxics control. EPA-440/4-85-032 or PB86-150067. National Technical Information Service, Springfield, VA.

U.S. EPA (United States Environmental Protection Agency). 1986. Quality criteria for water 1986. EPA-440/5-86-001. Office of Water, Washington, DC.

U.S. EPA (United States Environmental Protection Agency). 1987. Permit writer's guide to water quality-based permitting for toxic pollutants. EPA-440/4-87-005. Office of Water, Washington, DC.

U.S. EPA (United States Environmental Protection Agency). 1988. Ambient water quality criteria for aluminum. EPA-440/5-86-008. Office of Water, Washington, DC.

U.S. EPA (United States Environmental Protection Agency). 1991. Technical support document for water quality-based toxics control. EPA-505/2-90-001. Office of Water, Washington, DC.

U.S. EPA (United States Environmental Protection Agency). 1994a. Method 200.7 (Rev. 4.4): Determination of metals and trace elements in water and wastes by inductively coupled plasma-atomic emission spectrometry. Environmental Monitoring Systems Laboratory, Office of Research and Development, U. S. Environmental Protection Agency, Cincinnati, OH. 59 pp.

U.S. EPA (United States Environmental Protection Agency). 1994b. Method 200.8 (Rev. 5.4): Determination of trace elements in waters and wastes by inductively coupled plasma - mass spectrometry. Environmental Monitoring Systems Laboratory, Office of Research and Development, U. S. Environmental Protection Agency, Cincinnati, OH. 58 pp.

U.S. EPA (United States Environmental Protection Agency). 1996. Method 1669: Sampling Ambient Water for Trace Metals at EPA Water Quality Criteria Levels. U.S. Environmental Protection Agency, Office of Water, Engineering and Analysis Division. Washington, D.C. 39 pp.

U.S. EPA (United States Environmental Protection Agency). 1998a. Guidelines for ecological risk assessment. EPA/630/R-95/002F. Risk Assessment Forum, Washington, DC.

U.S. EPA (United States Environmental Protection Agency). 1998b. Total vs. total recoverable metals. Memorandum from W.A. Telliard to P. Sosinski. Dated August 19, 1998.

U.S. EPA (United States Environmental Protection Agency). 1999a. Integrated approach to assessing the bioavailability and toxicity of metals in surface water and sediments. EPA-822-E-99-001. Office of Water, Washington, DC.

U.S. EPA (United States Environmental Protection Agency). 1999b. 1999 Update of ambient water quality criteria for ammonia. EPA-822-R-99-014. National Technical Information Service, Springfield, VA.

U.S. EPA (United States Environmental Protection Agency). 1999c. National recommended water quality criteria – correction. Office of Water. EPA 822-Z-99-001.

U.S. EPA (United States Environmental Protection Agency). 2000. A SAB Report: Review of the biotic ligand model of the acute toxicity of metals.

U.S. EPA (United States Environmental Protection Agency). 2001. 2001 update of ambient water quality criteria for cadmium. EPA-822-R-01-001. Office of Water, Office of Science and Technology, Washington, DC. April 2001.

U.S. EPA (United States Environmental Protection Agency). 2002. National recommended water quality criteria: 2002. EPA-822-R-02-047. Office of Water, Office of Science and Technology, Washington, DC. November 2002.

U.S. EPA (United States Environmental Protection Agency). 2004. Trace metal clean sampling of natural waters. U.S. EPA Region 9 Laboratory Field Sampling Guidance Document #1229, Richmond, CA. 25 pp.

U.S. EPA (United States Environmental Protection Agency). 2007a. Framework for metals risk assessment. EPA 120/R-07/001. Office of the Science Advisor, Risk Assessment Forum, U.S. Environmental Protection Agency. Washington, DC. 172 pp.

U.S. EPA (United States Environmental Protection Agency). 2007b. Aquatic life ambient freshwater quality criteria - copper, 2007 Revision. EPA-822-R-07-001. Office of Water, Office of Science and Technology, Washington, DC. February 2007.

U.S. EPA (United States Environmental Protection Agency). 2008. White Paper: Aquatic Life Criteria for Contaminants of Emerging Concern, Part I: General Challenges and Recommendations. OW/ORD Emerging Contaminants Workgroup. Office of Water, Washington, DC. June 2008.

U.S. EPA (United States Environmental Protection Agency). 2012. The current state of understanding regarding test conditions and methods for water only toxicity testing with *Hyalella azteca.* Draft – November 19, 2012.

U.S. EPA (United States Environmental Protection Agency). 2013. Aquatic life ambient water quality criteria for ammonia – freshwater. EPA-822-R-13-001. Office of Water, Washington, DC.

U.S. EPA (United States Environmental Protection Agency). 2014. Water quality standards handbook. EPA-820-B-14-008. Office of Water, Washington, DC. Available online at: https://www.epa.gov/wqs-tech/water-quality-standards-handbook.

U.S. EPA (United States Environmental Protection Agency). 2017. National recommended water quality criteria - aqutic life criteria table. Webpage (last updated March 30, 2017), Office of Water, Office of Science and Technology. Washington, DC. Available online at: https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table (accessed 4.11.17).

USGS (United States Geological Survey). 1964. Chemical composition of snow in the Northern Sierra Nevada and other areas. Geochemistry of water. United States Geological Survey, U.S. Department of Interior. USGS Water Supply Paper 1535-J.

USGS (United States Geological Survey). 1972. Environmental geochemistry. Geochemical survey of Missouri. United States Geological Survey, Branch of Regional Geochemistry Open-file report 92,102.

USGS (United States Geological Survey). 1993. Understanding our fragile environment, lessons from geochemical studies. U.S. Geological Survey Circular 1105. U.S. Department of the Interior. U.S. Geological Survey, Denver, CO. 34 pp.

USGS (United States Geological Survey). 2013. Mineral commodity summaries. January 2013. (Also available at http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/).

van Coillie, R. and A. Rousseau. 1974. Mineral composition of the scales of *Catostomus commersoni* from two different waters: Studies using electron microprobe analysis. J. Fish. Res. Board Can. 31: 63-66.

van Dam, H., G. Suurmond and C.J.F. ter Braak. 1981. Impact of acidification on diatoms and chemistry of Dutch moorland pools. Hydrobiol. 83: 425-459.

Van Hoecke, K., K.A.C. De Schamphelaere, S. Ramirez-Garcia, P. Van Der Meeren, G. Smagghe and C.R. Janssen. 2011. Influence of alumina coating on characteristics and effects of SiO_2 nanoparticles in algal growth inhibition assays at various pH and organic matter contents. Environ. Int. 37: 1118-1125.

Varrica, D., A. Aiuppa and G. Dongarra. 2000. Volcanic and anthropogenic contribution to heavy metal content in lichens from Mt. Etna and Vulcano Island (Sicily). Environ. Pollut. 108(2): 153-162.

Vazquez, M.D., J.A. Fernandez, J. Lopez and A. Carballeira. 2000. Effects of water acidity and metal concentration on accumulation and within-plant distribution of metals in the aquatic bryophyte *Fontinalis antipyretica*. Water Air Soil Pollut. 120(1/2): 1-19.

Velzeboer, R., M. Drikas, C. Donati, M. Burch and D. Steffensen. 1995. Release of geosmin by *Anabaena circinalis* following treatment with aluminium sulphate. Water Sci. Technol. 31(11): 187-194.

Velzeboer, I., A.J. Handriks, M.J. Ragas and D. Van de Meent. 2008. Aquatic ecotoxicity tests of some nanomaterial's. Environ. Toxicol. Chem. 27(9): 1942-1947.

Verbost, P.M., F.P.J. Lafeber, F.A.T. Spanings, E.M. Aarden and S.E.W. Bonga. 1992. Inhibition of Ca^{2+} uptake in freshwater carp, *Cyprinus carpio*, during short-term exposure to aluminum. J. Exp. Zool. 262(3): 247-254.

Verbost, P.M., M.H.G. Berntssen, F. Kroglund, E. Lydersen, H.E. Witters, B.O. Rosseland and B. Salbu. 1995. The toxic mixing zone of neutral and acidic river water: acute aluminium toxicity in brown trout (*Salmo trutta* L.). Water Air Soil Pollut. 85(2): 341-346.

Vieira, V.A.R.O., T.G. Correia and R.G. Moreira. 2013. Effects of aluminum on the energetic substrates in neotropical freshwater *Astyanax bimaculatus* (Teleostei: Characidae) females. Comp. Biochem. Physiol. Part C: Toxicol. Pharmacol. 157(1): 1-8.

Vinay, T.N., C.S. Park, H.Y. Kim and S.J. Jung. 2013. Toxicity and dose determination of quillaja saponin, aluminum hydroxide and squalene in olive flounder (*Paralichthys olivaceus*). Vet. Immunol. Immunopathol. (0).

Vincent, C.D., A.J. Lawlor and E. Tipping. 2001. Accumulation of Al, Mn, Fe, Cu, Zn, Cd and Pb by the bryophyte *Scapania undulata* in three upland waters of different pH. Environ. Pollut. 114(1): 93-100.

Vuai, S.A.H. and A. Tokuyama. 2011. Trend of trace metals in precipitation around Okinawa Island, Japan. Atmos. Res. 99: 80-84.

Vuori, K.M. 1996. Acid-induced acute toxicity of aluminium to three species of filter feeding caddis larvae (Trichoptera, Arctopsychidae and Hydropsychidae). Fresh. Biol. 35(1): 179-188.

Vuorinen, M., P.J. Vuorinen, J. Hoikka and S. Peuranen. 1993. Lethal and sublethal threshold values of aluminium and acidity to pike (*Esox lucius*), whitefish (*Coregonus lavaretus pallasi*), pike perch (*Stizostedion lucioperca*) and roach (*Rutilus rutilus*) yolk-sac fry. Sci. Total Environ. Suppl.: 953-967.

Vuorinen, M., P.J. Vuorinen, M. Rask and J. Suomela. 1994a. The sensitivity to acidity and aluminium of newly-hatched perch (*Perca fluviatilis*) originating from strains from four lakes with different degrees. In: R. Muller and R. Lloyd (*Eds*.), Sublethal and Chronic Effects of Pollutants on Freshwater Fish, Chapter 24, Fishing News Books, London, 273-282.

Vuorinen, P.J., M. Rask, M. Vuorinen, S. Peuranen and J. Raitaniemi. 1994b. The sensitivity to acidification of pike (*Esox lucius*), whitefish (*Coregonus lavaretus*) and roach (*Rutilus rutilus*): comparison of field and laboratory studies. In: R. Muller and R. Lloyd (*Eds*.), Sublethal and Chronic Effects of Pollutants on Freshwater Fish, Chapter 25, Fishing News Books, London, 283-293.

Vuorinen, P.J., M. Keinanen, S. Peuranen and C. Tigerstedt. 2003. Reproduction, blood and plasma parameters and gill histology of vendace (*Coregonus albula* L.) in long-term exposure to acidity and aluminum. Ecotoxicol. Environ. Saf. 54(3): 255-276.

Wakabayashi, M., R. Konno and T. Nishiido. 1988. Relative lethal sensitivity of two *Daphnia* species to chemicals. Tokyo-to Kankyo Kagaku Kenkyusho Nenpo: 126-128.

Walker, R.L., C.M. Wood and H.L. Bergman. 1988. Effects of low pH and aluminum on ventilation in the brook trout (*Salvelinus fontinalis*). Can. J. Fish. Aquat. Sci. 45: 1614-1622.

Walker, R.L., C.M. Wood and H.L. Bergman. 1991. Effects of long-term preexposure to sublethal concentrations of acid and aluminum on the ventilatory response to aluminum challenge in brook trout (*Salvelinus fontinalis*). Can. J. Fish. Aquat. Sci. 48(10): 1989-1995.

Wallen, I.E., W.C. Greer and R. Lasater. 1957. Toxicity to *Gambusia affinis* of certain pure chemical in turbid waters. Sew. Indust. Wastes 29(6): 695-711.

Walton, R.C., C.R. McCrohan, F.R. Livens and K.N. White. 2009. Tissue accumulation of aluminium is not a predictor of toxicity in the freshwater snail, *Lymnaea stagnalis*. Environ. Pollut. 157(7): 2142-2146.

Walton, R.C., C.R. McCrohan, F. Livens and K.N. White. 2010a. Trophic transfer of aluminium through an aquatic grazer-omnivore food chain. Aquat. Toxicol. 99: 93-99.

Walton, R.C., K.N. White, F. Livens and C.R. McCrohan. 2010b. The suitability of gallium as a substitute for aluminum in tracing experiments. BioMetals 23: 221-230.

Wang, D., P.J. Collins and X. Gao. 2006. Optimising indoor phosphine fumigation of paddy rice bag-stacks under sheeting for control of resistant insects. J. Stored Prod. Res. 42: 207-217.

Wang, D., J. Hu, B.E. Forthaus and J. Wang. 2011. Synergistic toxic effect of nano-Al_2O_3 and As(V) on *Ceriodaphnia dubia*. Environ. Pollut. 159: 3003-3008.

Wang, H., R.L. Wick and B. Xing. 2009. Toxicity of nanoparticulate and bulk ZnO, Al_2O_3 and TiO_2 to the nematode *Caenorhabditis elegans*. Environ. Pollut. 157: 1171-1177.

Wang, N., C. Ivey, E. Brunson, D. Cleveland, W. Brumbaugh and C. Ingersoll. 2016. Columbia Environmental Research Center (CERC) preliminary data summary for acute and chronic aluminum toxicity tests with freshwater mussels and amphipods. Memorandum to Diana Eignor. Dated January 14th. U.S. Geological Survey, CERC, Columbia, MO.

Wang, N., C.D. Ivey, E.L. Brunson, D. Cleveland, C.G. Ingersoll, W.A. Stubblefield and A.S. Cardwell. 2018. Acute and chronic toxicity of aluminum to a unionid mussel (*Lampsilis siliquoidea*) and an amphipod (*Hyalella azteca*) in water-only exposures. Environ. Toxicol. Chem. 37(1): 61-69.

Ward, R.J.S., C.R. McCrohan and K.N. White. 2006. Influence of aqueous aluminium on the immune system of the freshwater crayfish *Pacifasticus leniusculus*. Aquat. Toxicol. 77(2): 222-228.

Waring, C.P. and J.A. Brown. 1995. Ionoregulatory and respiratory responses of brown trout, *Salmo trutta*, exposed to lethal and sublethal aluminium in acidic soft waters. Fish Physiol. Biochem. 14(1): 81-91.

Waring, C.P., J.A. Brown, J.E. Collins and P. Prunet. 1996. Plasma prolactin, cortisol, and thyroid responses of the brown trout (*Salmo trutta*) exposed to lethal and sublethal aluminium in acidic soft waters. Gen. Comp. Endocrinol. 102(3): 377-385.

Waterman, A.J. 1937. Effect of salts of heavy metals on development of the sea urchin, *Arbacia punctulata*. Biol. Bull. 73(3): 401-420.

Wauer, G. and H.C. Teien. 2010. Risk of acute toxicity for fish during aluminium application to hardwater lakes. Sci. Total Environ. 408(19): 4020-4025.

Weatherley, N.S., S.J. Ormerod, S.P. Thomas and R.W. Edwards. 1988. The response of macroinvertebrates to experimental episodes of low pH with different forms of aluminium, during a natural state. Hydrobiol. 169: 225-232.

Weatherley, N.S., A.P. Rogers, X. Goenaga and S.J. Ormerod. 1990. The survival of early life stages of brown trout (*Salmo trutta* L.) in relation to aluminium speciation in upland Welsh streams. Aquat. Toxicol. 17(3): 213-230.

Weatherley, N.S., G.P. Rutt, S.P. Thomas and S.J. Ormerod. 1991. Liming acid streams: Aluminium toxicity to fish in mixing zone. Water Air Soil Pollut. 55(3-4): 345-353.

Westholm, L.J. 2006. Substrates for phosphorus removal - Potential benefits for on-site wastewater treatment? Wat. Res. 40: 23-36.

White, K.N., A.I. Ejim, R.C. Walton, A.P. Brown, R. Jugdaohsingh, J.J. Powell and C.R. McCrohan. 2008. Avoidance of aluminum toxicity in freshwater snails involves intracellular silicon-aluminum biointeraction. Environ. Sci. Technol. 42(6): 2189-2194.

Whitehead, C. and J.A. Brown. 1989. Endocrine responses of brown trout, *Salmo trutta* L., to acid, aluminum, and lime dosing in a Welsh Hill stream. J. Fish. Biol. 35: 59-71.

Wilkinson, K.J. and P.G.C. Campbell. 1993. Aluminum bioconcentration at the gill surface of juvenile Atlantic salmon in acidic media. Environ. Toxicol. Chem. 12: 2083-2095.

Wilkinson, K.J., P.G.C. Campbell and P. Couture. 1990. Effect of fluoride complexation on aluminum toxicity towards juvenile Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 47: 1446-1452.

Wilkinson, K.J., P.M. Bertsch, C.H. Jagoe and P.G.C. Campbell. 1993. Surface complexation of aluminum on isolated fish gill cells. Environ. Sci. Technol. 27: 1132-1138.

Williams, P. L. and D.B. Dusenbery. 1990. Aquatic toxicity testing using the nematode, *Caenorhabditis elegans*. Environ. Toxicol. Chem. 9(10): 1285-1290.

Williams, R.J.P. 1999. What is wrong with aluminium? The J.D. Birchall memorial lecture. J. Inorg. Biochem. 76: 81-88.

Williams, C.A., J.L. Moore, R.J. Richards and C.A. Williams. 2011. Assessment of surface-water quantity and quality, Eagle River Watershed, Colorado, 1947-2007. Scientific Investigations Report. U.S. Geological Survey.

Williams, J.D. and R.J. Neves. 1995. Freshwater mussels: A neglected and declining aquatic resource. In: E.T. LaRoe, G.S. Farris, C.E. Puckett, P.D. Doran and M.J. Mac (*Eds.*). Our Living Resources. National Biological Service, Washington, DC. pp. 177-199.

Williams, J.D., M.L. Warren, K.S. Cummins, J.L. Harris and R.J. Neves. 1993. Conservation status of freshwater mussels of the United States and Canada. Fisheries 18: 6-22.

Wilson, R.W. 1996. Physiological and metabolic costs of acclimation to chronic sub-lethal acid and aluminium exposure in rainbow trout. In: E.W. Taylor (*Ed.*), Symp. Ester Meet. Soc. Exp. Biol. Semin., Ser. No. 57, Toxicology of Aquatic Pollution: Physiological, Molecular, and Cellular Approaches, Canterbury, England, Cambridge Univ. Press, Cambridge, England, 143-167.

Wilson, R.W. 2012. Chapter 2: Aluminum. In: C.M Wood, A.P. Farrel and C.J. Brauner (*Eds*.), Homeostasis and toxicology of non-essential metals: Volume 31B. Elsevier Inc.

Wilson, R.W. and C.M. Wood. 1992. Swimming performance, whole body ions, and gill Al accumulation during acclimation to sublethal aluminium in juvenile rainbow trout (*Oncorhynchus mykiss*). Fish Physiol. Biochem. 10(2): 149-159.

Wilson, R.W., H.L. Bergman and C.M. Wood. 1994a. Metabolic costs and physiological consequences of acclimation to aluminum in juvenile rainbow trout (*Oncorhynchus mykiss*). 1: Acclimation specificity, resting physiology, feeding, and growth. Can. J. Fish. Aquat. Sci. 51: 527-535.

Wilson, R.W., H.L. Bergman and C.M. Wood. 1994b. Metabolic costs and physiological consequences of acclimation to aluminum in juvenile rainbow trout (*Oncorhynchus mykiss*). 2: Gill morphology. Can. J. Fish. Aquat. Sci. 51(3): 536-544.

Wilson, R.W., C.M. Wood and D.F. Houlihan. 1996. Growth and protein turnover during acclimation to acid and aluminum in juvenile rainbow trout (*Oncorhynchus mykiss*). Can. J. Fish. Aquat. Sci. 53(4): 802-811.

Wilson, S.P. and R.V. Hyne. 1997. Toxicity of acid-sulfate soil leachate and aluminum to embryos of the Sydney rock oyster. Ecotoxicol. Environ. Saf. 37: 30-36.

Winter, A.R., J.W. Nichols and R.C. Playle. 2005. Influence of acidic to basic water pH and natural organic matter on aluminum accumulation by gills of rainbow trout (*Oncorhynchus mykiss*). Can. J. Fish. Aquat. Sci. 62(10): 2303-2311.

Witters, H.E. 1986. Acute acid exposure of rainbow trout, *Salmo gairdneri* Richardson: effects of aluminium and calcium on ion balance and haematology. Aquat. Toxicol. 8(3): 197-210.

Witters, H., J.H.D. Vangenechten, S. Van Puymbroeck and O.L.J. Vanderborght. 1984. Interference of aluminum and pH on the Na-influx in an aquatic insect *Corixa punctata* (Illig.). Bull. Environ. Contam. Toxicol. 32: 575-579.

Witters, H.E., J.H.D. Vangenechten, S. Van Puymbroeck and O.L.J. Vanderborght. 1987a. Ionoregulatory and haematological responses of rainbow trout *Salmo gairdneri* Richardson to chronic acid and aluminium stress. Ann. Soc. R. Zool. Belg. 117: 411-420.

Witters, H.E., J.H.D. Vanganechten, S. Van Puymbroeck and O.L.J. Vanderborght. 1987b. Physiological study on the recovery of rainbow trout (*Salmo gairdneri* Richardson) from acid and Al stress. In: H. Barth (*Ed.*), Reversibility of acidification. Elsevier, London: 67-75.

Witters, H.E., S. Van Puymbroeck, I. Van den Sande and O.L.J. Vanderborght. 1990a. Haematological disturbances and osmotic shifts in rainbow trout, *Oncorhynchus mykiss* (Walbaum) under acid and aluminium exposure. J. Comp. Physiol. B Biochem. Syst. Environ. Physiol. 160: 563-571.

Witters, H.E., S. Van Puymbroeck., J.H.D. Vangenechten and O.L.J. Vanderborght. 1990b. The effect of humic substances on the toxicity of aluminium to adult rainbow trout, *Oncorhynchus mykiss* (Walbaum). J. Fish Biol. 37(1): 43-53.

Witters, H.E., S. Van Puymbroeck and O.L.J. Vanderborght. 1991. Adrenergic response to physiological disturbances in rainbow trout, *Oncorhynchus mykiss*, exposed to aluminum at acid pH. Can. J. Fish. Aquat. Sci. 48(3): 414-420.

Witters, H.E., S. Van Puymbroeck, A.J.H. Stouthart and S.E. Wendelaar Bonga. 1996. Physicochemical changes of aluminium in mixing zones: mortality and physiological disturbances in brown trout (*Salmo trutta* L.). Environ. Toxicol. Chem. 15(6): 986-996.

Wold, L.A. 2001. Some effects of aluminum sulfate and arsenic sulfide on *Daphnia pulex* and *Chironomus tentans*. Ph.D. Thesis, Washington State Univ., Pullman, WA, 134 p.

Wold, L.A., B.C. Moore and N. Dasgupta. 2005. Life-history responses of *Daphnia pulex* with exposure to aluminum sulfate. Lake Reserv. Manag. 21(4): 383-390.

Wood, J.M. 1984. Microbial strategies in resistance to metal ion toxicity. In: H Sigel (*Ed.*), Metal Ions in Biological Systems, Vol. 18. Circulation of Metals in the Environment. Marcel Dekker, NY, 333-351.

Wood, J.M. 1985. Effects of acidification on the mobility of metals and metalloids: An overview. Environ. Health Perspect. 63: 115-119.

Wood, C.M. and D.G. McDonald. 1987. The physiology of acid/aluminium stress in trout. Ann. Soc. R. Zool. Belg. 117(Suppl.): 399-410.

Wood, C.M., R.C. Playle, B.P. Simons, G.G. Goss and D.G. McDonald. 1988a. Blood gases, acid-base status, ions, and hematology in adult brook trout (*Salvelinus fontinalis*) under acid/aluminum exposure. Can. J. Fish. Aquat. Sci. 45: 1575-1586.

Wood, C.M., D.G. McDonald, C.E. Booth, B.P. Simons, C.G. Ingersoll and H.L. Bergman. 1988b. Physiological evidence of acclimation to acid/aluminum stress in adult brook trout (*Salvelinus fontinalis*). 1. Blood composition and net sodium fluxes. Can. J. Fish. Aquat. Sci. 45(9): 1587-1596.

Wood, C.M., B.P. Simons, D.R. Mount and H.L. Bergman. 1988c. Physiological evidence of acclimation to acid/aluminum stress in adult brook trout (*Salvelinus fontinalis*). 2. Blood parameters by cannulation. Can. J. Fish. Aquat. Sci. 45(9): 1597-1605.

Wood, C.M., D.G. McDonald, C.G. Ingersoll, D.R. Mount, O.E. Johannsson, S. Landsberger and H.L. Bergman. 1990a. Whole body ions of brook trout (*Salvelinus fontinalis*) alevins: responses of yolk-sac and swim-up stages to water acidity, calcium and aluminum and recovery effects. Can. J. Fish. Aquat. Sci. 47(8): 1604-1615.

Wood, C.M., D.G. McDonald, C.G. Ingersoll, D.R. Mount, O.E. Johannsson, S. Landsberger and H.L. Bergman. 1990b. Effects of water acidity, calcium and aluminum on whole body ions of brook trout (*Salvelinus fontinalis*) continuously exposed from fertilization to swim-up: a study by instrumental neutron activation analysis. Can. J. Fish. Aquat. Sci. 47: 1593-1603.

Woodburn, K., R. Walton, C. McCrohan and K. White. 2011. Accumulation and toxicity of aluminium-contaminated food in the freshwater crayfish, *Pacifastacus leniusculus*. Aquat. Toxicol. 105: 535-542.

Woodward, D.F., A.M. Farag, M.E. Mueller, E.E. Little and F.A. Vertucci. 1989. Sensitivity of endemic Snake River cutthroat trout to acidity and elevated aluminum. Trans. Am. Fish. Soc. 118(3): 630-643.

Wooldridge, C.R. and D.P. Wooldridge. 1969. Internal damage in an aquatic beetle exposed to sublethal concentrations of inorganic ions. Ann. Entomol. Soc. Am. 62(4): 921-933.

Wren, C. D. and G.L. Stephenson. 1991. The effect of acidification on the accumulation and toxicity of metals to freshwater invertebrates. Environ. Pollut. 71: 205-241.

Wren, C.D., H.R. MacCrimmon and B.R. Loescher. 1983. Examination of bioaccumulation and biomagnification of metals in a Precambrian Shield Lake. Water Air Soil Pollut. 19: 277-291.

Wu, P., C.Y. Liao, B. Hu, K.K. Yi, W.Z. Jin, J.J. Ni and C. He. 2000. QTLs and epistasis for aluminum tolerance in rice (*Oryza sativa* L.) at different seedling stages. Theor. Appl. Genet. 100: 1295-1303.

Wu, S., J. Lu, Q. Rui, S. Yu, T. Cai and D. Wang. 2011. Aluminum nanoparticle exposure in L1 larvae results in more severe lethality toxicity than in L4 larvae or young adults by strengthening the formation of stress response and intestinal lipofuscin accumulation in nematodes. Environ. Toxicol. Pharmacol. 31(1): 179-188.

Yang, Q., Y. Wang, J. Zhang, W. Shi, C. Qian and X. Peng. 2007. Identification of aluminum-responsive proteins in rice roots by a proteomic approach: Cysteine synthase as a key player in Al response. Proteomics 7: 737-749.

Yang, R., and C.M.G. van den Berg. 2009. Metal complexation by humic substances in seawater. Environ. Sci. Technol. 43(19): 7192-7197.

Yokel, R.A. and M.S. Golub (*Eds*.). 1997. Research Issues in Aluminum Toxicity. Taylor and Francis, Washington, DC.

Yoshimura, E., S. Nagasaka, Y. Sato, K. Satake and S. Mori. 1999. Extraordinary high aluminum tolerance of the acidophilic thermophilic alga, *Cyanidium caldarium*. Soil Sci. Plant Nutr. 45(3): 721-724.

Youson, J.H. and C.M. Neville. 1987. Deposition of aluminum in the gill epithelium of rainbow trout (*Salmo gairdneri* Richardson) subjected to sublethal concentrations of the metal. Can. J. Zool. 65(3): 647-656.

Ytrestoyl, T., B. Finstad and R.S. McKinley. 2001. Swimming performance and blood chemistry in Atlantic salmon spawners exposed to acid river water with elevated aluminium concentrations. J. Fish Biol. 58: 1025-1038.

Zaifnejad, M., R.B. Clark and C.Y. Sullivan. 1997. Aluminum and water stress effects on growth and proline of sorghum. J. Plant Physiol. 150(3): 338-344.

Zaini, Z. and B.T. Mercado. 1984. Calcium-aluminum interaction on the growth of two rice cultivars in culture solution. Philipp. Agric. 67: 93-99.

Zarini, S., D. Annoni and O. Ravera. 1983. Effects produced by aluminium in freshwater communities studied by "enclosure" method. Environ. Technol. Lett. 4: 247-256.

Zhou, Y. and R.A. Yokel. 2005. The chemical species of aluminum influences its paracellular flux across and uptake into Caco-2 cells, a model of gastrointestinal absorption. Toxicol. Sci. 87(1): 15-26.

Zhou, Y., W.R. Harris and R.A. Yokel. 2008. The influence of citrate, maltolate and fluoride on the gastrointestinal absorption of aluminum at a drinking water-relevant concentration: a ^{26}Al and ^{14}C study. J. Inorg. Biochem. 102(4): 798-808.

Zhu, X., L. Zhu, Z. Duan, R. Qi, Y. Li and Y. Lang. 2008. Comparative toxicity of several metal oxide nanoparticle aqueous suspensions to zebrafish (*Danio rerio*) early developmental stage. J. Environ. Sci. Health Part A 43(3): 278-284.

Zhu, X., L. Zhu, Y. Chen and S. Tian. 2009. Acute toxicities of six manufactured nanomaterial suspensions to *Daphnia magna*. J. Nanopart. Res. 11: 67-75.

Zuiderveen, J.A. and W.J. Birge. 1997. The relationship between chronic values in toxicity tests with *Ceriodaphnia dubia*. Environ. Toxicol. Risk Assess. 551-556.

Appendix A ACCEPTABLE ACUTE TOXICITY DATA OF ALUMINUM TO FRESHWATER AQUATIC ANIMALS

Appendix A. Acceptable Acute Toxicity Data of Aluminum to Freshwater Aquatic Animals

(Bold values are used in SMAV calculation).
(Species are organized phylogenetically).

Species	Method[a]	Chemical	Total Hardness (mg/L as CaCO$_3$)	pH	DOC (mg/L)	LC$_{50}$ / EC$_{50}$ (µg/L)	Normalized Acute Value[b] (µg/L)	Species Mean Acute Value (µg/L)	Reference
Worm (adult, 1.0 cm), *Nais elinguis*	R, M, T	Aluminum sulfate	17.89 (±1.74)	6.51 (±0.01)	3.2	3,874	**9,224**	9,224	Shuhaimi-Othman et al. 2012a, 2013
Snail (adult), *Physa sp.*	S, M, T	Aluminum chloride	47.4 (±4.51)	6.59	1.1[d]	>23,400	**>52,593**	-	Call 1984; Call et al. 1984
Snail (adult), *Physa sp.*	S, M, T	Aluminum chloride	47.4 (±4.51)	7.55	1.1[d]	30,600	**27,057**	-	Call 1984; Call et al. 1984
Snail (adult), *Physa sp.*	S, M, T	Aluminum chloride	47.4 (±4.51)	8.17	1.1[d]	>24,700	>19,341[c]	-	Call 1984; Call et al. 1984
Snail (adult), *Physa sp.*	S, M, T	Aluminum chloride	47.4 (±4.51)	7.46	1.1[d] (aged solution)	55,500	**51,539**	41,858	Call 1984; Call et al. 1984
Snail (adult, 1.5-2.0 cm, 22.5 mg), *Melanoides tuberculata*	R, M, T	Aluminum sulfate	18.72 (±1.72)	6.68 (±0.22)	3.2	68,230	**119,427**	119,427	Shuhaimi-Othman et al. 2012b, 2013
Fatmucket (juvenile, 6 d), *Lampsilis siliquoidea*	R, M, T	Aluminum chloride	107 (±6.3)	8.19 (±0.22)	0.5	>54,300	>57,735[f]	-	Ivey et al. 2014
Fatmucket (juvenile, 7-8 d, 0.38 mm), *Lampsilis siliquoidea*	F, M, T	Aluminum nitrate	106 (104-108)	6.12 (6.10-6.13)	0.48	>6,302	**>29,492**	>29,492	Wang et al. 2016, 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, A	Aluminum chloride	50.0	7.42 (±0.02)	1.1[d]	1,900	**1,771**	-	McCauley et al. 1986
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, A	Aluminum chloride	50.5	7.86 (±0.04)	1.1[d]	1,500	**1,170**	-	McCauley et al. 1986
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, A	Aluminum chloride	50.0	8.13 (±0.03)	1.1[d]	2,560	**1,974**	-	McCauley et al. 1986

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	LC_{50} / EC_{50} (µg/L)	Normalized Acute Value[b] (µg/L)	Species Mean Acute Value (µg/L)	Reference
Cladoceran (<24 hr), *Ceriodaphnia dubia*	R, M, T	Aluminum chloride	25 (24-26)	7.5 (7.0-8.0)	0.5[d]	720	**1,321**	-	ENSR 1992d
Cladoceran (<24 hr), *Ceriodaphnia dubia*	R, M, T	Aluminum chloride	49 (46-52)	7.65 (7.3-8.0)	0.5[d]	1,880	**2,516**	-	ENSR 1992d
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum chloride	95 (94-96)	7.9 (7.7-8.1)	0.5[d]	2,450	**2,559**	-	ENSR 1992d
Cladoceran (<24 hr), *Ceriodaphnia dubia*	R, M, T	Aluminum chloride	193 (192-194)	8.05 (7.8-8.3)	0.5[d]	>99,600	**>88,933**	-	ENSR 1992d
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, NR	Aluminum sulfate	90 (80-100)	7.15 (7.0-7.3)	0.5[d]	3,727	**5,243**	-	Fort and Stover 1995
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, NR	Aluminum sulfate	90 (80-100)	7.15 (7.0-7.3)	0.5[d]	5,673	**7,981**	-	Fort and Stover 1995
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, NR	Aluminum sulfate	89	8.2	0.5[d]	2,880	**3,189**	-	Soucek et al. 2001
Cladoceran (<24 hr), *Ceriodaphnia dubia*	R, U, T	Aluminum chloride	142 (±2)	8.2 (±1)	1.6[d]	153,440	**77,169**		Griffitt et al. 2008
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	6.01 (5.99-6.03)	0.5[d]	71.12	**2,009**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	6.05 (6.02-6.07)	2	686.5	**7,721**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	6.09 (6.03-6.15)	4	1,558.1	**10,568**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	6.01 (5.95-6.06)	0.5[d] (solution aged 3 hrs)	68.1	**1,924**	-	European Al Association 2009; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	6.03 (5.95-6.10)	0.5[d] (solution aged 27 hrs)	163.0	**4,394**	-	European Al Association 2009; Gensemer et al. 2018

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	LC_{50} / EC_{50} (µg/L)	Normalized Acute Value[b] (µg/L)	Species Mean Acute Value (µg/L)	Reference
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	5.97 (5.92-6.01)	0.5[d] (solution aged 51 hrs)	178.5	**5,546**	-	European Al Association 2009; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	5.92 (5.87-5.96)	0.5[d] (solution aged 99 hrs)	141.0	**4,945**	-	European Al Association 2009; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	6.99 (6.96-7.01)	0.5[d]	>1,300	**>5,842**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	7.85 (7.77-7.93)	0.5[d]	>5,000	**>9,735**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	6.80 (6.55-7.04)	2	>10,000	**>26,061**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	7.82 (7.49-8.14)	2	>15,000	**>12,984**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	6.77 (6.51-7.03)	4	>10,000	**>18,075**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	7.66 (7.39-7.93)	4	>15,000	**>9,538**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	7.91 (7.82-7.99)	0.5[d] (solution aged 3 hrs)	>2,000	**>3,793**	-	European Al Association 2009; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	10.6	7.89 (7.83-7.95)	0.5[d] (solution aged 27 hrs)	>2,000	**>3,812**	-	European Al Association 2009; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	60	6.04 (6.02-6.05)	0.5[d]	110.8	**867.5**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	60	5.98 (5.90-6.05)	2	1,137.1	**4,376**	-	European Al Association 2009

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	LC_{50} / EC_{50} (µg/L)	Normalized Acute Value[b] (µg/L)	Species Mean Acute Value (µg/L)	Reference
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	60	5.73 (5.39-6.06)	4	8,046.7	**34,704**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	60	6.71 (6.44-6.98)	0.5[d]	>10,000	**>26,800**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	60	7.83 (7.74-7.92)	0.5[d]	>5,000	**>5,975**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	60	6.79 (6.55-7.03)	2	>10,000	**>10,615**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	60	7.67 (7.41-7.92)	2	>15,000	**>8,154**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	60	6.68 (6.35-7.01)	4	>15,000	**>12,073**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	60	7.62 (7.35-7.89)	4	>15,000	**>5,487**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	120	6.06 (5.97-6.14)	2	3,386.8	**6,889**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	120	5.60 (5.22-5.97)	4	10,484.2	**34,985**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	120	6.93 (6.84-7.02)	0.5[d]	>5,000	**>7,361**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	120	7.88 (7.80-7.95)	0.5[d]	>5,000	**>4,896**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	120	6.76 (6.43-7.09)	2	>15,000	**>11,400**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	120	7.71 (7.46-7.95)	2	>15,000	**>6,471**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	120	6.60 (6.21-6.98)	4	>15,000	**>9,047**	-	European Al Association 2009
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, U, T	Aluminum nitrate	120	7.60 (7.32-7.87)	4	>15,000	**>4,366**	-	European Al Association 2009

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	LC_{50} / EC_{50} (µg/L)	Normalized Acute Value[b] (µg/L)	Species Mean Acute Value (µg/L)	Reference
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum nitrate	10.6	6.03 (6.02-6.03)	0.5[d] (stock solution not buffered)	119.71	**3,227**	-	European Al Association 2010
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum nitrate	10.6	6.03 (6.02-6.03)	0.5[d] (stock solution buffered)	274.78	**7,407**	-	European Al Association 2010
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum nitrate	10.6	6.03 (6.02-6.03)	0.5[d] (test solution MES buffered)	119.98	**3,234**	-	European Al Association 2010
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum nitrate	10.6	6.07 (6.06-6.07)	0.5[d] (0.0 µM PO_4 in test solution)	92.495	**2,273**	-	European Al Association 2010
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum nitrate	10.6	6.09 (6.08-6.09)	0.5[d] (12.0 µM PO_4 in test solution)	313.37	7,355[g]	-	European Al Association 2010
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum nitrate	10.6	6.10 (6.09-6.11)	0.5[d] (60.0 µM PO_4 in test solution)	332.35	7,625[g]	-	European Al Association 2010
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum nitrate	10.6	7.08 (7.06-7.09)	0.5[d] (test solution HCl buffered)	>886.4	**>3,528**	-	European Al Association 2010
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum nitrate	10.6	7.79 (7.70-7.88)	0.5[d] (test solution HEPES buffered)	>4,278.3	**>8,625**	-	European Al Association 2010

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	LC_{50} / EC_{50} (µg/L)	Normalized Acute Value[b] (µg/L)	Species Mean Acute Value (µg/L)	Reference
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum nitrate	10.6	7.53 (7.45-7.61)	0.5[d] (test solution NaOH adjusted)	132.04	**322.4**	-	European Al Association 2010
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum nitrate	60.0	6.01 (5.99-6.03)	0.5[d] (stock solution not buffered)	463.26	**3,845**	-	European Al Association 2010
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S, M, T	Aluminum nitrate	60.0	5.99 (5.98-5.99)	0.5[d] (stock solution buffered)	>859.0	**>7,415**	5,863	European Al Association 2010
Cladoceran (0-24 hr), *Ceriodaphnia reticulata*	S, U, T	Aluminum chloride	45.1	7.25 (6.8-7.7)	1.1[d]	2,800	3,070[f]	-	Shephard 1983
Cladoceran (0-24 hr), *Ceriodaphnia reticulata*	F, M, T	Aluminum chloride	45.1	6.0	1.1[d]	304	**1,967**	-	Shephard 1983
Cladoceran (0-24 hr), *Ceriodaphnia reticulata*	F, M, T	Aluminum chloride	4.0	5.5	1.1[d]	362	**53,910**	10,299	Shephard 1983
Cladoceran (0-24 hr), *Daphnia magna*	S, U, NR	Aluminum chloride	48.5 (44-53)	7.8 (7.4-8.2)	1.1[d]	3,900	**3,117**	-	Biesinger and Christensen 1972
Cladoceran (0-24 hr), *Daphnia magna*	S, M, T	Aluminum sulfate	220	7.60 (7.05-8.15)	1.6[d]	38,200	**15,625**	-	Kimball 1978
Cladoceran (0-24 hr), *Daphnia magna*	S, U, T	Aluminum chloride	45.1	7.25 (6.8-7.7)	1.1[d]	2,800	**3,070**	-	Shephard 1983
Cladoceran (<24 hr), *Daphnia magna*	S, U, T	Aluminum nitrate	168	5.99 (5.98-5.99)	0.5[d]	>500	**>2,075**	-	European Al Association 2009
Cladoceran (<24 hr), *Daphnia magna*	S, U, T	Aluminum nitrate	168	6.98 (6.97-6.98)	0.5[d]	>500	>598.9[c]	-	European Al Association 2009
Cladoceran (<24 hr), *Daphnia magna*	S, U, T	Aluminum nitrate	168	7.93 (7.92-7.94)	0.5[d]	>500	>449.2[c]	-	European Al Association 2009

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	LC_{50} / EC_{50} (µg/L)	Normalized Acute Value[b] (µg/L)	Species Mean Acute Value (µg/L)	Reference
Cladoceran (<24 hr), *Daphnia magna*	S, U, T	Aluminum nitrate	168	7.92 (7.90-7.93)	0.5[d]	795.0	**713.2**	-	European Al Association 2009
Cladoceran (<24 hr), *Daphnia magna*	S, U, T	Aluminum nitrate	168	7.95 (7.92-7.97)	2	>1,200	>472.9[c]	-	European Al Association 2009
Cladoceran (<24 hr), *Daphnia magna*	S, U, T	Aluminum nitrate	168	7.93 (7.92-7.94)	3	>1,200	>369.9[c]	2,944	European Al Association 2009
Cladoceran (adult), *Daphnia pulex*	R, U, T	Aluminum chloride	142 (±2)	8.2 (±1)	1.6[d]	3,650	**1,836**	1,836	Griffitt et al. 2008
Ostracod (adult, 1.5 mm, 0.3 mg), *Stenocypris major*	R, M, T	Aluminum sulfate	15.63 (±2.74)	6.51 (±0.01)	3.2	3,102	**8,000**	8,000	Shuhaimi-Othman et al. 2011a, 2013
Amphipod (4 mm), *Crangonyx pseudogracilis*	R, U, T	Aluminum sulfate	50 (45-55)	6.75 (6.7-6.8)	1.6[d]	9,190	**12,901**	12,901	Martin and Holdich 1986
Amphipod (juvenile, 7 d, 1.32 mm), *Hyalella azteca*	F, M, T	Aluminum nitrate	105 (103-108)	6.13 (6.09-6.16)	0.48	>5,997	**>27,766**	>27,766	Wang et al. 2016, 2018
Midge (3rd-4th instar larvae), *Chironomus plumosus*	S, U, T	Aluminum chloride	80	7.0 (±0.5)	1.6[d]	30,000	**25,216**	25,216	Fargasova 2001, 2003
Midge (2nd-3rd instar larvae), *Paratanytarsus dissimilis*	S, U, T	Aluminum sulfate	17.43	7.28 (6.85-7.71)	2.8[d]	>77,700	**>70,647**	>70,647	Lamb and Bailey 1981, 1983
Rainbow trout (alevin), *Oncorhynchus mykiss*	S, U, T	Aluminum sulfate	14.3	5.5	0.4	160	10,037[f]	-	Holtze 1983

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	LC_{50} / EC_{50} (µg/L)	Normalized Acute Value[b] (µg/L)	Species Mean Acute Value (µg/L)	Reference
Rainbow trout (alevin), *Oncorhynchus mykiss*	S, U, T	Aluminum sulfate	14.3	5.5	0.4	310	8,467[f]	-	Holtze 1983
Rainbow trout (fingerling), *Oncorhynchus mykiss*	S, M, T	Aluminum chloride	47.4 (±4.51)	6.59 (±0.15)	1.1[d]	7,400	13,495[f]	-	Call et al. 1984
Rainbow trout (fingerling), *Oncorhynchus mykiss*	S, M, T	Aluminum chloride	47.4 (±4.51)	7.31 (±0.89)	1.1[d]	14,600	11,879[f]	-	Call et al. 1984
Rainbow trout (fingerling), *Oncorhynchus mykiss*	S, M, T	Aluminum chloride	47.4 (±4.51)	8.17 (±0.42)	1.1[d]	>24,700	>7,664[f]	-	Call et al. 1984
Rainbow trout (fingerling), *Oncorhynchus mykiss*	S, M, T	Aluminum chloride	47.4 (±4.51)	7.46 (±0.14)	1.1[d] (18 d aged solution)	8,600	5,915[f]	-	Call et al. 1984
Rainbow trout (juvenile, 1-3 g), *Oncorhynchus mykiss*	F, M, T	Aluminum chloride	26.35 (25.3-27.4)	7.61 (7.58-7.64)	0.5[d]	>9,840	**>7,216**	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), *Oncorhynchus mykiss*	F, M, T	Aluminum chloride	45.5 (44.6-46.4)	7.59 (7.55-7.62)	0.5[d]	>8,070	**>5,766**	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), *Oncorhynchus mykiss*	F, M, T	Aluminum chloride	88.05 (86.6-89.5)	7.60 (7.58-7.62)	0.5[d]	>8,160	**>5,390**	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), *Oncorhynchus mykiss*	F, M, T	Aluminum chloride	127.6 (124.8-130.4)	7.61 (7.58-7.64)	0.5[d]	>8,200	**>5,164**	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), *Oncorhynchus mykiss*	F, M, T	Aluminum chloride	23.25 (21.9-24.6)	8.28 (7.97-8.58)	0.5[d]	6,170	**1,685**	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), *Oncorhynchus mykiss*	F, M, T	Aluminum chloride	35.4 (33.1-37.7)	8.30 (8.02-8.58)	0.5[d]	6,170	**1,680**	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), *Oncorhynchus mykiss*	F, M, T	Aluminum chloride	83.6 (83.0-84.2)	8.31 (8.06-8.56)	0.5[d]	7,670	**2,180**	-	Gundersen et al. 1994

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	LC_{50} / EC_{50} (µg/L)	Normalized Acute Value[b] (µg/L)	Species Mean Acute Value (µg/L)	Reference
Rainbow trout (juvenile, 1-3 g), *Oncorhynchus mykiss*	F, M, T	Aluminum chloride	128.5 (112.5-144.5)	8.31 (8.06-8.56)	0.5[d]	6,930	**2,026**	3,312	Gundersen et al. 1994
Atlantic salmon (sac fry, ≈0.2 g), *Salmo salar*	S, U, T	Aluminum chloride	6.8 (6.6-7.0)	5.5	0.5[d]	584	**20,749**	-	Hamilton and Haines 1995
Atlantic salmon (sac fry, ≈0.2 g), *Salmo salar*	S, U, T	Aluminum chloride	6.8 (6.6-7.0)	6.5	0.5[d]	599	**3,599**	8,642	Hamilton and Haines 1995
Brook trout (14 mo., 210 mm, 130 g), *Salvelinus fontinalis*	F, M, T	Aluminum sulfate	-	6.5	-	3,600	NA[e]	-	Decker and Menendez 1974
Brook trout (14 mo., 210 mm, 130 g), *Salvelinus fontinalis*	F, M, T	Aluminum sulfate	-	6.0	-	4,400	NA[e]	-	Decker and Menendez 1974
Brook trout (14 mo., 210 mm, 130 g), *Salvelinus fontinalis*	F, M, T	Aluminum sulfate	-	5.5	-	4,000	NA[e]	-	Decker and Menendez 1974
Brook trout (0.6 g, 4.4-7.5 cm), *Salvelinus fontinalis*	S, U, T	Aluminum sulfate	40	5.6	1.6[d]	6,530	**30,038**	-	Tandjung 1982
Brook trout (0.6 g, 4.4-7.5 cm), *Salvelinus fontinalis*	S, U, T	Aluminum sulfate	18	5.6	1.6[d]	3,400	**24,514**	-	Tandjung 1982
Brook trout (0.6 g, 4.4-7.5 cm), *Salvelinus fontinalis*	S, U, T	Aluminum sulfate	2	5.6	1.6[d]	370	**9,187**	18,913	Tandjung 1982

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	LC_{50} / EC_{50} (µg/L)	Normalized Acute Value[b] (µg/L)	Species Mean Acute Value (µg/L)	Reference
Green sunfish (juvenile, 3 mo.), *Lepomis cyanellus*	S, M, T	Aluminum chloride	47.4 (±4.51)	7.55 (±0.13)	1.1[d]	>50,000	**>31,087**	>31,087	Call et al. 1984
Guppy, *Poecilia reticulata*	R, M, T	Aluminum sulfate	18.72 (±1.72)	6.68 (±0.2)	3.2	6,760	**9,061**	9,061	Shuhaimi-Othman et al. 2013
Rio Grande silvery minnow (larva, 3-5 dph), *Hybognathus amarus*	R, M, T	Aluminum chloride	140	8.1 (7.9-8.4)	0.5[d]	>59,100	**>21,779**	>21,779	Buhl 2002
Fathead minnow (adult), *Pimephales promelas*	S, U, NR	Aluminum sulfate	-	7.6	-	>18,900	NA[e]	-	Boyd 1979
Fathead minnow (juvenile, 32-33 d), *Pimephales promelas*	S, M, T	Aluminum chloride	47.4 (±4.51)	7.61	1.1[d]	>48,200	**>28,019**	-	Call et al. 1984
Fathead minnow (juvenile, 32-33 d), *Pimephales promelas*	S, M, T	Aluminum chloride	47.4 (±4.51)	8.05	1.1[d]	>49,800	**>17,678**	-	Call et al. 1984
Fathead minnow (juvenile, 11 mm, 3 mg dw), *Pimephales promelas*	F, U, T	Aluminum chloride	21.6 (±1.31)	6.5 (±0.2)	0.9	>400	>1,181[c]	-	Palmer et al. 1989
Fathead minnow (juvenile, 11 mm, 3 mg dw), *Pimephales promelas*	F, U, T	Aluminum chloride	21.6 (±1.31)	7.5 (±0.2)	0.9	>400	>304.5[c]	-	Palmer et al. 1989
Fathead minnow (larva, 7 mm, 0.31 mg, 12 dph), *Pimephales promelas*	F, U, T	Aluminum chloride	21.6 (±1.31)	7.5 (±0.2)	0.9	>400	>304.5[c]	-	Palmer et al. 1989
Fathead minnow (yolk-sac larva, 1 dph), *Pimephales promelas*	F, U, T	Aluminum chloride	21.6 (±1.31)	6.5 (±0.2)	0.9	>400	>1,181[c]	-	Palmer et al. 1989

Species	Method[a]	Chemical	Total Hardness (mg/L as CaCO$_3$)	pH	DOC (mg/L)	LC$_{50}$ / EC$_{50}$ (µg/L)	Normalized Acute Value[b] (µg/L)	Species Mean Acute Value (µg/L)	Reference
Fathead minnow (yolk-sac larva, 1 dph), *Pimephales promelas*	F, U, T	Aluminum chloride	21.6 (±1.31)	7.5 (±0.2)	0.9	>400	>304.5[c]	-	Palmer et al. 1989
Fathead minnow (larva, 4-6 dph), *Pimephales promelas*	R, M, T	Aluminum chloride	140	8.1 (7.9-8.4)	0.5[d]	>59,100	**>21,779**	>22,095	Buhl 2002
Smallmouth bass (larva, 48 hr post hatch), *Micropterus dolomieui*	S, M, T	Aluminum sulfate	12.15 (12.1-12.2)	5.05 (4.7-5.4)	1.6[d]	130	**2,442**	-	Kane 1984; Kane and Rabeni 1987
Smallmouth bass (larva, 48 hr post hatch), *Micropterus dolomieui*	S, M, T	Aluminum sulfate	12.4 (12.0-12.8)	6.25 (6.0-6.5)	1.6[d]	>978.4	**>3,655**	-	Kane 1984; Kane and Rabeni 1987
Smallmouth bass (larva, 48 hr post hatch), *Micropterus dolomieui*	S, M, T	Aluminum sulfate	12.0	7.5 (7.2-7.8)	1.6[d]	>216.8	>153.4[c]	2,988	Kane 1984; Kane and Rabeni 1987
Green tree frog (tadpole, <1 dph), *Hyla cinerea*	R, M, T	Aluminum chloride	4.55	5.49 (5.48-5.50)	0.5[d]	>405.2	**>18,563**	>18,563	Jung and Jagoe 1995

[a] S=static, F=flow-through, U=unmeasured, M=measured, A=acid exchangeable aluminum, T=total aluminum, D=dissolved aluminum, NR=not reported.

[b] Normalized to pH 7, total hardness of 100 mg/L as CaCO$_3$ and DOC of 1.0 mg/L (see Section 2.7.1). Values in bold are used in SMAV calculations.

[c] Not used to calculate SMAV because either a more definitive value is available or value is considered an outlier.

[d] When definitive DOC values were not reported by the authors: a DOC value of 0.5 mg/L was used when dilution water was reconstituted, 1.1 mg/L when dilution water was Lake Superior, MN water, 2.8 mg/L when dilution water was Liberty Lake, WA water, 1.6 mg/L when dilution water was tap or well water, or half the detection limit when the reported value was less than the detection limit, based on recommendations in the 2007 Freshwater Copper AWQC (U.S. EPA 2007b).

[e] Missing water quality parameters and/or dilution water type needed to estimate water quality parameters, so values cannot be normalized.

[f] Not used to calculate SMAV because flow-through measured test(s) available.

[g] Phosphate in exposure media is providing an ameliorating effect against aluminum.

Appendix B ACCEPTABLE ACUTE TOXICITY DATA OF ALUMINUM TO ESTUARINE/MARINE AQUATIC ANIMALS

Appendix B. Acceptable Acute Toxicity Data of Aluminum to Estuarine/Marine Aquatic Animals

(Bold values are used in SMAV calculation).
(Species are organized phylogenetically).

Species	Method[a]	Chemical	Salinity (g/kg)	pH	LC_{50} / EC_{50} (µg/L)	Species Mean Acute Value (µg/L)	Reference
Polychaete worm, *Capitella capitata*	S, U	Aluminum chloride	-	-	**404.8**	404.8	Petrich and Reish 1979
Polychaete worm, *Ctenodrilus serratus*	S, U	Aluminum chloride	-	-	**97.15**	97.15	Petrich and Reish 1979
Polychaete worm, *Neanthes arenaceodentata*	S, U	Aluminum chloride	-	-	**>404.8**	>404.8	Petrich and Reish 1979
Copepod (adult), *Nitokra spinipes*	S, U	Aluminum chloride	7	8	**10,000**	10,000	Bengtsson 1978
American oyster (fertilized eggs, ≤1 hr), *Crassostrea virginica*	S, U	Aluminum chloride	25	7.0-8.5	**>1,518**	>1,518	Calabrese et al. 1973

[a] S=static, F=flow-through, U=unmeasured, M=measured.

Appendix C ACCEPTABLE CHRONIC TOXICITY DATA OF ALUMINUM TO FRESHWATER AQUATIC ANIMALS

Appendix C. Acceptable Chronic Toxicity Data of Aluminum to Freshwater Aquatic Animals

(Bold values are used in SMCV calculation).
(Species are organized phylogenetically).

Species	Test[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	EC$_{20}$ Endpoint	EC$_{20}$ (µg/L)	Normalized Chronic Value[b] (µg/L)	Species Mean Chronic Value (µg/L)	Reference
Oligochaete (<24 hr), *Aeolosoma sp.*	17 d	Aluminum nitrate	48	5.95 (5.8-6.1)	<0.5[c]	Reproduction (population size)	1,235	**20,514**	20,514	OSU 2012e; Cardwell et al. 2018
Rotifer (newly hatched, <2 hr), *Brachionus calyciflorus*	48 hr	Aluminum nitrate	100	6.45 (6.4-6.5)	<0.5[c]	Reproduction (population size)	431.0	**1,845**	-	OSU 2012c; Cardwell et al. 2018
Rotifer (newly hatched, <2 hr), *Brachionus calyciflorus*	48 hr	Aluminum nitrate	63	6.3 (5.98-6.56)	1.39	Reproduction (population size)	1,751	**4,518**	-	OSU 2018e
Rotifer (newly hatched, <2 hr), *Brachionus calyciflorus*	48 hr	Aluminum nitrate	105	6.3 (6.02-6.55)	1.39	Reproduction (population size)	2,066	**3,844**	-	OSU 2018e
Rotifer (newly hatched, <2 hr), *Brachionus calyciflorus*	48 hr	Aluminum nitrate	114	6.2 (5.98-6.47)	2.63	Reproduction (population size)	3,061	**4,323**	-	OSU 2018e
Rotifer (newly hatched, <2 hr), *Brachionus calyciflorus*	48 hr	Aluminum nitrate	105	6.1 (5.89-6.63)	3.77	Reproduction (population size)	4,670	**6,653**	-	OSU 2018e
Rotifer (newly hatched, <2 hr), *Brachionus calyciflorus*	48 hr	Aluminum nitrate	185	6.3 (6.05-6.54)	1.33	Reproduction (population size)	1,604	**2,132**	3,539	OSU 2018e
Great pond snail (newly-hatched, <24 hr), *Lymnaea stagnalis*	30 d	Aluminum nitrate	117	6.0 (5.6-6.4)	<0.5[c]	Biomass	745.7	**5,945**	-	OSU 2012b; Cardwell et al. 2018

Species	Test[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	EC_{20} Endpoint	EC_{20} (µg/L)	Normalized Chronic Value[b] (µg/L)	Species Mean Chronic Value (µg/L)	Reference
Great pond snail (newly-hatched, <24 hr), *Lymnaea stagnalis*	30 d	Aluminum nitrate	121 (121-122)	6.15 (6.08-6.45)	1.37 (1.29-1.45)	Biomass	833.4	**1,812**	-	OSU 2018f
Great pond snail (newly-hatched, <24 hr), *Lymnaea stagnalis*	30 d	Aluminum nitrate	124 (121-127)	6.17 (6.06-6.41)	1.45 (1.38-1.51)	Biomass	1,951	**3,902**	-	OSU 2018f
Great pond snail (newly-hatched, <24 hr), *Lymnaea stagnalis*	30 d	Aluminum nitrate	117 (116-118)	5.98 (5.86-6.16)	3.85 (3.60-4.20)	Biomass	1,392	**2,251**	3,119	OSU 2018f
Fatmucket (6 wk, 1.97 mm), *Lampsilis siliquoidea*	28 d	Aluminum nitrate	105.5 (105-106)	6.04 (5.95-6.12)	0.40 (0.34-0.45)	Biomass	169	**1,026**	1,026	Wang et al. 2016, 2018
Cladoceran (≤16 hr), *Ceriodaphnia dubia*	LC	Aluminum chloride	50	7.15 (±0.05)	1.1[c]	Reproduction (young/adult)	1,780	**2,031**	-	McCauley et al. 1986
Cladoceran (≤16 hr), *Ceriodaphnia dubia*	LC	Aluminum chloride	50.5	7.61 (±0.11)	1.1[c]	Reproduction (young/adult)	<1,100 (MATC)	<925.5[f]	-	McCauley et al. 1986
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum chloride	25 (24-26)	7.65 (7.3-8.0)	0.5[c]	Reproduction (young/female)	1,557	**2,602**	-	ENSR 1992b
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum chloride	47 (46-48)	7.7 (7.3-8.1)	0.5[c]	Reproduction (young/female)	808.7	**1,077**	-	ENSR 1992b
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum chloride	94 (92-96)	8.2 (7.9-8.5)	0.5[c]	Reproduction (young/female)	647.2	**708.8**	-	ENSR 1992b
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum chloride	196 (194-198)	8.45 (8.1-8.8)	0.5[c]	Reproduction (young/female)	683.6	**746.8**	-	ENSR 1992b
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	25	6.34	0.5[c]	Reproduction	36.6	**291.7**	-	European Al Association 2010; Gensemer et al. 2018

Species	Test[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	EC_{20} Endpoint	EC_{20} (µg/L)	Normalized Chronic Value[b] (µg/L)	Species Mean Chronic Value (µg/L)	Reference
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	60	6.4	0.5[c]	Reproduction	160.3	**667.9**	-	European Al Association 2010; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	120	6.38	0.5[c]	Reproduction	221.6	**619.4**	-	European Al Association 2010; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	25	6.34	2	Reproduction	377.4	**1,315**	-	European Al Association 2010; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	60	6.38	2	Reproduction	631.3	**1,187**	-	European Al Association 2010; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	120	6.37	2	Reproduction	1,011.6	**1,254**	-	European Al Association 2010; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	25	6.33	4	Reproduction	622.6	**1,460**	-	European Al Association 2010; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	60	6.3	4	Reproduction	692.9	**981.4**	-	European Al Association 2010; Gensemer et al. 2018

Species	Test[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	EC_{20} Endpoint	EC_{20} (µg/L)	Normalized Chronic Value[b] (µg/L)	Species Mean Chronic Value (µg/L)	Reference
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	120	6.38	4	Reproduction	840.5	**678.9**	-	European Al Association 2010; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	25	6.37	2	Reproduction	353.0	**1,164**	-	Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	25	6.34	2	Reproduction	452.4	**1,576**	-	Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	25	6.35	2	Reproduction	439.7	**1,504**	-	Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	25	7.04	0.5	Reproduction (young/female)	250	**701.1**	-	CECM 2014; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	120	7.14	0.5	Reproduction (young/female)	860	**1,072**	-	CECM 2014; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	25	7.98	0.5	Reproduction (young/female)	700	**1,029**	-	CECM 2014; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	60	8.03	0.5	Reproduction (young/female)	1,010	**1,189**	-	CECM 2014; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	120	8.1	0.5	Reproduction (young/female)	870	**879.6**	-	CECM 2014; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	25	6.34	0.5	Reproduction (young/female)	260	**2,072**	-	CECM 2014; Gensemer et al. 2018
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	120	6.36	0.5	Reproduction (young/female)	390	**1,122**	-	CECM 2014; Gensemer et al. 2018

Species	Test[a]	Chemical	Total Hardness (mg/L as CaCO$_3$)	pH	DOC (mg/L)	EC$_{20}$ Endpoint	EC$_{20}$ (µg/L)	Normalized Chronic Value[b] (µg/L)	Species Mean Chronic Value (µg/L)	Reference
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	64	6.42	1.87	Reproduction (young/female)	828.6	**1,463**	-	OSU 2018a
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	133	6.325	8.71	Reproduction (young/female)	3,829	**1,973**	-	OSU 2018a
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	138	6.395	12.3	Reproduction (young/female)	6,224	**2,308**	-	OSU 2018a
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	428	6.295	1.64	Reproduction (young/female)	2,011	**1,388**	-	OSU 2018a
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	125	7.205	6.57	Reproduction (young/female)	6,401	**1,614**	-	OSU 2018a
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	127	7.185	12.01	Reproduction (young/female)	6,612	**1,170**	-	OSU 2018a
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	263	8.17	1.3	Reproduction (young/female)	3,749	**1,854**	-	OSU 2018a
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	425	8.21	1.2	Reproduction (young/female)	2,852	**1,372**	-	OSU 2018a
Cladoceran (<24 hr), *Ceriodaphnia dubia*	LC	Aluminum nitrate	125	8.7	1.04	Reproduction (young/female)	1,693	**1,530**	1,181	OSU 2018a
Cladoceran (<24 hr), *Daphnia magna*	LC	Aluminum nitrate	140	6.3	2	Reproduction (young/female)	791.0	**985.3**	985.3	European Al Association 2010; Gensemer et al. 2018
Amphipod (juvenile, 7-9 d), *Hyalella azteca*	28 d	Aluminum nitrate	95	6.35 (6.0-6.7)	0.51	Biomass	199.3	**665.9**	-	OSU 2012h; Cardwell et al. 2018
Amphipod (juvenile, 7 d, 1.31 mm), *Hyalella azteca*	28 d	Aluminum nitrate	106 (105-107)	6.04 (5.92-6.16)	0.33 (0.26-0.39)	Biomass	425	**2,890**	1,387	Wang et al. 2016, 2018

Species	Test[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	DOC (mg/L)	EC_{20} Endpoint	EC_{20} (µg/L)	Normalized Chronic Value[b] (µg/L)	Species Mean Chronic Value (µg/L)	Reference
Midge (1st instar larva, <24 hr), *Chironomus riparius*	30 d	Aluminum sulfate	11.8	5.58 (5.51-5.64)	1.8[e]	Adult midge emergence	29.55	**1,075**	-	Palawski et al. 1989
Midge (1st instar larva, <24 hr), *Chironomus riparius*	30 d	Aluminum sulfate	11.9	5.05 (4.99-5.1)	1.8[e]	Adult midge emergence	84.42	**15,069**	-	Palawski et al. 1989
Midge (1st instar larva, 3d), *Chironomus riparius*	28 d	Aluminum nitrate	91	6.6 (6.3-6.9)	0.51	Reproduction (# of eggs/case)	3,387	**8,181**	5,099	OSU 2012f; Cardwell et al. 2018
Atlantic salmon (embryo), *Salmo salar*	ELS	Aluminum sulfate	12.7	5.7 (5.6-5.8)	1.8[e]	Biomass	61.56	**434.4**	-	McKee et al. 1989
Atlantic salmon (fertilized eggs), *Salmo salar*	ELS	Aluminum sulfate	12.7	5.7 (5.6-5.8)	1.8[e]	Survival	154.2	1,088[d]	434.4	Buckler et al. 1995
Brook trout (eyed eggs), *Salvelinus fontinalis*	ELS	Aluminum sulfate	12.3	6.55 (6.5-6.6)	1.9	Biomass	164.4	**378.7**	-	Cleveland et al. 1989
Brook trout (eyed eggs), *Salvelinus fontinalis*	ELS	Aluminum sulfate	12.8	5.65 (5.6-5.7)	1.8	Biomass	143.5	**1,076**	638.2	Cleveland et al. 1989
Fathead minnow, *Pimephales promelas*	ELS	Aluminum sulfate	220	7.70 (7.27-8.15)	1.6[c]	Biomass	6,194	**2,690**	-	Kimball 1978
Fathead minnow (embryo, <24 hr), *Pimephales promelas*	ELS	Aluminum nitrate	96	6.20 (5.9-6.5)	<0.5[c]	Survival	428.6	**2,154**	2,407	OSU 2012g; Cardwell et al. 2018
Zebrafish (embryo, <36hpf), *Danio rerio*	ELS	Aluminum nitrate	83	6.15 (6.0-6.3)	<0.5[c]	Biomass	234.4	**1,342**	1,342	OSU 2013; Cardwell et al. 2018

[a] LC=Life cycle, ELS=Early life-stage.
[b] Normalized to pH 7, total hardness of 100 mg/L as $CaCO_3$ and DOC of 1.0 mg/L (see Section 2.7.1). Values in bold are used in SMCV calculations.
[c] When definitive DOC values were not reported by the authors: a DOC value of 0.5 mg/L was used when dilution water was reconstituted, 1.1 mg/L when dilution water was Lake Superior water, 1.6 mg/L when dilution water was tap or well water, or half the detection limit when the reported value was less than the detection limit, based on recommendations in the 2007 Freshwater Copper AWQC (U.S. EPA 2007b).
[d] Buckler et al. (1995) appears to be a republication of McKee et al. (1989), but does not report the most sensitive endpoint and therefore only the most sensitive endpoint used for calculation of the SMCV.
[e] DOC was taken from reported values in Cleveland et al. (1989) for a similar pH; all studies are from the same lab and used the same procedures to make the dilution water (well water plus reverse osmosis water mixture).
[f] Value is a MATC, poor dose response prevented an EC_{20} from being calculated; not used in SMCV calculation.

Appendix D ACCEPTABLE CHRONIC TOXICITY DATA OF ALUMINUM TO ESTUARINE/MARINE AQUATIC ANIMALS

Appendix D. Acceptable Chronic Toxicity Data of Aluminum to Estuarine/Marine Aquatic Animals

Species	Duration	Chemical	Salinity (g/kg)	pH	Chronic Limits (µg/L)	Chronic Value (µg/L)	Effect	Species Mean Chronic Value (µg/L)	Reference
Estuarine/Marine Species									

There are no acceptable estuarine/marine chronic toxicity data for aluminum.

Appendix E ACCEPTABLE TOXICITY DATA OF ALUMINUM TO FRESHWATER AQUATIC PLANTS

Appendix E. Acceptable Toxicity Data of Aluminum to Freshwater Aquatic Plants

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	Duration	Effect	Chronic Limits (µg/L)	Concentration (µg/L)	Reference
Freshwater Species									
Green alga, *Arthrodesmus octocornus*	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50	Pillsbury and Kingston 1990
Green alga, *Arthrodesmus indentatus*	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50	Pillsbury and Kingston 1990
Green alga, *Arthrodesmus quiriferus*	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50	Pillsbury and Kingston 1990
Green alga, *Dinobryon bavaricum*	S, M	-	-	5.7	21 d	NOEC (number of cells)	-	>200	Pillsbury and Kingston 1990
Green alga, *Elaktothrix sp.*	S, M	-	-	5.7	21 d	Number of cells	100-200	141.4	Pillsbury and Kingston 1990
Green alga, *Oedogonium sp.*	S, M	-	-	5.7	21 d	NOEC (number of cells)	-	>200	Pillsbury and Kingston 1990
Green alga, *Peridinium limbatum*	S, M	-	-	5.7	21 d	NOEC (number of cells)	-	>200	Pillsbury and Kingston 1990
Green alga, *Staurastrum arachne v. curvatum*	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50	Pillsbury and Kingston 1990

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	Duration	Effect	Chronic Limits (µg/L)	Concentration (µg/L)	Reference
Green alga, *Staurastrum longipes v. contractum*	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50	Pillsbury and Kingston 1990
Green alga, *Staurastrum pentacerum*	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50.0	Pillsbury and Kingston 1990
Green alga, *Mougeotia sp.*	S, U	Aluminum sulfate	-	4.1	14 d	NOEC (chlorophyll a)	-	3,600	Graham et al. 1996
Green alga, *Monoraphidium dybowskii*	S, U	Aluminum chloride	-	5.0	12 d	EC50 (growth)	-	1,000	Claesson and Tornqvist 1988
Green alga, *Monoraphidium dybowskii*	S, U	Aluminum chloride	-	5.5	12 d	EC50 (growth)	-	1,000	Claesson and Tornqvist 1988
Green alga, *Monoraphidium dybowskii*	S, U	Aluminum chloride	-	6.0	12 d	EC50 (growth)	-	550	Claesson and Tornqvist 1988
Green alga, *Monoraphidium dybowskii*	S, U	Aluminum chloride	14.9	4.8	4 d	Growth	600-1,000	774.6	Hornstrom et al. 1995
Green alga, *Monoraphidium dybowskii*	S, U	Aluminum chloride	14.9	6.8	4 d	LOEC (growth)	-	200	Hornstrom et al. 1995
Green alga, *Monoraphidium griffithii*	S, U	Aluminum chloride	14.9	4.8	4 d	LOEC (growth)	-	100	Hornstrom et al. 1995
Green alga, *Monoraphidium griffithii*	S, U	Aluminum chloride	14.9	6.8	4 d	LOEC (growth)	-	100	Hornstrom et al. 1995

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	Duration	Effect	Chronic Limits (µg/L)	Concentration (µg/L)	Reference
Green alga, *Scenedesmus quadricauda*	S, U	Aluminum chloride	-	7.5	4 d	LOEC (growth inhibition)	-	1,500	Bringmann and Kuhn 1959b
Green alga, *Pseudokirchneriella subcapitata*	-	Sodium aluminate	15	7.0	14 d	Reduce cell counts and dry weight	990-1,320	1,143	Peterson et al. 1974
Green alga, *Pseudokirchneriella subcapitata*	S, U	Aluminum chloride	47.4 (±4.51)	7.6	4 d	EC50 (biomass)	-	570	Call et al. 1984
Green alga, *Pseudokirchneriella subcapitata*	S, U	Aluminum chloride	47.4 (±4.51)	8.2	4 d	EC50 (biomass)	-	460	Call et al. 1984
Green alga, *Pseudokirchneriella subcapitata*	S, U	Aluminum sulfate	-	5.5	4 d	LOEC (growth inhibition)	-	160	Kong and Chen 1995
Green alga, *Stichococcus sp.*	S, U	Aluminum chloride	-	5.0	9 d	IC50 (growth rate)	-	560	Tornqvist and Claesson 1987
Green alga, *Stichococcus sp.*	S, U	Aluminum chloride	-	5.0	9 d	EC50 (growth)	-	500	Claesson and Tornqvist 1988
Green alga, *Stichococcus sp.*	S, U	Aluminum chloride	-	5.5	9 d	EC50 (growth)	-	220	Claesson and Tornqvist 1988
Diatom, *Asterionella ralfsii var. americana*	S, M	Aluminum chloride	-	5.0	7-9 d	Growth	404.7-620.5	501.1	Gensemer 1989
Diatom, *Asterionella ralfsii var. americana*	S, M	Aluminum chloride	-	6.0	7-9 d	Growth	404.7-647.5	511.9	Gensemer 1989

Species	Method[a]	Chemical	Total Hardness (mg/L as $CaCO_3$)	pH	Duration	Effect	Chronic Limits (µg/L)	Concentration (µg/L)	Reference
Diatom, *Asterionella ralfsii var. americana*	S, M	-	-	5.7	21 d	LOEC (number of live cells)	-	50	Pillsbury and Kingston 1990
Diatom, *Cyclotella meneghiniana*	S, U	Aluminum chloride	-	7.9	16 d	Partially inhibit growth	-	809.6	Rao and Subramanian 1982
Diatom, *Cyclotella meneghiniana*	S, U	Aluminum chloride	-	7.9	16 d	Algistatic	-	3,238	Rao and Subramanian 1982
Diatom, *Cyclotella meneghiniana*	S, U	Aluminum chloride	-	7.9	16 d	Algicidal	-	6,477	Rao and Subramanian 1982
Eurasian watermilfoil, *Myriophyllum spicatum*	S, U	-	95.93	-	32 d	IC50 (root dry weight)	-	2,500	Stanley 1974
Duckweed, *Lemna minor*	S, M	Aluminum chloride	47.4 (±4.51)	7.6	4 d	NOEC (reduce frond production)	-	>45,700	Call et al. 1984
Duckweed, *Lemna minor*	S, M	Aluminum chloride	47.4 (±4.51)	8.2	4 d	NOEC (reduce frond production)	-	>45,700	Call et al. 1984

[a] S=static, F=flow-through, U=unmeasured, M=measured.

Appendix F ACCEPTABLE TOXICITY DATA OF ALUMINUM TO ESTUARINE/MARINE AQUATIC PLANTS

Appendix F. Acceptable Toxicity Data of Aluminum to Estuarine/Marine Aquatic Plants

Species	Method[a]	Chemical	Salinity (g/kg)	pH	Duration	Effect	Chronic Limits (µg/L)	Concentration (µg/L)	Reference
Estuarine/Marine Species									
Seagrass, *Halophila stipulacea*	R, U	-	35.0	6.5-7.0	12 d	Observed protoplast necrosis	0.02698-0.2698	0.08532	Malea and Haritonidis 1996
Seagrass, *Halophila stipulacea*	R, U	-	35.0	6.5-7.0	12 d	Greater than 50% mortality of teeth cells	-	269.8	Malea and Haritonidis 1996
Seagrass, *Halophila stipulacea*	R, U	-	35.0	6.5-7.0	12 d	Less than 50% mortality of teeth cells	-	26.98	Malea and Haritonidis 1996

[a] S=static, F=flow-through, U=unmeasured, M=measured.

Appendix G ACCEPTABLE BIOACCUMULATION DATA OF ALUMINUM BY AQUATIC ORGANISMS

Appendix G. Acceptable Bioaccumulation Data of Aluminum by Aquatic Organisms

Species	Lifestage	Chemical	Concentration in water (µg/L)	Total Hardness (mg/L as $CaCO_3$)	pH	Tissue	Duration	BCF or BAF	Reference
Freshwater Species									
Snail, *Lymnaea stagnalis*	-	Aluminum nitrate	242	208	7	Digestive gland	30 d	4.26	Dobranskyte et al. 2004
Snail, *Lymnaea stagnalis*	-	Aluminum nitrate	242	208	7	Soft tissue	15 d	2.29	Dobranskyte et al. 2004
Brook trout, *Salvelinus fontinalis*	30 d	Aluminum sulfate	214.0	~12.5	5.3	Whole body	14 d	142	Cleveland et al. 1991a
Brook trout, *Salvelinus fontinalis*	30 d	Aluminum sulfate	223.5	~12.5	6.1	Whole body	14 d	104	Cleveland et al. 1991a
Brook trout, *Salvelinus fontinalis*	30 d	Aluminum sulfate	267.6	~12.5	7.2	Whole body	56 d	14.2	Cleveland et al. 1991a
Atlantic salmon, *Salmo salar*	larva	Aluminum sulfate	33	12.8	5.5	Whole body	60 d (embryo to post-hatch)	76	Buckler et al. 1995
Atlantic salmon, *Salmo salar*	larva	Aluminum sulfate	71	12.8	5.5	Whole body	60 d (embryo to post-hatch)	154	Buckler et al. 1995
Atlantic salmon, *Salmo salar*	larva	Aluminum sulfate	124	12.8	5.5	Whole body	60 d (embryo to post-hatch)	190	Buckler et al. 1995
Species	**Lifestage**	**Chemical**	**Concentration in water (µg/L)**	**Salinity (g/kg)**	**pH**	**Tissue**	**Duration**	**BCF or BAF**	**Reference**
Estuarine/Marine Species									

There are no acceptable estuarine/marine bioaccumulation data for aluminum.

Appendix H OTHER DATA ON EFFECTS OF ALUMINUM TO FRESHWATER AQUATIC ORGANISMS

Appendix H. Other Data on Effects of Aluminum to Freshwater Aquatic Organisms

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Freshwater Species								
Planktonic communities	Aluminum sulfate	1 hr	-	6.1-6.9	Decreased phosphate uptake and photosynthesis	50	Nalewajko and Paul 1985	Community exposure
Algal community	Aluminum sulfate	28 d	-	4.8	Growth	100-500 (NOEC-LOEC)	Genter and Amyot 1994	Community exposure
Microcosm community	Aluminum chloride	21 d	-	-	Production rate	2,000-5,000 (NOEC-LOEC)	Sugiura 2001	Community exposure
Blue-green alga, *Aphanizomenon flos-aquae*	Aluminum sulfate	22 hr	12.6	8.0	IC50 (nitrogen fixation)	>3,942	Peterson et al. 1995	Duration
Green alga, *Dunaliella acidophila*	Aluminum chloride	4-5 d	-	1.0	IC50 (photosynthesis)	>269,800	Gimmler et al. 1991	Lack of exposure details
Green alga, *Dunaliella acidophila*	Aluminum chloride	4-5 d	-	7.0	IC50 (photosynthesis)	134,900	Gimmler et al. 1991	Lack of exposure details
Green alga, *Dunaliella acidophila*	Aluminum chloride	4-5 d	-	1.0	IC50 (growth)	>269,800	Gimmler et al. 1991	Lack of exposure details
Green alga, *Dunaliella parva*	Aluminum chloride	4-5 d	-	7.0	IC50 (photosynthesis)	26,980	Gimmler et al. 1991	Lack of exposure details
Green alga, *Dunaliella parva*	Aluminum chloride	4-5 d	-	5.5	IC50 (growth)	1,619	Gimmler et al. 1991	Lack of exposure details
Green alga, *Chlorella sp.*	Aluminum sulfate	72 hr	1.0 (DOC = 1 mg/L)	5.0	IC50 (growth)	275	Trenfield et al. 2012	Duration
Green alga, *Chlorella sp.*	Aluminum sulfate	72 hr	1.0 (DOC = 2 mg/L)	5.0	IC50 (growth)	613	Trenfield et al. 2012	Duration
Green alga, *Chlorella sp.*	Aluminum sulfate	72 hr	4.1 (DOC = 1 mg/L)	5.0	IC50 (growth)	437	Trenfield et al. 2012	Duration

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Green alga, *Chlorella sp.*	Aluminum sulfate	72 hr	4.1 (DOC = 2 mg/L)	5.0	IC50 (growth)	801	Trenfield et al. 2012	Duration
Green alga, *Chlorella pyrenoidosa*	Aluminum sulfate	26 d	-	4.6	Reduced growth	6,000-12,000 (NOEC-LOEC)	Foy and Gerloff 1972	pH too low
Green alga, *Chlorella pyrenoidosa*	Aluminum chloride	5 d	-	5.0	Growth	50-100 (NOEC-LOEC)	Parent and Campbell 1994	pH too low
Green alga, *Chlorella vulgaris*	Aluminum chloride	3-4 mo.	-	<7.0	Inhibited growth	4,000	De Jong 1965	Lack of exposure details
Green alga, *Chlorella vulgaris*	Aluminum chloride	15 d	-	6.8	LC50	107,952	Rai et al. 1998	Lack of exposure details
Green alga, *Chlorella vulgaris*	Aluminum chloride	15 d	-	6.0	LC50	5,937	Rai et al. 1998	Lack of exposure details
Green alga, *Chlorella vulgaris*	Aluminum chloride	3 d	-	4.5	LC50	4,048	Rai et al. 1998	Lack of exposure details
Green alga, *Monoraphidium dybowskii*	Aluminum chloride	9 d	-	5.0	IC56 (growth rate)	1,800	Tornqvist and Claesson 1987	Atypical endpoint
Green alga, *Monoraphidium dybowskii*	Aluminum chloride	9 d	-	5.0	IC42 (growth rate)	560	Tornqvist and Claesson 1987	Atypical endpoint
Green alga, Desmo*desmus subspicatus*	Aluminum chloride	72 hr	-	-	EC50 (growth) - flask	2,206	Eisentraeger et al. 2003	Duration
Green alga, Desmo*desmus subspicatus*	Aluminum chloride	72 hr	-	-	EC50 (growth) - flask	2,894	Eisentraeger et al. 2003	Duration
Green alga, Desmo*desmus subspicatus*	Aluminum chloride	72 hr	-	-	EC50 (growth) - 24 well microplate	2,834	Eisentraeger et al. 2003	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, Desmo*desmus subspicatus*	Aluminum chloride	72 hr	-	-	EC50 (growth) - 24 well microplate	3,340	Eisentraeger et al. 2003	Duration
Green alga, Desmo*desmus subspicatus*	Aluminum chloride	72 hr	-	-	EC50 (growth) - 96 well microplate	2,773	Eisentraeger et al. 2003	Duration
Green alga, Desmo*desmus subspicatus*	Aluminum chloride	72 hr	-	-	EC50 (growth) - 96 well microplate	2,915	Eisentraeger et al. 2003	Duration
Green alga, Desmo*desmus subspicatus*	Aluminum chloride	72 hr	-	-	EC50 (biomass) - flask	2,028	Eisentraeger et al. 2003	Duration
Green alga, Desmo*desmus subspicatus*	Aluminum chloride	72 hr	-	-	EC50 (biomass) - flask	2,423	Eisentraeger et al. 2003	Duration
Green alga, Desmo*desmus subspicatus*	Aluminum chloride	72 hr	-	-	EC50 (unidentified) - flask	2,605	Eisentraeger et al. 2003	Duration
Green alga, Desmo*desmus subspicatus*	Aluminum chloride	72 hr	-	-	EC50 (unidentified) - flask	2,467	Eisentraeger et al. 2003	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	6.25	EC50 (biomass)	28.3	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	7.23-7.26	EC50 (biomass)	155.5	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	8.05-8.12	EC50 (biomass)	851.4	European Al Association 2009; Gensemer et al. 2018	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	6.29-6.30	EC50 (biomass)	76.4	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	7.12-7.13	EC50 (biomass)	232.9	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	7.90-8.12	EC50 (biomass)	516.2	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	6.22-6.24	EC50 (biomass)	74.2	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	7.10-7.13	EC50 (biomass)	226.3	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	7.94-8.11	EC50 (biomass)	366.9	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	6.25	EC50 (growth rate)	72.1	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	7.23-7.26	EC50 (growth rate)	345.6	European Al Association 2009; Gensemer et al. 2018	Duration

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	8.05-8.12	EC50 (growth rate)	1,351.8	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	6.29-6.30	EC50 (growth rate)	206.2	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	7.12-7.13	EC50 (growth rate)	584.0	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	7.90-8.12	EC50 (growth rate)	1,607.2	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	6.22-6.24	EC50 (growth rate)	323.4	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	7.10-7.13	EC50 (growth rate)	550.1	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	7.94-8.11	EC50 (growth rate)	889.1	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	6.19-6.23	EC50 (biomass)	669.9	European Al Association 2009; Gensemer et al. 2018	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	6.96-7.05	EC50 (biomass)	1,815.8	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	7.74-7.96	EC50 (biomass)	2,157.0	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	6.13-6.19	EC50 (biomass)	1,030.1	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	6.97-7.04	EC50 (biomass)	2,266.7	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	7.82-8.04	EC50 (biomass)	927.1	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	6.09-6.18	EC50 (biomass)	1,451.5	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	6.94-7.12	EC50 (biomass)	2,591.7	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	7.87-8.05	EC50 (biomass)	774.2	European Al Association 2009; Gensemer et al. 2018	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	6.19-6.23	EC50 (growth rate)	1,181.1	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	6.96-7.05	EC50 (growth rate)	2,896.0	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	7.74-7.96	EC50 (growth rate)	4,980.9	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	6.13-6.19	EC50 (growth rate)	1,473.5	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	6.97-7.04	EC50 (growth rate)	4,332.3	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	7.82-8.04	EC50 (growth rate)	2,000.0	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	6.09-6.18	EC50 (growth rate)	2,100.1	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	6.94-7.12	EC50 (growth rate)	3,645.8	European Al Association 2009; Gensemer et al. 2018	Duration

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	7.87-8.05	EC50 (growth rate)	1,639.9	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	6.09-6.19	EC50 (biomass)	778.2	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	6.98-7.10	EC50 (biomass)	2,630.2	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	7.82-7.98	EC50 (biomass)	2,229.7	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	6.10-6.19	EC50 (biomass)	1,273.7	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	7.0-7.05	EC50 (biomass)	2,736.4	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	7.78-7.87	EC50 (biomass)	1,660.2	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	6.09-6.24	EC50 (biomass)	1,572.8	European Al Association 2009; Gensemer et al. 2018	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	7.0-7.09	EC50 (biomass)	3,546.2	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	7.77-7.81	EC50 (biomass)	1,521.2	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	6.09-6.19	EC50 (growth rate)	1,443.9	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	6.98-7.10	EC50 (growth rate)	3,845.9	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	7.82-7.98	EC50 (growth rate)	4,716.1	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	6.10-6.19	EC50 (growth rate)	1,890.7	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	7.0-7.05	EC50 (growth rate)	4,260.0	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	7.78-7.87	EC50 (growth rate)	2,905.0	European Al Association 2009; Gensemer et al. 2018	Duration

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	6.09-6.24	EC50 (growth rate)	2,429.3	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	7.0-7.09	EC50 (growth rate)	4,930.0	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	7.77-7.81	EC50 (growth rate)	2,556.3	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Solution aged 3 hr (DOC = 0 mg/L)	6.23-6.24	EC50 (growth)	196.2	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Solution aged 27 hr (DOC = 0 mg/L)	6.12-6.23	EC50 (growth)	182.7	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Solution aged 3 hr (DOC = 0 mg/L)	7.93-8.06	EC50 (growth)	1,762.4	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Solution aged 27 hr (DOC = 0 mg/L)	7.93-8.23	EC50 (growth)	1,328.0	European Al Association 2009; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Medium not buffered (DOC = 0 mg/L)	7.80-8.21	EC50 (growth rate)	1,282.1	European Al Association 2010; Gensemer et al. 2018	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	8.05-8.12	EC50 (growth rate)	1,351.8	European Al Association 2010; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	7.99-8.08	EC50 (growth rate)	1,476.6	European Al Association 2010; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	7.65-7.70	EC50 (growth rate)	1,417.9	European Al Association 2010; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Medium not buffered (DOC = 0 mg/L)	7.80-8.21	EC50 (biomass)	626.6	European Al Association 2010; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	8.05-8.12	EC50 (biomass)	851.4	European Al Association 2010; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	7.99-8.08	EC50 (biomass)	717.9	European Al Association 2010; Gensemer et al. 2018	Duration
Green alga, *Pseudokirchneriella subcapitata*	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	7.65-7.70	EC50 (biomass)	563.3	European Al Association 2010; Gensemer et al. 2018	Duration
Red alga, *Cyanidium caldarium*	Aluminum chloride	5-10 d	-	2	Reduced growth rate by 42%	5,396,000	Yoshimura et al. 1999	Lack of exposure details; pH too low
Protozoa, *Euglena gracilis*	Aluminum chloride	10 min	-	6.0-7.0	Some survival	111,800	Ruthven and Cairns 1973	Single-cell organism

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Protozoa (1 wk), *Euglena gracilis*	Aluminum chloride	7 d	-	-	Growth	10,000-15,000 (NOEC-LOEC)	Danilov and Ekelund 2002	Single-cell organism
Protozoa, *Chilomonas paramecium*	Aluminum chloride	10 min	-	5.5-7.4	Some survival	110	Ruthven and Cairns 1973	Single-cell organism
Protozoa, *Microregma heterostoma*	Aluminum chloride	28 hr	-	7.5-7.8	Incipient inhibition	12,000	Bringmann and Kuhn 1959a	Single-cell organism
Protozoa, *Peranema trichoporum*	Aluminum chloride	10 min	-	5.5-6.5	Some survival	62,600	Ruthven and Cairns 1973	Single-cell organism
Protozoa, *Tetrahymena pyriformis*	Aluminum chloride	10 min	-	5.5-6.5	Some survival	100	Ruthven and Cairns 1973	Single-cell organism
Protozoa, *Tetrahymena pyriformis*	Aluminum chloride	96 hr	-	6.5	IC50 (growth)	15,000	Sauvant et al. 2000	Single-cell organism
Protozoa, *Tetrahymena pyriformis*	Aluminum sulfate	96 hr	-	6.5	IC50 (growth)	10,000	Sauvant et al. 2000	Single-cell organism
Protozoa, *Tetrahymena pyriformis*	Aluminum nitrate	96 hr	-	6.5	IC50 (growth)	14,000	Sauvant et al. 2000	Single-cell organism
Rotifer (0-2 hr), *Brachionus calyciflorus*	Aluminum chloride	24 hr	90 (80-100)	7.5	LC50	>3,000	Snell et al. 1991	Lack of exposure details and effects
Nematode (3-4 d, adult), *Caenorhabditis elegans*	Aluminum nitrate	-	-	-	LC50	1,800	Williams and Dusenbery 1990	Test species fed
Nematode, *Caenorhabditis elegans*	Aluminum nitrate	24 hr	-	4.5-6.5	LC50	49,000	Dhawan et al. 2000	Duration; test species fed
Nematode, *Caenorhabditis elegans*	Aluminum nitrate	24 hr	-	4.5-6.5-	EC50 (movement)	3,000	Dhawan et al. 2000	Duration; test species fed
Nematode, *Caenorhabditis elegans*	Aluminum chloride	48 hr	-	-	LC50	18,150	Chu and Chow 2002	Duration
Nematode (adult), *Caenorhabditis elegans*	Aluminum chloride	4 hr	-	-	EC50 (rate of movement)	1,241	Anderson et al. 2004	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Tubificid worm, *Tubifex tubifex*	Aluminum ammonium sulfate	96 hr	245	7.6	EC50 (death and immobility)	50,230	Khangarot 1991	Inappropriate form of toxicant
Planarian (adult), *Dugesia tigrina*	Aluminum chloride	48 hr	47.4	7.48	Mortality	>16,600 (NOEC)	Brooke 1985	Duration
Planarian, *Dugesia tigrina*	-	48 hr	~47.42	7.48	LC50	>23,200	Lange 1985	Duration
Brown hydra, *Hydra oligactis*	Aluminum sulfate	72 hr	-	-	86% mortality	475,000	Kovacevic et al. 2007	Duration
Brown hydra, *Hydra oligactis*	Aluminum sulfate	72 hr	-	-	Tail growth	250,000 (LOEC)	Kovacevic et al. 2007	Duration; atypical endpoint
Green hydra, *Hydra viridissima*	Aluminum sulfate	72 hr	-	-	LC50	475,000-480,000	Kovacevic et al. 2007	Duration
Green hydra, *Hydra viridissima*	Aluminum sulfate	72 hr	-	-	Tail growth	250,000-475,000 (NOEC-LOEC)	Kovacevic et al. 2007	Duration; atypical endpoint
Green hydra, *Hydra viridissima*	Aluminum nitrate	7 d	1.0 (DOC = 1 mg/L)	5.0	IC50 (population growth rate)	56	Trenfield et al. 2012	Duration
Green hydra, *Hydra viridissima*	Aluminum nitrate	7 d	1.0 (DOC = 2 mg/L)	5.0	IC50 (population growth rate)	90	Trenfield et al. 2012	Duration
Green hydra, *Hydra viridissima*	Aluminum nitrate	7 d	4.1 (DOC = 1 mg/L)	5.0	IC50 (population growth rate)	152	Trenfield et al. 2012	Duration
Green hydra, *Hydra viridissima*	Aluminum nitrate	7 d	4.1 (DOC = 2 mg/L)	5.0	IC50 (population growth rate)	166	Trenfield et al. 2012	Duration

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Snail, *Amnicola limosa*	Aluminum	96 hr	15.3	3.5	LC50	>1,000	Mackie 1989	pH too low
Snail, *Amnicola limosa*	Aluminum	96 hr	15.3	4.0	LC50	>400	Mackie 1989	pH too low
Snail, *Amnicola limosa*	Aluminum	96 hr	15.3	4.5	LC50	>400	Mackie 1989	pH too low
Snail (adult, 3.5-5.6 g), *Lymnaea stagnalis*	Aluminum nitrate	30 d	-	7.0	Increase in number of granules	300	Elangovan et al. 2000	Unmeasured chronic exposure
Snail (Adult, 3.5-5.6 g), *Lymnaea stagnalis*	Aluminum nitrate	30 d	~74.0	7.0	BCF = 4,500 (whole soft tissue)	234	Elangovan et al. 1997	Steady state not reached
Snail (Adult, 3.5-5.6 g), *Lymnaea stagnalis*	Aluminum nitrate	30 d	~74.0	7.0	BCF = 15,000 (whole soft tissue)	285	Elangovan et al. 1997	Steady state not reached
Snail (25-35 mm), *Lymnaea stagnalis*	Aluminum nitrate	30 d	-	7.3	BCF = 444 (digestive gland)	500	Desouky et al. 2003	Steady state not reached
Zebra mussel (veliger larvae, 135-157 µm), *Dreissena polymorpha*	Aluminum sulfate	24 hr	137.1	7.42-7.48	LC50	130,500	Mackie and Kilgour 1995	Duration
Pea cockle, *Pisidium casertanum*	-	96 hr	15.3	3.5	LC50	>1,000	Mackie 1989	pH too low
Pea cockle, *Pisidium casertanum*	-	96 hr	15.3	4.0	LC50	>400	Mackie 1989	pH too low
Pea cockle, *Pisidium casertanum*	-	96 hr	15.3	4.5	LC50	>400	Mackie 1989	pH too low
Ridged-beak peaclam, *Pisidium compressum*	-	96 hr	15.3	3.5	LC50	>1,000	Mackie 1989	pH too low
Ridged-beak peaclam, *Pisidium compressum*	-	96 hr	15.3	4.0	LC50	>400	Mackie 1989	pH too low
Ridged-beak peaclam, *Pisidium compressum*	-	96 hr	15.3	4.5	LC50	>400	Mackie 1989	pH too low

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Cladoceran (<24 hr), *Ceriodaphnia sp.*	Aluminum chloride	8 d	47.4	7.68	LC50	8,600	Call et al. 1984	Duration
Cladoceran (<24 hr), *Ceriodaphnia sp.*	Aluminum chloride	48 hr	47.4	7.68	LC50	3,690	Call et al. 1984	Species not defined; other data available for the genus
Cladoceran (<24 hr), *Ceriodaphnia sp.*	Aluminum chloride	48 hr	47.4	7.36	LC50	2,300 (aged solution)	Call et al. 1984	Species not defined; other data available for the genus
Cladoceran (<24 hr), *Ceriodaphnia sp.*	Aluminum chloride	LC (3 broods)	47.4	7.68	Reproduction	4,900-12,100 (NOEC-LOEC)	Call et al. 1984	Species not defined; other data available for the genus
Cladoceran, *Ceriodaphnia dubia*	Aluminum chloride	LC (3 broods)	90 (80-100)	-	IC25 (reproduction)	566	Zuiderveen and Birge 1997	Unmeasured chronic exposure
Cladoceran, *Ceriodaphnia dubia*	Aluminum chloride	LC (3 broods)	90 (80-100)	-	IC25 (reproduction)	641	Zuiderveen and Birge 1997	Unmeasured chronic exposure
Cladoceran (<24 hr), *Ceriodaphnia dubia*	Aluminum nitrate	LC (3 broods)	10.6 Solution not filtered (DOC = 0 mg/L)	7.74-7.90	Reproduction - # of juveniles	10.0-100.0 (NOEC-LOEC)	European Al Association 2009	Unmeasured chronic exposure
Cladoceran (<24 hr), *Ceriodaphnia dubia*	Aluminum nitrate	LC (3 broods)	10.6 Solution filtered (DOC = 0 mg/L)	7.79-7.91	Reproduction - # of juveniles	500.0-1,000.0 (NOEC-LOEC)	European Al Association 2009	Unmeasured chronic exposure
Cladoceran (<24 hr), *Ceriodaphnia dubia*	Aluminum nitrate	LC (3 broods)	10.6 Solution not filtered (DOC = 0 mg/L)	6.62-7.03	Reproduction - # of juveniles	100.0-1,000.0 (NOEC-LOEC)	European Al Association 2009	Unmeasured chronic exposure
Cladoceran (<24 hr), *Ceriodaphnia dubia*	Aluminum nitrate	LC (3 broods)	10.6 Solution filtered (DOC = 0 mg/L)	6.66-7.04	Reproduction - # of juveniles	100.0-1,000.0 (NOEC-LOEC)	European Al Association 2009	Unmeasured chronic exposure

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Cladoceran (mature), *Daphnia catawba*	Aluminum chloride	72 hr	8.07	6.5	Reduced survival	1,020	Havas and Likens 1985b	Duration
Cladoceran (<8 hr), *Daphnia magna*	Aluminum sulfate	16 hr	-	-	Incipient immobilization	10,717	Anderson 1944	Duration
Cladoceran (<8 hr), *Daphnia magna*	Potassium aluminum sulfate	16 hr	-	-	Incipient immobilization	15,677	Anderson 1944	Duration, inappropriate form of toxicant
Cladoceran, *Daphnia magna*	Aluminum chloride	48 hr	-	7.5	Toxic effect	1,000,000	Bringmann and Kuhn 1959a	Endpoint not clearly defined
Cladoceran (≥12 hr), *Daphnia magna*	Aluminum chloride	21 d	45.3	7.74	EC16 (reduced reproduction)	320	Biesinger and Christensen 1972	Unmeasured chronic exposure
Cladoceran (≥12 hr), *Daphnia magna*	Aluminum chloride	21 d	45.3	7.74	EC50 (reduced reproduction)	680	Biesinger and Christensen 1972	Unmeasured chronic exposure
Cladoceran (≥12 hr), *Daphnia magna*	Aluminum chloride	21 d	45.3	7.74	LC50	1,400	Biesinger and Christensen 1972	Unmeasured chronic exposure
Cladoceran, *Daphnia magna*	Sodium aluminate	96 hr	27	7	Mortality	>40,000	Peterson et al. 1974	LC50 or EC50 endpoint not defined
Cladoceran (≥12 hr), *Daphnia magna*	Aluminum sulfate	28 d	220	8.3	Reproduction	4,260 (NOEC)	Kimball 1978	Control survival (70%)
Cladoceran (≥12 hr), *Daphnia magna*	Aluminum sulfate	28 d	220	8.3	Survival	540-1,020 (NOEC-LOEC)	Kimball 1978	Control survival (70%)
Cladoceran (0-24 hr), *Daphnia magna*	-	28 d	-	-	Survival and reproduction	1,890-4,260 (NOEC-LOEC)	Stephan 1978	Author reported that the results are considered questionable for one reason or another [not provided]

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Cladoceran (14 d), *Daphnia magna*	-	7 d	-	-	Survival and reproduction	3,300-8,400 (NOEC-LOEC)	Stephan 1978	Author reported that the results are considered questionable for one reason or another [not provided]
Cladoceran, *Daphnia magna*	-	28 d	-	-	LC50	38,000	Stephan 1978	Author reported that the results are considered questionable for one reason or another [not provided]
Cladoceran, *Daphnia magna*	Aluminum chloride	48 hr	45.4	7.61	EC50	>25,300	Brooke 1985	No dose response observed
Cladoceran, *Daphnia magna*	Aluminum chloride	48 hr	8.26	6.5	Mortality	320	Havas 1985	Dilution water is lake water, atypical endpoint
Cladoceran, *Daphnia magna*	Aluminum chloride	24 hr	8.26	6.5	BCF = 18,000	20	Havas 1985	Duration, lack of exposure details; dilution water is lake water
Cladoceran, *Daphnia magna*	Aluminum chloride	24 hr	8.26	6.5	BCF = 9,600	320	Havas 1985	Duration, lack of exposure details; dilution water is lake water
Cladoceran, *Daphnia magna*	Aluminum chloride	24 hr	8.26	6.5	BCF = 11,000	1,020	Havas 1985	Duration, lack of exposure details; dilution water is lake water

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Cladoceran, *Daphnia magna*	Aluminum chloride	24 hr	33.35	6.5	BCF = 18,000	20	Havas 1985	Duration, lack of exposure details; dilution water is lake water
Cladoceran, *Daphnia magna*	Aluminum chloride	24 hr	33.35	6.5	BCF = 14,700	1,020	Havas 1985	Duration, lack of exposure details; dilution water is lake water
Cladoceran, *Daphnia magna*	Aluminum chloride	48 hr	-	6.5	Loss of sodium	1,020	Havas and Likens 1985a	Dilution water is lake water, atypical endpoint
Cladoceran, *Daphnia magna*	Aluminum ammonium sulfate	48 hr	240	7.6	LC50	59,600	Khangarot and Ray 1989	Inappropriate form of toxicant
Isopod (7 mm), *Asellus aquaticus*	Aluminum sulfate	72 hr	50	6.75	LC50	4,370	Martin and Holdich 1986	Duration
Amphipod, *Gammarus pseudolimnaeus*	Aluminum chloride	96 hr	47.4	7.53	LC50	22,000	Call et al. 1984	Test species fed
Amphipod, *Hyalella azteca*	-	96 hr	15.3	5.0	LC50	>1,000	Mackie 1989	Not enough information in the paper to determine is acceptable test conditions are met
Amphipod, *Hyalella azteca*	-	96 hr	15.3	5.5	LC50	>400	Mackie 1989	Not enough information in the paper to determine is acceptable test conditions are met

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Amphipod, *Hyalella azteca*	-	96 hr	15.3	6.0	LC50	>400	Mackie 1989	Not enough information in the paper to determine is acceptable test conditions are met
Amphipod (1-11 d), *Hyalella azteca*	-	7 d	18	7.39-8.27	LC50	89	Borgmann et al. 2005	Duration, control mortality (≥80 %)
Amphipod (1-11 d), *Hyalella azteca*	-	7 d	-	8.21-8.46	LC50	>3,150	Borgmann et al. 2005	Duration, control mortality (≥80 %)
Crayfish (80-160 cm), *Pacifastacus leniusculus*	Aluminum nitrate	20 d	-	-	BCF = 3.44 (flexor muscle)	436	Alexopoulos et al. 2003	More accumulation in the controls than exposure
Crayfish (80-160 cm), *Pacifastacus leniusculus*	Aluminum nitrate	20 d	-	-	BCF = 527.5 (gill content)	436	Alexopoulos et al. 2003	Gill content not whole body
Crayfish (larvae), *Procambarus clarkii*	-	30 min	-	-	Oxygen consumption	>100,000 (NOEC)	Becker and Keller 1983	Duration
Caddisfly (larva, 5th instar), *Arctopsyche ladogensis*	Aluminum sulfate	4 d	-	5.0	EC50 (frequency of abnormalities)	938-1,089	Vuori 1996	Atypical endpoint, effect range reported
Damselfly, *Enallagma sp.*	-	96 hr	15.3	3.5	LC50	>1,000	Mackie 1989	pH too low
Damselfly, *Enallagma sp.*	-	96 hr	15.3	4.0	LC50	>400	Mackie 1989	pH too low
Damselfly, *Enallagma sp.*	-	96 hr	15.3	4.5	LC50	>400	Mackie 1989	pH too low
Midge (1st instar larva, 3d), *Chironomus riparius*	Aluminum nitrate	10 d	91	6.5-6.7	Survival	4,281.8->4,281.9 (NOEC-LOEC)	OSU 2012f; Cardwell et al. 2018	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Midge (1st instar larva, 3d), *Chironomus riparius*	Aluminum nitrate	10 d	91	6.5-6.7	Growth-dry weight	1,100.2-2,132.7 (NOEC-LOEC)	OSU 2012f; Cardwell et al. 2018	Duration
Midge, *Paratanytarsus dissimilis*	Aluminum sulfate	55 d	17.43	6.63	Survival	800 (LOEC)	Lamb and Bailey 1981, 1983	Not a flow-through chronic exposure
Dragonfly (last instar nymph), *Libellula julia*	Aluminum chloride	96 hr	-	4	Oxygen uptake inhibition	3,000-30,000 (NOEC-LOEC)	Rockwood et al. 1990	Atypical endpoint
Golden trout (alevin), *Oncorhynchus aguabonita aguabonita*	Aluminum sulfate	7 d	4.89	5.0	Survival	97-293 (NOEC-LOEC)	DeLonay 1991; DeLonay et al. 1993	Duration
Golden trout (swim-up larvae), *Oncorhynchus aguabonita aguabonita*	Aluminum sulfate	7 d	4.89	5.0	Survival	97-293 (NOEC-LOEC)	DeLonay 1991; DeLonay et al. 1993	Duration
Cutthroat trout (egg/embryo), *Oncorhynchus clarkii*	-	7 d	42.5	5	Survival	300->300 (NOEC-LOEC)	Woodward et al. 1989	Duration
Cutthroat trout (egg/embryo), *Oncorhynchus clarkii*	-	7 d	42.5	5	Growth	300->300 (NOEC-LOEC)	Woodward et al. 1989	Duration
Cutthroat trout (alevin, 2 d post hatch), *Oncorhynchus clarkii*	-	7 d	42.5	5	Survival	50-100 (NOEC-LOEC)	Woodward et al. 1989	Duration
Cutthroat trout (alevin/larvae), *Oncorhynchus clarkii*	-	7 d	42.5	5	Growth	50->50 (NOEC-LOEC)	Woodward et al. 1989	Duration
Cutthroat trout (swim-up larvae), *Oncorhynchus clarkii*	-	7 d	42.5	5	Survival	<50-50 (NOEC-LOEC)	Woodward et al. 1989	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Rainbow trout (fingerling), *Oncorhynchus mykiss*	Aluminum chloride	-	28.3	8.48	LT50=7.46 d	5,140	Freeman and Everhart 1971	Atypical endpoint, test species fed
Rainbow trout (fingerling), *Oncorhynchus mykiss*	Aluminum chloride	-	28.3	8.99	LT50=2.96 d	5,200	Freeman and Everhart 1971	Atypical endpoint, test species fed
Rainbow trout (fingerling), *Oncorhynchus mykiss*	Aluminum chloride	-	46.8	8.02	LT50=31.96 d	5,230	Freeman and Everhart 1971	Atypical endpoint, test species fed
Rainbow trout (fingerling), *Oncorhynchus mykiss*	Aluminum chloride	-	56.6	6.8	LT50=38.90 d	5,140	Freeman and Everhart 1971	Atypical endpoint, test species fed
Rainbow trout (fingerling), *Oncorhynchus mykiss*	Aluminum chloride	-	56.6	6.52	LT50=43.90 d	513	Freeman and Everhart 1971	Atypical endpoint, test species fed
Rainbow trout (embryo), *Oncorhynchus mykiss*	Aluminum chloride	Fert. to hatch	-	7.0-9.0	No reduced fertility	5,200	Freeman and Everhart 1971	Lack of exposure details
Rainbow trout (embryo/larvae), *Oncorhynchus mykiss*	Aluminum chloride	28 d	104	7.4	EC50 (death and deformity)	560	Birge 1978; Birge et al. 1978	Duration
Rainbow trout (juvenile), *Oncorhynchus mykiss*	Aluminum sulfate	10 d	25	7	0% dead	200,000	Hunter et al. 1980	Duration, test species fed
Rainbow trout (juvenile), *Oncorhynchus mykiss*	Aluminum sulfate	96 hr	25	8	40% dead	50,000	Hunter et al. 1980	Lack of exposure details
Rainbow trout (juvenile), *Oncorhynchus mykiss*	Aluminum sulfate	42 hr	25	8.5	100% dead	50,000	Hunter et al. 1980	Duration; lack of exposure details
Rainbow trout (juvenile), *Oncorhynchus mykiss*	Aluminum sulfate	42 hr	25	9	100% dead	50,000	Hunter et al. 1980	Duration; lack of exposure details
Rainbow trout, *Oncorhynchus mykiss*	-		-	5.0	LC50	160	Holtze 1983	pH too low
Rainbow trout, *Oncorhynchus mykiss*	-		-	4.5	LC50	120	Holtze 1983	pH too low

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Rainbow trout (embryo/larvae), *Oncorhynchus mykiss*	Aluminum sulfate	8 d	14.3	6.5	No effect	1,000	Holtze 1983	Duration, lack of exposure details
Rainbow trout (embryo/larvae), *Oncorhynchus mykiss*	Aluminum sulfate	8 d	14.3	7.2	No effect	1,000	Holtze 1983	Duration, lack of exposure details
Rainbow trout (eyed embryo), *Oncorhynchus mykiss*	Aluminum sulfate	8 d	14.3	6.5	14.2% dead	1,000	Holtze 1983	Duration, lack of exposure details
Rainbow trout (eyed embryo), *Oncorhynchus mykiss*	Aluminum sulfate	8 d	14.3	7.2	14.2% dead	1,000	Holtze 1983	Duration, lack of exposure details
Rainbow trout (juvenile, 5-8 cm), *Oncorhynchus mykiss*	Aluminum sulfate	24 hr	-	6	Opercula rate	200-500 (NOEC-LOEC)	Ogilvie and Stechey 1983	Duration, atypical endpoint
Rainbow trout (juvenile, 5-8 cm), *Oncorhynchus mykiss*	Aluminum sulfate	24 hr	-	6	Cough frequency	100-200 (NOEC-LOEC)	Ogilvie and Stechey 1983	Duration, atypical endpoint
Rainbow trout (3.5 g), *Oncorhynchus mykiss*	Aluminum sulfate	6 d	11.2	5.09-5.31	LC50	175	Orr et al. 1986	Duration
Rainbow trout (alevin, 23-26 dph), *Oncorhynchus mykiss*	Aluminum sulfate	6 d	10.3	5.8	LC50	>1,050	Hickie et al. 1993	Duration
Rainbow trout (alevin, 16-19 dph), *Oncorhynchus mykiss*	Aluminum sulfate	6 d	10.3	4.9	LC50	88	Hickie et al. 1993	Duration, pH too low
Rainbow trout (alevin, 23-26 dph), *Oncorhynchus mykiss*	Aluminum sulfate	6 d	10.3	4.9	LC50	91	Hickie et al. 1993	Duration, pH too low
Rainbow trout (92-220 g), *Oncorhynchus mykiss*	-	1 hr	-	5.4	Gill content (50 µg/g)	954	Handy and Eddy 1989	Duration

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Rainbow trout (juvenile, 1-3 g), *Oncorhynchus mykiss*	Aluminum chloride	16 d	20.3	8.3	LC50	1,940	Gundersen et al. 1994	Duration
Rainbow trout (juvenile, 1-3 g), *Oncorhynchus mykiss*	Aluminum chloride	16 d	103.0	8.3	LC50	3,910	Gundersen et al. 1994	Duration
Rainbow trout (embryo), *Oncorhynchus mykiss*	Aluminum chloride	7-12 d	100	7.0-7.8	LC50	560	Birge et al. 2000	Duration
Chinook salmon (juvenile), *Oncorhynchus tshawytscha*	Sodium aluminate	96 hr	28.0	7.00	LC50	>40,000	Peterson et al. 1974	Inappropriate form of toxicant
Atlantic salmon (eggs), *Salmo salar*	Aluminum sulfate	60 d	13.5	5.5	RNA/DNA content	33-264 (NOEC-LOEC)	McKee et al. 1989	Atypical endpoint
Atlantic salmon (>1 yr, 5.9 g), *Salmo salar*	-	7 d	10.4	4.5	LC50	88	Wilkinson et al. 1990	Duration
Atlantic salmon (eggs), *Salmo salar*	Aluminum sulfate	60 d	12.8	5.5	Time to hatch	>264 (NOEC)	Buckler et al. 1995	Atypical endpoint
Atlantic salmon (larva), *Salmo salar*	Aluminum sulfate	60 d	12.8	5.5	Behavior-swimming & feeding activity	<33 (NOEC)	Buckler et al. 1995	Atypical endpoint
Atlantic salmon (juvenile, 1.4 g), *Salmo salar*	Aluminum sulfate	5 d	10.6	4.47	LC50	259	Roy and Campbell 1995	Duration
Atlantic salmon (juvenile, 1.4 g), *Salmo salar*	Aluminum sulfate	5 d	10.6	4.42	LC50	283	Roy and Campbell 1995	Duration
Atlantic salmon (juvenile, 1.4 g), *Salmo salar*	Aluminum sulfate	5 d	10.6	4.83	LC50	121	Roy and Campbell 1995	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Atlantic salmon (juvenile, 1.4 g), *Salmo salar*	Aluminum sulfate	5 d	10.6	5.26	LC50	54	Roy and Campbell 1995	Duration
Atlantic salmon (juvenile, 1.4 g), *Salmo salar*	Aluminum sulfate	5 d	10.6	5.24	LC50	51	Roy and Campbell 1995	Duration
Atlantic salmon (juvenile, 6.8 g), *Salmo salar*	Aluminum sulfate	96 hr	10.6	4.86	LC50	75.54	Roy and Campbell 1995	pH too low
Atlantic salmon (juvenile, 1.8 g), *Salmo salar*	Aluminum sulfate	96 hr	10.6	4.99	LC50	79.60	Roy and Campbell 1997	pH too low
Atlantic salmon (juvenile, 1.8 g), *Salmo salar*	Aluminum sulfate	96 hr	10.6	4.96	LC50	124.1	Roy and Campbell 1997	pH too low
Brook trout (alevins, 23.6 mm, 13.4 mg), *Salvelinus fontinalis*	-	15 min	7.2	6.9	Avoidance	389	Gunn and Noakes 1986	Duration, atypical endpoint
Brook trout (juvenile), *Salvelinus fontinalis*	Aluminum hydroxide	24 d	8-10	4.4	Survival	<200-200 (NOEC-LOEC)	Siddens et al. 1986	Duration
Brook trout (juvenile), *Salvelinus fontinalis*	Aluminum hydroxide	24 d	8-10	4.9	Survival	<200-200 (NOEC-LOEC)	Siddens et al. 1986	Duration
Brook trout (1.5 yr), *Salvelinus fontinalis*	-	147 d	Ca = 8 mg/L	5.2	100% survival	54	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), *Salvelinus fontinalis*	-	147 d	Ca = 8 mg/L	5.2	93% survival	162	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), *Salvelinus fontinalis*	-	147 d	Ca = 8 mg/L	4.8	100% survival	162	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), *Salvelinus fontinalis*	-	147 d	Ca = 8 mg/L	4.8	50% survival	486	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), *Salvelinus fontinalis*	-	147 d	Ca = 0.5 mg/L	5.2	93% survival	54	Mount 1987	Unmeasured chronic exposure

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Brook trout (1.5 yr), *Salvelinus fontinalis*	-	147 d	Ca = 0.5 mg/L	5.2	86% survival	162	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), *Salvelinus fontinalis*	-	147 d	Ca = 0.5 mg/L	4.8	86% survival	162	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), *Salvelinus fontinalis*	-	147 d	Ca = 0.5 mg/L	4.8	36% survival	486	Mount 1987	Unmeasured chronic exposure
Brook trout (eggs), *Salvelinus fontinalis*	Aluminum sulfate	60 d	12.5	5.5	Strike frequency	142-292 (NOEC-LOEC)	Cleveland et al. 1989	Atypical endpoint
Brook trout (eggs), *Salvelinus fontinalis*	Aluminum sulfate	60 d	12.5	6.5	Strike frequency	350->350 (NOEC-LOEC)	Cleveland et al. 1989	Atypical endpoint
Brook trout (1 yr), *Salvelinus fontinalis*	Aluminum chloride	28 d	250	4.4	Survival	131-332 (NOEC-LOEC)	Ingersoll et al. 1990a	Duration; pH too low
Goldfish (60-90 mm), *Carassius auratus*	Aluminum potassium sulfate	96 hr	-	6.8	Reduced survival time	5,700	Ellis 1937	Atypical endpoint; no LC50 reported
Goldfish (eggs), *Carassius auratus*	Aluminum chloride	7 d	195	7.4	EC50 (death and deformity)	150	Birge 1978	Duration
Goldfish (embryo), *Carassius auratus*	Aluminum chloride	7-12 d	100	7.0-7.8	LC50	330	Birge et al. 2000	Duration
Common carp (95 g), *Cyprinus carpio*	Aluminum sulfate	4 hr	-	5.2	Ca 2+ flux	30-100 (NOEC-LOEC)	Verbost et al. 1992	Duration, atypical endpoint
Rio Grande silvery minnow (larva, 3-5 dph), *Hybognathus amarus*	Aluminum chloride	96 hr	140	8.1	EC50 (death and immobility)	>59,100	Buhl 2002	Atypical endpoint
Fathead minnow (juvenile), *Pimephales promelas*	Aluminum sulfate	8 d	220	7.3	LC50	22,400	Kimball 1978	Duration, test species fed

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Fathead minnow (juvenile), *Pimephales promelas*	Aluminum sulfate	96 hr	220	7.34	LC50	35,000	Kimball 1978	Test species fed
Fathead minnow (adult), *Pimephales promelas*	Aluminum chloride	-	-	-	50% reduction in AChE	18,000	Olson and Christensen 1980	Duration unknown, atypical endpoint
Fathead minnow (juvenile, 11 mm), *Pimephales promelas*	Aluminum chloride	96 hr	21.6	5.5	LC50	>50	Palmer et al. 1989	Measured dissolved total Al greater than (unmeasured) nominal total Al.
Fathead minnow (larvae, <24 hr), *Pimephales promelas*	Aluminum chloride	7 d	46	7.5	Growth (weight)	400-740 (NOEC-LOEC)	ENSR 1992a	Duration
Fathead minnow (larvae, <24 hr), *Pimephales promelas*	Aluminum chloride	7 d	194	8.2	Growth (weight)	630-700 (NOEC-LOEC)	ENSR 1992a	Duration
Fathead minnow (≤7 d), *Pimephales promelas*	Aluminum chloride	96 hr	25 (24-26)	8.05 (7.2-8.9)	LC50	1,160	ENSR 1992c	Test species fed
Fathead minnow (≤7 d), *Pimephales promelas*	Aluminum chloride	96 hr	44 (42-46)	8.1 (7.5-8.7)	LC50	8,180	ENSR 1992c	Test species fed
Fathead minnow (≤7 d), *Pimephales promelas*	Aluminum chloride	96 hr	97 (96-98)	8.05 (7.6-8.5)	LC50	20,300	ENSR 1992c	Test species fed
Fathead minnow (≤7 d), *Pimephales promelas*	Aluminum chloride	96 hr	193 (192-194)	8.2 (7.8-8.6)	LC50	44,800	ENSR 1992c	Test species fed
Fathead minnow (larva, 4-6 dph), *Pimephales promelas*	Aluminum chloride	96 hr	140	8.1	EC50 (death and immobility)	>59,100	Buhl 2002	Atypical endpoint
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	12 (DOC = <0.08 mg/L)	6.0	EC20 (mean dry biomass)	127.2	OSU 2012a; Gensemer et al. 2018	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	12 (DOC = 0.92 mg/L)	6.1	EC20 (mean dry biomass)	425.7	OSU 2012a; Gensemer et al. 2018	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	12 (DOC = 1.73 mg/L)	6.1	EC20 (mean dry biomass)	632.8	OSU 2012a; Gensemer et al. 2018	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	16 (DOC = 3.35 mg/L)	6.0	EC20 (mean dry biomass)	828.8	OSU 2012a; Gensemer et al. 2018	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	24 (DOC = 0.19 mg/L)	6.1	EC20 (mean dry biomass)	135.8	OSU 2012a; Gensemer et al. 2018	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	60 (DOC = 0.22 mg/L)	6.0	EC20 (mean dry biomass)	314.3	OSU 2012a; Gensemer et al. 2018	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	60 (DOC = 0.86 mg/L)	6.1	EC20 (mean dry biomass)	633.9	OSU 2012a; Gensemer et al. 2018	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	56 (DOC = 1.74 mg/L)	6.0	EC20 (mean dry biomass)	1,325.8	OSU 2012a; Gensemer et al. 2018	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	60 (DOC = 3.51 mg/L)	6.0	EC20 (mean dry biomass)	2,523	OSU 2012a; Gensemer et al. 2018	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	116 (DOC = 0.088 mg/L)	6.1	EC20 (mean dry biomass)	624.1	OSU 2012a; Gensemer et al. 2018	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	116 (DOC = 0.88 mg/L)	6.1	EC20 (mean dry biomass)	773.4	OSU 2012a; Gensemer et al. 2018	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	108 (DOC = 1.56 mg/L)	6.0	EC20 (mean dry biomass)	1,493.7	OSU 2012a; Gensemer et al. 2018	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	112 (DOC = 3.27 mg/L)	6.0	EC20 (mean dry biomass)	2,938	OSU 2012a; Gensemer et al. 2018	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	134 (DOC = 7.0 mg/L)	6.0	EC20 (mean dry biomass)	4,618	OSU 2018b	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	131 (DOC = 11.5 mg/L)	6.0	EC20 (mean dry biomass)	9,511	OSU 2018b	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	422 (DOC = 1.1 mg/L)	6.8	EC20 (mean dry biomass)	2,969	OSU 2018b	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	135 (DOC = 7.2 mg/L)	7.0	EC20 (mean dry biomass)	8,047	OSU 2018b	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	125 (DOC = 11.6 mg/L)	7.0	EC20 (mean dry biomass)	12,542	OSU 2018b	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	288 (DOC = 1.1 mg/L)	8.1	EC20 (mean dry biomass)	5,634	OSU 2018b	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	396 (DOC = 1.6 mg/L)	8.1	EC20 (mean dry biomass)	13,274	OSU 2018b	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	49 (DOC = 0.8 mg/L)	6.1	EC20 (mean dry biomass)	885	OSU 2018d	Duration
Fathead minnow (larva, <24 hr), *Pimephales promelas*	Aluminum nitrate	7 d	94 (DOC = 1.6 mg/L)	6.0	EC20 (mean dry biomass)	1,817	OSU 2018d	Duration
Zebrafish (egg, 1 d), *Danio rerio*	Aluminum chloride	24 hr	40	5	Median day to hatch	16,400 (NOEC)	Dave 1985	Duration

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Zebrafish (egg, 1 d), *Danio rerio*	Aluminum chloride	24 hr	40	6	Median day to hatch	16,400 (NOEC)	Dave 1985	Duration
Zebrafish (egg, 1 d), *Danio rerio*	Aluminum chloride	24 hr	40	7	Median day to hatch	16,400 (NOEC)	Dave 1985	Duration
Zebrafish (egg, 1 d), *Danio rerio*	Aluminum chloride	24 hr	40	8	Median day to hatch	16,400 (NOEC)	Dave 1985	Duration
Zebrafish (egg, 1 d), *Danio rerio*	Aluminum chloride	24 hr	40	9	Median survival time	<500-500 (NOEC-LOEC)	Dave 1985	Duration
Zebrafish (larva, 7-8 d), *Danio rerio*	Aluminum chloride	48 hr	40	7	LC50	106,000	Dave 1985	Duration
Zebrafish (larva, 7-8 d), *Danio rerio*	Aluminum chloride	48 hr	40	7.4-7.9	LC50	80,000	Dave 1985	Duration
Zebrafish (3 cm, 5g), *Danio rerio*	Aluminum chloride	4 d	-	-	LC50	56,920	Anandhan and Hemalatha 2009	Lack of exposure details (assumed fed too)
Zebrafish (adult, female), *Danio rerio*	Aluminum chloride	48 hr	142	8.2	LC50	>7,920	Griffitt et al. 2008	Duration
Zebrafish (fry, <24 hr), *Danio rerio*	Aluminum chloride	48 hr	142	8.2	LC50	>10,000	Griffitt et al. 2008	Duration
Zebrafish (adult, female), *Danio rerio*	Aluminum chloride	48 hr	142	6.8	100% mortality	12,500	Griffitt et al. 2011	Duration
Zebrafish (adult, female), *Danio rerio*	Aluminum chloride	48 hr	142	6.8	No mortality	5,000	Griffitt et al. 2011	Duration
Smallmouth bass (eyed egg), *Micropterus dolomieu*	F, M	11 d	15.7	4.8	Survival	100-200 (NOEC-LOEC)	Holtze and Hutchinson 1989	Duration; pH too low
Largemouth bass (juvenile), *Micropterus salmoides*	Aluminum sulfate	7 d	64-80	6.6-7.4	0% dead	50,000	Sanborn 1945	Duration
Largemouth bass (eggs/fry), *Micropterus salmoides*	Aluminum chloride	8 d	93-105	7.2-7.8	LC50	170	Birge et al. 1978	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Largemouth bass (embryo), *Micropterus salmoides*	Aluminum chloride	7-12 d	100	7.0-7.8	LC50	190	Birge et al. 2000	Duration
Striped bass (160 d), *Morone saxatilis*	Aluminum sulfate	7 d	12.5-12.8	7.2	Survival	174-348.8 (NOEC-LOEC)	Buckler et al. Manuscript, 1987	Duration
Striped bass (160 d), *Morone saxatilis*	Aluminum sulfate	7 d	12.5-12.8	6.5	Survival	87.2-174.4 (NOEC-LOEC)	Buckler et al. Manuscript, 1987	Duration
Striped bass (160 d), *Morone saxatilis*	Aluminum sulfate	7 d	12.5-12.8	6	Survival	21.8-43.6 (NOEC-LOEC)	Buckler et al. Manuscript, 1987	Duration
Pike (yolk-sac fry), *Esox lucius*	Aluminum sulfate	10 d	18	4	LC50	~160	Vuorinen et al. 1993	Duration, pH too low
Pike (yolk-sac fry), *Esox lucius*	Aluminum sulfate	10 d	18	4.25	LC50	~325	Vuorinen et al. 1993	Duration, pH too low
Pike (yolk-sac fry), *Esox lucius*	Aluminum sulfate	10 d	18	4.5	LC50	~600	Vuorinen et al. 1993	Duration, pH too low
Pike (yolk-sac fry), *Esox lucius*	Aluminum sulfate	10 d	18	4.75	LC50	~1,000	Vuorinen et al. 1993	Duration, pH too low
White sucker (eyed egg), *Catostomus commersoni*	-	96 hr	15.7	4.8	Survival	100-200 (NOEC-LOEC)	Holtze and Hutchinson 1989	Atypical endpoint; pH too low
Lake whitefish (cleavage egg), *Coregonus clupeaformis*	-	12 d	15.7	4.8	Survival	300 (NOEC)	Holtze and Hutchinson 1989	Duration; pH too low
Bullfrog (embryo), *Rana catesbeiana*	Aluminum chloride	10-12 d	100	7.0-7.8	LC50	80	Birge et al. 2000	Duration
Leopard frog (embryo, 3 hr, Gosner stage 3-4), *Rana pipiens*	Aluminum chloride	4-5 d	2.0	4.6	LC50	811	Freda and McDonald 1990	pH too low

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Leopard frog (embryo, 3 hr, Gosner stage 3-4), *Rana pipiens*	Aluminum chloride	4-5 d	2.0	4.8	LC50	403	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, Gosner stage 20), *Rana pipiens*	Aluminum chloride	96 hr	2.0	4.4	LC50	>250	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, Gosner stage 20), *Rana pipiens*	Aluminum chloride	96 hr	2.0	4.6	LC50	>250	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, 3 wk), *Rana pipiens*	Aluminum chloride	96 hr	2.0	4.2	LC50	>1,000	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, 3 wk), *Rana pipiens*	Aluminum chloride	96 hr	2.0	4.4	LC50	>1,000	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, 3 wk), *Rana pipiens*	Aluminum chloride	96 hr	2.0	4.6	LC50	>1,000	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, 3 wk), *Rana pipiens*	Aluminum chloride	96 hr	2.0	4.8	LC50	>1,000	Freda and McDonald 1990	pH too low
Leopard frog (embryos), *Rana pipiens*	Aluminum chloride	96 hr	2.0	4.8	LC50	471	Freda et al. 1990	pH too low
Leopard frog (embryo), *Rana pipiens*	Aluminum chloride	10-11 d	100	7.0-7.8	LC50	90	Birge et al. 2000	Duration
Wood frog (eggs), *Rana sylvatica*	-	24 hr	7.78	5.75	Hatch success	20->20 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
Wood frog (eggs), *Rana sylvatica*	-	24 hr	7.78	4.75	Hatch success	100->100 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
Wood frog (eggs), *Rana sylvatica*	-	24 hr	7.78	4.415	Hatch success	10-20 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
Wood frog (eggs), *Rana sylvatica*	-	24 hr	7.78	4.14-5.75	Survival	200 (NOEC)	Clark and LaZerte 1985	Duration

Species	**Chemical**	**Duration**	**Total Hardness (mg/L as $CaCO_3$)**	**pH**	**Effect**	**Concentration (µg/L)**	**Reference**	**Reason Other Data**
Wood frog (larva, Gosner stage 25), *Rana sylvatica*	Aluminum sulfate	43-102 d	109.9-119.5	4.68-4.70	Survival and growth	2,000 (NOEC)	Peles 2013	pH too low
Spring peeper (embryo), *Pseudacris crucifer*	Aluminum chloride	7 d	100	7.0-7.8	LC50	90	Birge et al. 2000	Duration
Green tree frog (tadpole), *Hyla cinerea*	Aluminum chloride	96 hr	1.5	5.5	Growth	<150-150 (NOEC-LOEC)	Jung and Jagoe 1995	Atypical endpoint
Green tree frog (tadpole), *Hyla cinerea*	Aluminum chloride	96 hr	1.5	4.5	Growth	<150-150 (NOEC-LOEC)	Jung and Jagoe 1995	Atypical endpoint
Green tree frog (tadpole), *Hyla cinerea*	Aluminum chloride	96 hr	1.5	4.5	LC50	277	Jung and Jagoe 1995	pH too low
American toad (eggs), *Bufo americanus*	-	24 hr	7.78	5.75	Hatch success	20->20 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
American toad (eggs), *Bufo americanus*	-	24 hr	7.78	4.75	Hatch success	100->100 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
American toad (eggs), *Bufo americanus*	-	24 hr	7.78	4.14	Hatch success	5-10 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
American toad (eggs), *Bufo americanus*	-	24 hr	7.78	4.14	Hatch success	<10-10 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
American toad (eggs), *Bufo americanus*	-	24 hr	7.78	4.14-5.75	NOEC (survival)	200	Clark and LaZerte 1985	Duration
American toad (tadpoles, Gosner stage 26), *Bufo americanus*	Aluminum chloride	96 hr	2.0	4.5	LC50	672	Freda et al. 1990	pH too low
Common toad (spawn, 0-48 hr), *Bufo bufo*	Aluminum nitrate	7 d	50	6.0	Survival	>320 (NOEC)	Gardner et al. 2002	Duration
Common toad (spawn, 0-48 hr), *Bufo bufo*	Aluminum nitrate	7 d	50	7.5	Survival	>320 (NOEC)	Gardner et al. 2002	Duration

Species	Chemical	Duration	Total Hardness (mg/L as $CaCO_3$)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Fowler's toad (embryo), *Bufo fowleri*	Aluminum chloride	7 d	100	7.0-7.8	LC50	280	Birge et al. 2000	Duration
Narrow-mouthed toad (eggs), *Gastrophryne carolinensis*	Aluminum chloride	7 d	195	7.4	EC50 (death and deformity)	50	Birge 1978	Duration
Narrow-mouthed toad (eggs), *Gastrophryne carolinensis*	Aluminum chloride	7 d	100	7.0-7.8	LC50	50	Birge et al. 2000	Duration
Marbled salamander (eggs), *Ambystoma opacum*	Aluminum chloride	8 d	93-105	7.2-7.8	EC50 (death and deformity)	2,280	Birge et al. 1978	Duration
Marbled salamander (embryo), *Ambystoma opacum*	Aluminum chloride	9-10 d	100	7.0-7.8	LC50	2,280	Birge et al. 2000	Duration

Appendix I OTHER DATA ON EFFECTS OF ALUMINUM TO ESTUARINE/MARINE AQUATIC ORGANISMS

Appendix I. Other Data on Effects of Aluminum to Estuarine/Marine Aquatic Organisms

Species	Chemical	Duration	Salinity (g/kg)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Estuarine/Marine Species								
Phytoplankton, *Dunaliella tertiolecta*	Aluminum nitrate	72 hr	-	8.2	IC25 (inhibit growth)	18,160	Sacan et al. 2007	Duration
Phytoplankton, *Dunaliella tertiolecta*	Aluminum nitrate	72 hr	-	8.2	SC20 (stimulate growth)	4,660	Sacan et al. 2007	Duration
Diatom, *Nitzschia closterium*	Aluminum chloride	72 hr	-	8.2	IC50 (growth rate)	190	Harford et al. 2011	Duration
Polychaete worm, *Ctenodrilus serratus*	Aluminum chloride	21 d	-	7.6-8	Reproduction	20-40 (NOEC-LOEC)	Petrich and Reish 1979	Unmeasured chronic exposure
Sea urchin (embryo), *Paracentrotus lividus*	Aluminum sulfate	72 hr	-	-	69.7% developmental effects	539.6	Caplat et al. 2010	Difficult to determine effect concentration
Bay mussel (28.0 mm), *Mytilus edulis*	Alum (potassium)	24 hr	30	4.4-7.3	LC50	>6,400,000	Robinson and Perkins 1977	Duration
Common winkle (13.3 mm), *Littorina littorea*	Alum (potassium)	24 hr	30	4.4-7.3	LC50	>6,400,000	Robinson and Perkins 1977	Duration
European shore crab (12.6 mm), *Carcinus maenas*	Alum (potassium)	24 hr	30	4.4-7.3	LC50	2,500,000	Robinson and Perkins 1977	Duration
Hermit crab (11.4 mm), *Eupagurus bernhardus*	Alum (potassium)	24 hr	30	4.4-7.3	LC50	250,000	Robinson and Perkins 1977	Duration

Species	Chemical	Duration	Salinity (g/kg)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Yellow crab (embryo, 4-lobed stage), *Cancer anthonyi*	-	7 d	34	7.8	Survival	<10,000-10,000 (NOEC-LOEC)	MacDonald et al. 1988	Duration, unmeasured chronic exposure
Yellow crab (embryo, 4-lobed stage), *Cancer anthonyi*	-	7 d	34	7.8	Hatching of embryos	<10,000-10,000 (NOEC-LOEC)	MacDonald et al. 1988	Duration, unmeasured chronic exposure
Daggerblade grass shrimp (embryo, 3 d), *Palaemonetes pugio*	-	12 d	20	7.6-8.1	LC50	1,079	Rayburn and Aladdin 2003	Duration

Appendix J LIST OF ALUMINUM STUDIES NOT USED IN DOCUMENT ALONG WITH REASONS

Appendix J. List of Aluminum Studies Not Used in Document Along with Reasons

Author	Title	Date	Organism(s)	Concentration (μg/L)	Reason Unused
Aarab et al.	Histopathology alterations and histochemistry measurements in mussel, *Mytilus edulis* collected offshore from an aluminum smelter industry (Norway)	2008	Bay mussel, *Mytilus edulis*	-	Not applicable; no aluminum toxicity data
Abdelhamid and El-Ayouty	Effect of catfish (*Clarias lazera*) composition of ingestion rearing water contaminated with lead or aluminum compounds	1991	Catfish, *Clarias lazera*	6 wk 50,000 0.33 corrected mortality	Not North American species; dilution water not characterized
Abdel-Latif	The influence of calcium and sodium on aluminum toxicity in Nile tilapia (*Oreochromis niloticus*)	2008	Nile tilapia, *Oreochromis niloticus*	96 hr LC50=175.9	Dilution water not characterized; lack of exposure details
Abraham et al.	Quantified elemental changes in *Aspidisca cicada* and *Vorticella convallaria* after exposure to aluminum, copper, and zinc	1997	Protozoa, *Aspidisca cicada* Protozoa, *Vorticella convallaria*	-	Mixture
Adokoh et al.	Statistical evaluation of environmental contamination, distribution and source assessment of heavy metals (aluminum, arsenic, cadmium, and mercury) in some lagoons and an estuary along the coastal belt of Ghana	2011	-	-	Survey
Ahsan et al.	Comparative proteomic study of arsenic-induced differentially expressed proteins in rice roots reveals glutathione plays a central role during As stress	2008	-	-	Not applicable; no aluminum toxicity data
Al-Aarajy and Al-Saadi	Effect of heavy metals on physiological and biochemical features of *Anabaena cylindrica*	1998	Blue-green alga, *Anabaena cylindrica*	-	Only one exposure concentration; lack of exposure details (duration not reported)
Alessa and Oliveira	Aluminum toxicity studies in *Vaucheria longicaulis* var. *macounii* (Xanthophyta, Tribophyceae). I. Effects on cytoplasmic organization	2001a	Alga, *Vaucheria longicaulis* var. m*acouni*	10 hr 2,159 growth ceased	Only one exposure concentration
Alessa and Oliveira	Aluminum toxicity studies in *Vaucheria longicaulis* var. *macounii* (Xanthophyta, Tribophyceae). II. Effects on the F-Actin array	2001b	Alga, *Vaucheria longicaulis* var. m*acouni*	-	Lack of exposure details; dilution water not characterized; only one exposure concentration
Allin and Wilson	Behavioural and metabolic effects of chronic exposure to sublethal aluminum in acidic soft water in juvenile rainbow trout (*Oncorhynchus mykiss*)	1999	Rainbow trout, *Oncorhynchus mykiss*	6 wk 29.2 Reduced appetite	Only one exposure concentration

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Allin and Wilson	Effects of pre-acclimation to aluminum on the physiology and swimming behaviour of juvenile rainbow trout (*Oncorhynchus mykiss*) during a pulsed exposure	2000	Rainbow trout, *Oncorhynchus mykiss*	-	Pulsed exposures to pollutant
Alquezar et al.	Metal accumulation in the smooth toadfish, *Tetractenos glaber*, in estuaries around Sydney, Australia	2006	Toadfish, *Tetractenos glaber*	-	Not North American species; exposed to mixture
Alstad et al.	The significance of water ionic strength on aluminum in brown trout (*Salmo trutta* L.)	2005	Brown trout, *Salmo trutta*	650 Survival time =16-34 hr	No acclimation to test water; only one exposure concentration
Amato et al.	Concentrations, sources and geochemistry of airborne participate matter at a major European airport	2010	-	-	Not applicable; no aluminum toxicity data
Amenu	A comparative study of water quality conditions between heavily urbanized and less urbanized watersheds of Los Angeles Basin	2011	-	-	Not applicable; no aluminum toxicity data
Anderson	The apparent thresholds of toxicity to *Daphnia magna* for chlorides of various metals when added to Lake Erie water	1948	Cladoceran, *Daphnia magna*	64 hr 6,700 LOEC (mortality)	Lack of exposure details; control data not reported
Andersson	Toxicity and tolerance of aluminum in vascular plants	1988	-	-	Review
Andren and Rydin	Toxicity of inorganic aluminum at spring snowmelt-in-stream bioassays with brown trout (*Salmo trutta* L.)	2012	Brown trout, *Salmo trutta*	-	Mixture; dilution water is river water
Andren et al.	Effects of pH and aluminum on embryonic and early larval stages of Swedish brown frogs Rana arvalis, R. temporaria and R. dalmatina	1988	Brown frog, *Rana arvalis* Brown frog, *Rana temporaria* Brown frog, *Rana dalmatina*	15 d NOEC (mortality) =800, 800, & <800, respectively	Not North American species
Andrews et al.	Selected metals in sediments and streams in the Oklahoma part of the Tri-State Mining District, 2000-2006	2009	-	-	Survey
Annicchiarico et al.	PCBs, PAHs and metal contamination and quality index in marine sediments of the Taranto Gulf	2011	-	-	Survey; sediment

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Appelberg	Changes in haemolymph ion concentrations of *Astacus astacus* L. and *Pacifastacus leniusclus* (Dana) after exposure to low pH and aluminium	1985	Signal crayfish, *Pacifastacus leniusculus*	14 d 250 Decrease Na^+ haemolymph concentrations	Too few organisms per treatment (4 per treatmen); only 3 exposure concentrations
Arain et al.	Total dissolved and bioavailable elements in water and sediment samples and their accumulation in *Oreochromis mossambicus* of polluted Manchar Lake	2008	Mozambique tilapia, *Oreochromis mossambicus*	-	Survey
Arenhart et al.	Involvement of ASR genes in aluminium tolerance mechanisms in rice	2013	Rice	-	Scientific name not given
Arthur D. Little Inc.	Water quality criteria data book, volume 2; Inorganic chemical pollution of freshwater	1971	-	-	Review; results of previously published papers
AScI Corp.	Aluminum water-effect ratio for the 3M Middleway plant effluent discharge, Middleway, West virginia	1994	Cladoceran, *Daphnia magna* Rainbow trout, *Oncorhynchus mykiss*	-	Mixture
AScI Corp.	Aluminum water-effect ratio for Georgia-Pacific Corporation Woodland, Maine; Pulp and paper operations discharge and St. Croix River	1996	-	-	Review; results of previously published papers
Atland	Behavioural responses of brown trout, *Salmo trutta*, juveniles in concentration gradients of pH and Al - a laboratory study	1998	Atlantic salmon, *Salmo salar*	1 hr 200=avoidance, 70=no avoidance	Only two exposure concentrations
Atland and Barlaup	Avoidance behaviour of Atlantic salmo (*Salmo salar* L.) fry in waters of low pH and elevated aluminum concentration: laboratory experiments	1996	Atlantic salmon, *Salmo salar*	1 hr LC20=85, LC40=160	Only two exposure concentrations
Avis et al.`	Ultrastructural alterations in *Fusarium sambucinum* and *Heterobasidion annosum* treated with aluminum chloride and sodium metabisulfite	2009	Fungus, *Fusarium sambucinum* Fungus, *Heterobasidion annosum*	60 min LOEC (dead conidia) =269,880 for both species	Only two exposure concentrations
Baba and Gunduz	Effect of alteration zones on water quality: a case study from Biga Peninsula, Turkey	2010	-	-	Survey
Bailey et al.	Application of toxicity identification procedures to the echinoderm fertilization assay to identify toxicity in a municipal effluent	1995	Sand dollar, *Dendraster excentricus* Purple urchin, *Stronglocentrotus purpuratus*	-	Mixture; effluent

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Baker	Aluminum toxicity to fish as related to acid precipitation and Adirondack surface water quality	1981	Brook trout, *Salvelinus fontinalis* White sucker, *Catostomus commersoni*	14 d 46.7% survival=180, 43.4% survival=110	Only two exposure concentrations
Baker	Effects on fish metals associated with acidification	1982	-	-	Review; results of previously published papers
Baker and Schofield	Aluminum toxicity to fish in acidic waters	1982	-	-	Only two exposure concentrations; review of Baker 1982
Baldigo and Murdoch	Effect of stream acidification and inorganic aluminum on mortality of brook trout (Salvelinus fontinalis) in the Catskill Mountains, New York	1997	Brook trout, *Salvelinus fontinalis*	-	Mixture; fluctuating Catskill mountain stream chemical exposure
Ball et al.	Water-chemistry data for selected springs, geysers, and streams in Yellowstone National Park, Wyoming, 2006-2008	2010	-	-	Survey; occurrence
Ballance et al.	Influence of sediment biofilm on the behaviour of aluminum and its bioavailability to the snail *Lymnaea stagnalis* in neutral freshwater	2001	Snail, *Lymnaea stagnalis*	-	Not applicable; no aluminum toxicity data
Barbiero et al.	The effects of a continuous application of aluminum sulfate on lotic benthic invertebrates	1988	-	-	Exposure concentration not known; field dosing of Al sulfate to a reservoir
Barbour and Paul	Adding value to water resource management through biological assessment of rivers	2010	-	-	Not applicable; no aluminum toxicity data
Barcarolli and Martinez	Effects of aluminum in acidic water on hematological and physiological parameters of the neotropical fish *Leporinus macrocephalus* (Anostomidae)	2004	Neotropical fish, *Leporinus macrocephalus*	24 hr 15 Increase hematocrit %; decrease plasma Na, Cl; Increase plasma glucose	Not North American species; only one exposure concentration
Bargagli	Environmental contamination in Antarctic ecosystems	2008	-	-	Survey; occurrence
Barnes	The determination of specific forms of aluminum in natural water	1975	-	-	Not applicable; no aluminum toxicity data
Battram	The effects of aluminum and low pH on chloride fluxes in the brown trout, *Salmo trutta* L.	1988	Brown trout, *Salmo trutta*	-	Acclimation too short; too few organisms per concentration
Beattie and Tyler-Jones	The effects of low pH and aluminum on breeding success in the frog *Rana temporaria*	1992	European common frog, *Rana temporaria*	-	Not North American species; only 3 exposure concentrations

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Beattie et al.	The effects of pH, aluminum concentration and temperature on the embryonic development of the European common frog, *Rana temporaria*	1992	European common frog, *Rana temporaria*	-	Not North American species; cannot determine effect concentration; dose-response not well defined
Becker and Keller	The effects of iron and sulfate compounds on the growth of *Chlorella*	1973	Green alga, *Chlorella vulgaris*	30 d 163,972 Reduced growth	Too few exposure concentrations, lack of exposure details
Belabed et al.	Evaluation de la toxicite de quelques metaux lourds a l'aide du test daphnie	1994	-	-	Text in foreign language
Berg	Aluminum and manganese toxicities in acid coal mine wastes	1978	-	-	Review; results of previously published papers
Berg and Burns	The distribution of aluminum in the tissues of three fish species	1985	Channel catfish, *Ictalurus punctatus* Largemouth bass, *Micropterus salmoides* Gizzard shad, *Dorosoma cepedianum*	-	Exposure concentration not known; field accumulation study
Bergman	Development of biologically relevant methods for determination of bioavailable aluminum in surface waters	1992	Rainbow trout, *Oncorhynchus mykiss* Brook trout, *Salvelinus fontinalis*	-	Mixture; Al and organic acids
Bergman and Mattice	Lake acidification and fisheries project: adult brook trout (*Salvelinus fontinalis*) early life stages	1990	Brook trout, *Salvelinus fontinalis*	-	Review; results of previously published papers
Bergman et al.	Lake acidification and fisheries project: adult brook trout (*Salvelinus fontinalis*)	1988	Brook trout, *Salvelinus fontinalis*	-	Review; results of previously published papers
Berntssen et al.	Responses of skin mucous cells to aluminum exposure at low pH in Atlantic salmon (*Salmo salar*) smolts	1997	Atlantic salmon, *Salmo salar*	55.6, LT50=>80 hr, 91.0, LT50= 29 hr	Dilution water not characterized; not true control group
Bervoets et al.	Use of transplanted zebra mussels (*Dreissena polymorpha*) to assess the bioavailability of microcontaminants in Flemish surface waters	2005	Zebra mussel, *Dreissena polymorpha*	-	Exposure concentration not known; mixture; field accumulation study
Bexfield et al.	Potential chemical effects of changes in the source of water supply for the Albuquerque Bernalillo County Water Utility Authority	2008	-	-	Not applicable; no aluminum toxicity data
Birge et al.	Evaluation of aquatic pollutants using fish and amphibian eggs as bioassy organisms	1979	-	-	Results of previously published papers; review of Birge 1978
Birge et al.	Aquatic toxicity tests on inorganic elements occurring in oil shale	1980	-	-	Results of previously published papers; review of Birge 1978

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Birge et al.	The reproductive toxicology of aquatic contaminants	1981	-	-	Review; results of previously published papers
Birge et al.	Effects of chemical stresses on behavior of larval and juvenile fishes and amphibians	1993	Fathead minnow, *Pimephales promelas*	50 Reduced feeding	Only two exposure concentrations
Bjerknes et al.	Aluminum in acidic river water causes mortality of farmed Atlantic salmon (*Salmo salar* L.) in Norwegian fjords	2003	Atlantic salmon, *Salmo salar*	-	Exposure concentration not known; field study with run-off to fjord-based farms
Boniardi et al.	Effect of dissolved metals on the organic load removal efficiency of Lemna gibba	1999	Duckweed, *Lemna gibba*	7 d NOEC(growth)= >29,000	Excessive EDTA used (>200 µg/L)
Booth et al.	Effects of aluminum and low pH on net ion fluxes and ion balance in the brook trout (*Salvelinus fontinalis*)	1988	Brook trout, *Salvelinus fontinalis*	-	Mixture; low pH and Al
Bowry	Relative toxicity of different fumigants against the adults of lesser grain borer *Rhizopertha dominica* Fabr. and rice moth *Corcyra cephalonica* Staint	1985	-	-	Not applicable; terrestrial species
Bradford et al.	Effects of low pH and aluminum on two declining species of amphibians in the Sierra Nevada, California	1992	Mountain yellow-legged frog, *Rana muscosa* Yosemite toad, *Bufo canorus*	No effect on hatch time or growth at 75; Effect on hatch time and decrease growth at 75	Only one exposure concentration
Bradford et al.	Effects of low pH and aluminum on amphibians at high elevation in the Sierra Nevada, California	1994	Pacific chorus frog, *Pseudacris regilla* Long-toed salamander, *Ambystoma macrodactylum*	-	Only one exposure concentration at each pH level
Brady and Griffiths	Effects of pH and aluminum on the growth and feeding behaviour of smooth and palmate newt larvae	1995	Newt, *Triturus helveticus* Newt, *Triturus vulgaris*	14 d Reduce growth for both species at 222 and pH=7.0	Only one exposure concentration
Brodeur et al.	Increase of heart rate without elevation of cardiac output in adult Atlantic salmon (*Salmo salar*) exposed to acidic water and aluminum	1999	Atlantic salmon, *Salmo salar*	-	Mixture; dilution water is river water
Brodeur et al.	Effects of subchronic exposure to aluminum in acidic water on bioenergetics of Atlantic salmon (*Salmo salar*)	2001	Atlantic salmon, *Salmo salar*	36 d Decrease growth, but not food consumption at 50	Only one exposure concentration

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Brown	The effects of various cations on the survival of brown trout, *Salmo trutta* at low pHs	1981a	Brown trout, *Salmo trutta*	18 d Increase survival time at 250	Only two exposure concentrations
Brown	Effect of calcium and aluminum concentrations on the survival of brown trout (*Salmo trutta*) at low pH	1983	Brown trout, *Salmo trutta*	16 d 30% survival at 500 (Ca=2 mg/L); 0% survival at 500 (Ca=0.25 mg/L)	Only two exposure concentrations
Brown and Bruland	Dissolved and particulate aluminum in the Columbia River and coastal waters of Oregon and Washington: behavior in near-field and far-field plumes	2009	-	-	Survey; occurrence
Brown et al.	Report on a large fish kill resulting from natural acid water conditions in Australia	1983	-	-	Mixture; Al and low pH
Brown et al.	Effects of low ambient pH and aluminum on plasma kinetics of cortisol, T3, and T4 in rainbow trout (*Oncorhynchus mykiss*)	1990	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Brown et al.	Contaminant effects on the tleost fish thyroid	2004	-	-	Review; results of previously published papers
Brumbaugh and Kane	Variability of aluminum concentrations in organs and whole bodies of smallmouth bass (*Micropterus dolomieui*)	1985	Smallmouth bass, *Micropterus dolomieui*	-	Exposure concentration not known; field accumulation study
Budambula and Mwachiro	Metal status of Nairobo river waters and their bioaccumulation in *Labeo cylindricus*	2006	Fish, *Labeo cylindricus*	-	Not North American species; exposure concentration not known; field accumulation study
Buergel and Soltero	The distribution and accumulation of aluminum in rainbow trout following a whole-lake alum treatment	1983	-	-	Exposure concentration not known; field accumulation study
Burrows	Aquatic aluminum: chemistry, toxicology, and environmental prevalence	1977	-	-	Review; results of previously published papers

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Burton and Allan	Influence of pH, aluminum, and organic matter on stream invertebrates	1986	Stonefly, *Nemoura sp.* Isopod, *Asellus intermedius* Snail, *Physella heterostropha* Caddisfly, *Lepidostoma liba* Caddisfly, *Pycnopsyche guttifer*	28 d 35% survival at 500; 20% survival at 500; 55% survival at 500; 50% survival at 500; 70% survival at 500	Only two exposure concentrations
Cai et al.	Developmental characteristics and aluminum resistance of root border cells in rice seedlings	2011	Rice, *Oryza sativa*	-	Dilution water is distilled water
Calevro et al.	Toxic effects of aluminum, chromium and cadmium in intact and regenerating freshwater planarians	1998a	Planarian, *Dugesia etrusca*	15 d NOEC (mortality) =250; LOEC=500	Not North American species
Calevro et al.	Tests of toxicity and teratogenicity in biphasic vertebrates treated with heavy metals (Cr3+, Al3+, Cd2+)	1998b	Newt, *Triturus vulgaris meridionalis* Frog, *Rana esculenta*	170 hr NOEC (embryo development)=404.7; 120 hr NOEC (embryo development)=404.7	Not North American species, unmeasured chronic exposure
Calevro et al.	Bioassays for testing effects of Al, Cr and Cd using development in the amphibian *Pleurodeles waltl* and regeneration in the planarian *Dugesia etrusca*	1999	Planarian, *Dugesia etrusca*	14 d 100% mortality at 13,490 NOEC (regeneration)=1,349	Not North American species
Camargo et al.	Osmo-ionic alterations in a neotropical fish acutely exposed to aluminum	2007	Neotropical fish, *Prochilodus lineatus*	-	Not North American species; lack of exposure details; only one exposure concentration; abstract only
Camargo et al.	How aluminum exposure promotes osmoregulatory disturbances in the neotropical freshwater fish *Prochilus lineatus*	2009	Neotropical fish, *Prochilodus lineatus*	96 hr Increase hemoglobin; increase hematocrit %; decrease plasma ions and osmolarity at 438	Not North American species; only one exposure concentration
Camilleri et al.	Silica reduces the toxicity of aluminum to a Tropical Freshwater Fish (*Mogurnda mogurnda*)	2003	Australian spotted gudgeon, *Mogurnda mogurnda*	96 hr LC50=374; LC50=547	Not North American species

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Campbell et al.	Effect of aluminum and silica acid on the behavior of the freshwater snail *Lymnaea stagnalis*	2000	Snail, *Lymnaea stagnalis*	7 d Reduce behavioral state score (BSS) at 500	Only two exposure concentrations
Capdevielle and Scanes	Effect of dietary acid or aluminum on growth and growth-related hormones in mallard ducklings (*Anas platyrhynchos*)	1995	Mallard duck, *Anas platyrhynchos*	-	Dietary exposure; only two exposure concentrations
Capdevielle et al.	Aluminum and acid effects on calcium and phosphorus metabolism in young growing chickens (*Gallus gallus domesticus*) and mallard ducks (*Anas platyrhynchos*)	1998	Mallard duck, *Anas platyrhynchos*	-	Dietary exposure; only two exposure concentrations
Carballeira et al.	Biomonitoring of sporadic acidification of rivers on the basis of release of preloaded cadmium from the aquatic bryophyte *Fontinalis antipyretica* Hedw	2001	Bryophyte, *Fontinalis antipyretica*	-	Mixture; species prior exposed to Cd
Cardwell et al.	Toxic substances and water quality effects on larval marine organisms, technical report no. 45	1979	-	-	Not applicable; no aluminum toxicity data
Carter and Porter	Trace-element accumulation by *Hygrohypnum ochraceum* in the Upper Rio Grande Basin, Colorado and New Mexico, USA	1997	Bryophyte, *Hygrohypnum ochraceum*	-	Exposure concentration not known (not measured over time); field exposure with transplanted plants
Chakravorty et al.	Primary and secondary stress response of *Channa punctatus* to sublethal aluminium toxicity	2012	Snakehead catfish, *Channa punctatus*	96 hr LC50=220,000	Not North American species
Chamier and Tipping	Effects of aluminum in acid streams on growth and sporulation of aquatic hyphomycetes	1997	Fungi, *Tricladium splendens* Fungi, *Alatospora constricta* Fungi, *Varicosporium elodea*	-	Mixture; low pH and Al
Chang et al.	Response of the mussel *Anadonta grandi* to acid and aluminum. Comparison of blodd ions from laboratory and field results	1988	Mussel, *Anadonta grandi*	-	Mixture; aluminum sulphate added to a lake
Chapman et al.	Concentration factors of chemical elements in edible aquatic organisms	1968	-	-	Review; results of previously published papers
Chapman et al.	Why fish mortality in bioassays with aluminum reduction plant wastes don't always indicate chemical toxicity	1987	-	-	Not applicable; no aluminum toxicity data
Chen	Ecological risk assessment for aquatic species exposed to contaminants in Kelung River, Taiwan	2005	-	-	Not applicable; occurrence; no aluminum toxicity data

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Chen et al.	Environmental factors affecting settlement of quagga mussel (*Dreissena rostriformis bugensis*) veligers in Lake Mead, Nevada-Arizona, USA	2011	Quagga mussel, *Dreissena rostriformis bugensis*	-	Not applicable; no aluminum toxicity data
Chevalier et al.	Acidity and aluminum effects on osmo-iono-regulation in the brook trout	1987	Brook trout, *Salvelinus fontinalis*	7 d Addition of Al kept fish alive compared to control at 500 and pH=5.5	Only one exposure concentration
Christensen	Effects of metal cations and other chemicals upon the in vitro activity of twp enzymes in the blood plasma of the white sucker, *Catostomus commersoni* (lacepede)	1971/ 1972	White sucker, *Catostomus commersoni*	-	In vitro experiment
Christensen and Tucker	Effects of selected water toxicants on the in vitro activity of fish carbonic anhydrase	1976	Channel catfish, *Ictalurus punctatus*	-	Excised cells
Clark and Hall	Effects of elevated hydrogen ion and aluminum concentrations on the survival of amphibian embryos and larvae	1985	Toad, *Bufo americanus* Wood frog, *Rana sylvatica* Spotted salamander, *Ambystoma maculatum*	-	Exposure concentration not known; field experiment: dosed stream pools
Clark and LaZerte	Intraspecific variation in hydrogen ion and aluminum toxicity in *Bufo americanus* and *Ambystoma maculatum*	1987	Toad, *Bufo americanus* Spotted salamander, *Ambystoma maculatum*	-	Pre-exposure to pollutant
Cleveland et al.	Interactive toxicity of aluminum and acidity to early life stages of brook trout	1986	Brook trout, *Salvelinus fontinalis*	30 d Increase egg mortality at 318	Only one exposure concentration
Cleveland et al.	Sensitivity of brook trout to low pH, low calcium and elevated aluminum concentrations during laboratory pulse exposures	1991b	Brook trout, *Salvelinus fontinalis*	-	Only one exposure concentration; mixture; Al and acid pulses
Colman et al.	Determination of dilution factors for discharge of aluminum-containing wastes by public water-supply treatment facilities into lakes and reservoirs in Massachusetts	2011	-	-	Not applicable; no aluminum toxicity data

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Conklin et al.	Comparative toxicity of drilling muds: Role of chromium and petroleum hydrocarbons	1983	Grass shrimp, *Palaemonetes pugio* Sheepshead minnow, *Cyrpinodon variegatus*	-	Mixture; drilling mud
Cook and Haney	The acute effects of aluminum and acidity upon nine stream insects	1984	Five caddisflies, two mayflies, stonefly and beetle	-	Mixture; dilution water is river water
Correa et al.	Changes in oxygen consumption and nitrogen metabolism in the dragonfly *Somatochlora cingulata*	1985	Dragonfly, *Somatochlora cingulata*	96 hr No change in respiratory rate at 30	Lack of exposure details; dilution water not characterized; too few exposure concentration
Correa et al.	Oxygen consumption and ammonia excretion in the detritivore caddisfly *Limnephillus sp.* exposed to low pH and aluminum	1986	Caddisfly, *Limnephillus sp.*	-	Only one exposure concentration; mixture; low pH and Al
Correia et al.	Aluminum as an endocrine disruptor in female Nile tilapia (*Oreochromis niloticus*)	2010	Nile tilapia, *Oreochromis niloticus*	96 hr Increase gonad and decrease liver lipids at 1,600	Only one exposure concentration
Craig et al.	Water quality objectives development document: aluminum	1985	-	-	Review; results of previously published papers
Cravotta et al.	Abandoned mine drainage in the Swatara Creek Basin, southern anthracite coalfield, Pennsylvania, USA: 1. Stream water quality trends coinciding with the return of fish	2010	-	-	Mixture; dilution water is river water
Crawford et al.	A survey of metal and pesticide levels in stormwater retention pond sediments in coastal South Carolina	2010	-	-	Survey; occurrence
Crist et al.	Interaction of metal protons with algae. 3. Marine algae, with emphasis on lead and aluminum	1992	-	-	Bioaccumulation: steady state not reached
Cummins	Effects of aluminum and low pH on growth and development in *Rana temporaria* tadpoles	1986	Brown frog, *Rana temporaria*	18 d Decrease body mass and increase time to metamorph at 800	Not North American species; only two exposure concentrations
Dalziel et al.	The effects of low pH, low calcium concentrations and elevated aluminum concentrations on sodium fluxes in brown trout, *Salmo trutta* L.	1986	Brown trout, *Salmo trutta*	8 hr No effect on Na influx at 215.8	Only one exposure concentration
Delaune et al.	Total Hg, methyl Hg and other toxic heavy metals in a northern Gulf of Mexico Estuary: Louisiana Pontchartrain Basin	2008	-	-	Survey; occurrence

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Desouky	Tissue distribution and subcellular localization of trace metals on the pond snail *Lymnaea stagnalis* with special reference to the role of lysosomal granules in metal sequestration	2006	Snail, *Lymnaea stagnalis*	-	Bioaccumulation: exposure concentration not measured; inadequate exposure methods
Desouky	Metallothionein is up-regulated in molluscan responses to cadmium, but not aluminum, exposure	2012	Snail, *Lymnaea stagnalis* Zebra mussel, *Dreissena polymorpha*	-	Only one exposure concentration; possible prior exposure due to location collected in field
Desouky et al.	Influence of oligomeric silica and humic acids on aluminum accumulation in a freshwater grazing invertebrate	2002	Snail, *Lymnaea stagnalis*	-	Bioaccumulation: steady state not reached
DeWalle et al.	Episodic flow-duration analysis: a method of assessing toxic exposure of brook trout (*Salvelinus fontinalis*) to episodic increases in aluminum	1995	-	-	Not applicable; no aluminum toxicity data
Dickson	Liming toxicity of aluminum to fish	1983	-	-	Not applicable; no aluminum toxicity data
Dietrich and Schlatter	Aluminum toxicity to rainbow trout at low pH	1989a	Rainbow trout, *Oncorhynchus mykiss*	MT50=64 hrs at 200; MT50=45.5 hrs at 400 (pH=5.4); MT50=52 hrs at 400 (pH=5.6)	Only two exposure concentrations
Dietrich and Schlatter	Low levels of aluminum causing death of brown trout (*Salmo trutta fario*, L.) in a Swiss alpine lake	1989b	Brown trout, *Salmo trutta fario*	-	Mixture; exposure concentration varied over time; dilution water is lake water
Dietrich et al.	Aluminum and acid rain: mitigating effects of NaCl on aluminum toxicity to brown trout (*Salmo trutta fario*) in acid water	1989	Brown trout, *Salmo trutta fario*	-	No acclimation to test water; no aluminum toxicity data
Doke et al.	Habitat availability and benthic invertebrate population changes following alum treatment and hypolimnetic oxygenation in Newman Lake, Washington	1995	-	-	Mixture; alum added to lake; no species listed
Doudoroff and Katz	Critical review of literature on the toxicity of industrial wastes and their components to fish. II. The metals, as salts	1953	-	-	Review; results of previously published papers
Driscoll	A procedure for the fractionation of aqueous aluminum in dilute acidic waters	1984	-	-	Not applicable; no aluminum toxicity data
Driscoll	Aluminum in acidic surface waters: chemistry, transport, and effects	1985	-	-	Not applicable; no aluminum toxicity data

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Driscoll et al.	Effect of aluminum speciation on fish in dilute acidified waters	1980	Brook trout, *Salvelinus fontinalis*	14 d 28% survival at 420, pH=5.2; 42% survival at 480, pH=4.4	Lack of exposure details; only two exposure concentrations
Duis and Oberemm	Aluminum and calcium - Key factors determining the survival of vendace embryos and larvae in post-mining lakes?	2001	Vendace, *Coregonus albula*	Decrease hatch % at 2,100, pH=5.0	Not North American species; only one exposure concentration
Durrett et al.	The FRD3-mediated efflux of citrate into the root vasculature is necessary for efficient iron translocation	2007	-	-	Not applicable; no aluminum toxicity data
Dussault et al.	Effects of sublethal, acidic aluminum exposure on blood ions and metabolites, cardiac output, heart ratem and stroke volume of rainbow trout, *Oncorhynchus mykiss*	2001	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Dussault et al.	Effects of chronic aluminum exposure on swimming and cardiac performance in rainbow trout, *Oncorhynchus mykiss*	2004	Rainbow trout, *Oncorhynchus mykiss*	6 wk 75% survival at 32	Too few exposure concentrations; too few organisms per concentration
Dwyer et al.	Use of surrogates species in assessing contaminant risk to endangered and threatened species; final report - September 1995	1995	-	-	Not applicable; no aluminum toxicity data
Dwyer et al.	Assessing contaminant sensitivity of endangered and threatened aquatic species: part III. Effluent toxicity tests	2005	-	-	Not applicable; no aluminum toxicity data
Eaton et al.	A field and laboratory investigation of acid effects on largemouth bass, rock bass, black crappie, and yellow perch	1992	Rockbass, *Ambloplites rupestris* Largemouth bass, *Micropterus salmoides* Yellow perch, *Perca flavescens*	Hatch + 7 d NOEC (survival)=44.0; NOEC=44.0; NOEC=25.2	Too few exposure concentrations; control survival issues
Ecological Analysts, Inc.	Study on metals in food fish near the abandoned Vienna fly ash disposal area	1984	-	-	Field exposure, exposure concentrations not measured adequately
Eddy and Talbot	Formation of the perivitelline fluid in Atlantic salmon eggs (*Salmo salar*) in fresh water and in solutions of metal ions	1983	Atlantic salmon, *Salmo salar*	1 hr Inhibit perivitelline fluid formation at 26,980	Dilution water not characterized

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Eddy and Talbot	Sodium balance in eggs and dechlorinated embryos of the Atlantic salmon *Salmo salar* L. exposed to zinc, aluminum and acid waters	1985	Atlantic salmon, *Salmo salar*	-	Too few exposure concentrations; no true control group
Eisler et al.	Fourth annotated bibliography on biological effects of metals in aquatic environments (No. 2247-3132)	1979	-	-	Review
Elangovan et al.	Accumulation of aluminum by the freshwater crustacean Asellus aquaticus in neutral water	1999	Crustacean, *Asellus aquaticus*	-	Bioaccumulation: unmeasured concentration in exposure media
Elsebae	Comparative susceptibility of the Alareesh Marine Culture Center shrimp *Penaeus japonicus* and the brine shrimp *Artemia salina* to different insecticides and heavy metals	1994	Shrimp, *Penaeus japonicus*	96 hr LC50=0.001; LC50=0.0045; LC50=0.1	Not North American species; dilution water not characterized
Elwood et al.	Contribution of gut contents to the concentration and body burden of elements in Tipula spp. from a spring-fed stream	1976	-	-	Field exposure, exposure concentrations not measured adequately
Eriksen et al.	Short-term effects on riverine Ephemeroptera, Plecoptera, and Trichoptera of rotenone and aluminum sulfate treatment to eradicate *Gyrodactylus salaris*	2009	-	-	Mixture; mixed species exposure; dilution water is river water
Ernst et al.	Effects of habitat characteristics and water quality on macroinvertebrate communities along the Neversink River in southeastern New York, 1991-2001	2008	-	-	Not applicable; no aluminum toxicity data
Evans et al.	The effects of aluminum and acid on the gill morphology in rainbow trout, *Salmo gairdneri*	1988	Rainbow trout, *Oncorhynchus mykiss*	14 d LOEC (epithelial hyperplasma) = 269.8 (pH 5.2)	Only three exposure concentrations
Everhart and Freeman	Effect of chemical variations in aquatic environments. Vol. II. Toxic effects of aqueous aluminum to rainbow trout	1973	Rainbow trout, *Oncorhynchus mykiss*	45 d Reduced growth at 514 (pH=8 and pH=6.85)	Too few exposure concentrations; unmeasured chronic exposure
Exley	Avoidance of aluminum by rainbow trout	2000	Rainbow trout, *Oncorhynchus mykiss*	45 min. Avoidance at 33.73	No acclimation to test water
Exley et al.	Silicon, aluminium and the biological availability of phosphorus in algae	1993	Diatom, *Navicula pelliculosa* Green alga, *Chlorella vulgaris*	24 hr 269.8 inhibited growth rate; 24 hr 1,295 inhibited growth rate	Only one exposure concentration
Exley et al.	Polynuclear aluminum and acute toxicity in the fish	1994	-	-	Inappropriate form of toxicant; polynuclear aluminum

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Exley et al.	Kinetic constraints in acute aluminum toxicity in the rainbow trout (*Oncorhynchus mykiss*)	1996	Rainbow trout, *Oncorhynchus mykiss*	-	Only one exposure concentration; no control group
Exley et al.	Hydroxyaluminosilicates and acute aluminum toxicity to fish	1997	Rainbow trout, *Oncorhynchus mykiss*	-	Mixture; Al and Si
Fageria	Influence of aluminum in nutrient solutions on chemical composition in two rice cultivars at different growth stages	1985	Rice, *Oryza sativa*	-	Bioaccumulation study: exposure concentrations not measured
Famoso et al.	Development of a novel aluminum tolerance phenotyping platform used for comparisons of cereal aluminum tolerance and investigations into rice aluminum tolerance mechanisms	2010	Sorghum, *Sorghum bicolor* Wheat, *Triticum aestivum* Rice, *Oryza sativa*	-	Excessive EDTA in growth media (25 mg/L)
Farag et al. 1993	The effects of low pH and elevated aluminum on yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*)	1993	Yellowstone cutthroat trout, *Oncorhynchus clarki bouvieri*	7 d No effect on survival at 50	Too few exposure concentrations; poor control survival
Farringer	The determination of the acute toxicity of rotenone and Bayer 73 to selected aquatic organisms	1972	-	-	Not applicable; no aluminum toxicity data
Fernandez-Davila et al.	Aluminum-induced oxidative stress and neurotoxicity in grass carp (Cyprinidae-*Ctenopharingodon idella*)	2012	Grass carp, *Ctenopharingodon idella*	96 hr Increase lipid peroxidation, dopamine levels, SOD activity and decrease CAT activity in brain tissue at 100	Only one exposure concentration
Finn	The physiology and toxicology of salmonid eggs and larvae in relation to water quality criteria	2007	-	-	Review; results of previously published papers
Fischer and Gode	Toxicological studies in natural aluminum silicates as additives to detergents using freshwater organisms	1977	-	-	Text in foreign language
Fivelstad and Leivestad	Aluminum toxicity to Atlantic salmon (*Salmo salar* L.) and brown trout (*Salmo trutta* L.): Mortality and physiological response	1984	Atlantic salmon, *Salmo salar*	LT50=26 hr at 84.18; LT50=41 hr at 84.72; LT50=62 hr at 45.06	Lack of exposure details; dilution water not characterized
Fjellheim et al.	Effect of aluminium at low pH on the mortality of elvers (*Anguilla anguilla* L.), a laboratory experiment	1985	Eel, *Anguilla anguilla*	-	Only two exposure concentrations; dilution water not characterized

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Fok et al.	Determination of 3,5,3"-triiodo-L-thyronine (T3) levels in tissues of rainbow trout (*Salmo gairdneri*) and the effects of low ambient pH and aluminum.	1990	Rainbow trout, *Oncorhynchus mykiss*	-	Inappropriate form of toxicant ($AlKSO_4$); surgically altered test species
Folsom et al.	Comparative study of aluminum and copper transport and toxicity in an acid-tolerant freshwater green alga	1986	Green alga, *Chlorella saccarophila*	-	Lack of details; cannot determine effect concentration
France and Stokes	Influence of manganese, calcium, and aluminum on hydrogen ion toxicity to the amphipod *Hyalella azteca*	1987	Amphipod, *Hyalella azteca*	-	Mixture; Mn, Ca, pH and Al
Freda	The effects of aluminum and other metals on amphibians	1991	-	-	Review; results of previously published papers
Freeman	Recovery of rainbow trout from aluminum poisoning	1973	Rainbow trout, *Oncorhynchus mykiss*	-	Pre-exposure to pollutant
Frick and Herrmann	Aluminum accumulation in a lotic mayfly at low pH - a laboratory study	1990	Mayfly, *Heptagenia sulphurea*	-	Not North American species; lack of exposure details; cannot determine effect concentration
Fuma et al.	Ecological effects of various toxic agents on the aquatic microcosm in comparison with acute ionizing radiation	2003	Bacteria, *Escherichia coli* Protozoa, *Tetrahymena thermophila* Protozoa, *Euglena gracilis*	-	Mixture; radiation and Al
Gagen	Aluminum toxicity and sodium loss in three salmonid species along a pH gradient in a mountain stream	1986	-	-	Exposure concentration not known; field exposure
Gagen et al.	Mortality of brook trout, mottled sculpins, and slimy sculpins during acidic episodes	1993	Brook trout, *Salvelinus fontinalis* Mottled sculpin, *Cottus bairdi* Slimy sculpin, *Cottus cognatus*	-	Mixture; exposure concentration varied over time; dilution water is river water
Galindo et al.	Genotoxic effects of aluminum on the neotropical fish *Prochilodus lineatus*	2010	Neotropical fish, *Prochilodus lineatus*	96 hr Increase COMET score and number of damaged necleoids at 438	Not North American species, only one exposure concentration
Gallon et al.	Hydrophonic study of aluminum accumulation by aquatic plants: effects of fluoride and pH	2004	Five aquatic plants	-	Bioaccumulation: steady state not reached

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Galloway et al.	Water quality and biological characteristics of the Middle Fork of the Saline River, Arkansas, 2003-06	2008	-	-	Not applicable; no aluminum toxicity data
Garcia-Garcia et al.	Impact of chromium and aluminum pollution on the diversity of zooplankton: a case study in the Chimaliapan wetland (Ramsar Site) (Lerma Basin, Mexico)	2012	-	-	Mixture; dilution water is wetland water
Garcia-Medina et al.	Aluminum-induced oxidative stress in lymphocytes of common carp (*Cyprinus carpio*)	2010	Common carp, *Cyprinus carpio*	96 hr Increase lipid peroxidation and decrease SOD activity at 50	Too few exposure concentrations, dilution water not characterized
Garcia-Medina et al.	Genotoxic and cytotoxic effects induced by aluminum in the lymphocytes of the common carp (*Cyprinus carpio*)	2011	Common carp, *Cyprinus carpio*	96 hr DNA damage: T/N index at 50	Too few exposure concentrations, dilution water not characterized
Garcia-Medina et al.	The relationship of cytotoxic and genotoxic damage with blood aluminum levels and oxidative stress induced by this metal in common carp (*Cyprinus carpio*) erythrocytes	2013	Common carp, *Cyprinus carpio*	96 hr LOEC (reduced USOD and NADPH on erythocytes) = 50	Only three exposure concentrations
Gardner and Al-Hamdani	Interactive effects of aluminum and humic substances on Salvinia	1997	-	-	Not applicable; no aluminum toxicity data
Gardner et al.	Towards the establishment of an environmental quality standard for aluminum in surface waters	2008	-	-	Not applicable; no aluminum toxicity data
Gascon et al.	The interaction of pH, calcium and aluminum concentrations on the survival and development of wood frog (*Rana sylvatica*) eggs and tadpoles	1987	Wood frog, *Rana sylvatica*	100% mortality at 200	Only two exposure concentrations; lack of exposure details; duration not reported
Geiger et al.	Acute toxicities of organic chemicals to fathead minnows (*Pimephales promelas*) Volume V	1990	Fathead minnows, *Pimephales promelas*	-	Not applicable; no aluminum toxicity data
Gensemer	Role of aluminum and growth rate on changes in cell size and silica content of silica-limited populations of *Asterionella ralfsii* var. *americana* (Bacillariophyceae).	1990	Diatom, *Asterionella ralfsii* var. *americana*	21 d Decrease mean cell length, total surface area and biovolume at 75.54	Only two exposure concentrations
Gensemer	The effects of pH and aluminum on the growth of the acidophilic diatom *Asterionella ralfsii* var. *americana*	1991a	Diatom, *Asterionella ralfsii* var. *americana*	-	Review of Gensemer 1989 thesis
Gensemer	The effects of aluminum on phosphorus and silica-limited growth in *Asterionella ralfsii* var. *americana*	1991b	Diatom, *Asterionella ralfsii* var. *americana*	-	Growth stimulation study, not toxicity

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Gensemer and Playle	The bioavailability and toxicity of aluminum in aquatic environments	1999	-	-	Review; results of previously published papers
Gensemer et al.	Comparative effects of pH and aluminum on silica-limited growth and nutrient uptake in *Asterionella ralfsii* var. *americana* (Bacillariophyceae)	1993	Diatom, *Asterionella ralfsii* var. *americana*	-	Only one exposure concentration; cannot determine effect concentration
Gensemer et al.	Interactions of pH and aluminum on cell length reduction in *Asterionella ralfsii* var. *americana* Korn	1994	Diatom, *Asterionella ralfsii* var. *americana*	25 d No effect on cell length at 539.6	Only one exposure concentration; dilution water not characterized
Genter	Benthic algal populations respond to aluminum, acid, and aluminum-acid mixture in artificial streams	1995	Green alga, *Cosmarium melanosporum* Blue-green alga, *Schizothrix calcicola* Diatom, *Achnanthes minutissima* Diatom, *Naviculoids*	28 d Increased growth at 200	Only one exposure concentration
Gibbons et al.	Effects of multiphase restoration, particularly aluminum sulfate application, on the zooplankton community of a eutrophic lake in eastern Washington	1984	-	-	Exposure concentration not known; population/ community changes of a lake exposed to Al over a series of years
Gill et al.	Assessment of water-quality conditions in Fivemile Creek in the vicinity of the Fivemile Creek Greenway, Jefferson County, Alabama, 2003-2005	2008	-	-	Not applicable; no aluminum toxicity data
Gladden	The effect of aluminum on cortisol levels in goldfish (*Carassius auratus*)	1987	Goldfish, *Carassius auratus*	-	Surgically altered test species
Goossenaerts et al.	A microanalytical study of the gills of aluminum-exposed rainbow trout (*Salmo gairdneri*)	1988	Rainbow trout, *Oncorhynchus mykiss*	72 hr Increase the Al-content of the gills at 190	Duration too short, only one exposure concentration
Gopalakrishnan et al.	Toxicity of heavy metals on embryogenesis and larvae of the marine sedentary polychaete *Hydroides elegans*	2007	Polychaete, *Hydroides elegans*	-	Pre-exposure to pollutant
Goss and Wood	The effects of acid and acid/aluminum exposure on circulating plasma cortisol levels and other blood parameters in the rainbow trout, *Salmo gairdneri*	1988	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered fish
Greger et al.	Aluminum effects on *Scenedesmus obtusiusculus* with different phosphorus status. I. Mineral uptake	1992a	Green alga, *Scenedesmus obtusiusculus*	-	Excessive EDTA in growth media (108 µm Na_2EDTA)

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Greger et al.	Aluminum effects on *Scenedesmus obtusiusculus* with different phosphorus status. II. Growth, photosynthesis and pH	1992b	Green alga, *Scenedesmus obtusiusculus*	-	Excessive EDTA in growth media (108 µm Na_2EDTA)
Gregor et al.	Growth assays with mixed cultures of cyanobacteria and algae assessed by in vivo fluorescence: One step closer to real ecosystems?	2008	Green alga, *Pseudokirchneriella subcapitata* Blue-green alga, *Aphanothece clathrata*	-	Inappropriate form of toxicant (PAX-18)
Guerold et al.	Occurrence of aluminum in chloride cells of *Perla marginata* (Plecoptera) after exposure to low pH and elevated aluminum concentration	1995	Stonefly, *Perla marginata*	-	Not North American species; Bioaccumulation: steady state not reached
Gunn and Keller	Spawning site water chemistry and lake trout (*Salvelinus namaycush*) sac fry survival during spring snow melt	1984	Lake trout, *Salvelinus namaycush*	-	Mixture, Al and low pH
Gunn and Noakes	Latent effects of pulse exposure to aluminum and low pH on size, ionic composition, and feeding efficiency of lake trout (*Salvelinus namaycush*) alevins	1987	Lake trout, *Salvelinus namaycush*	5 d LOEC (growth)=<100	Only two exposure concentrations
Guo et al.	Involvement of antioxidative defense system in rice seedlings exposed to aluminum toxicity and phosphorus deficiency	2012	Rice, *Oryza sativa*	-	Excessive chelator in growth media (5 mg/L Fe-citrate)
Guthrie et al.	Aquatic bacterial populations and heavy metals-II. Influence of chemical content of aquatic environments on bacterial uptake of chemical elements	1977	Bacterial population	-	Exposure concentration not known; field accumulation study
Guzman et al.	Implementing *Lecane quadridentata* acute toxicity tests to assess the toxic effects of selected metals (Al, Fe and Zn)	2010	Rotifer, *Lecane quadridentata*	48 hr LC50=1,572	Not North American species
Hackett	Ecological aspects of the nutrition of *Deschampsia flexuosa* (L.) Trin. III. Investigation of phosphorus requirement and response to aluminium in water culture, and a study of growth in soil	1967	Wavy hair grass, *Deschampsia flexuosa*	-	Not applicable; terrestrial species
Hall et al.	Mortality of striped bass larvae in relation to contaminants and water quality in a Chesapeake Bay tributary	1985	Striped bass, *Morone saxatilis*	-	Exposed to mixture, high control mortality (15-25%); dilution water is river water
Hamilton-Taylor et al.	Depositional fluxes of metals and phytoplankton in Windermere as measured by sediment traps	1984	-	-	Effluent or mixture

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Handy and Eddy	Surface absorption of aluminium by gill tissue and body mucus of rainbow trout, *Salmo gairdneri*, at the onset of episodic exposure	1989	Rainbow trout, *Oncorhynchus mykiss*	1 hr Gill content=50 µg/g at 954	Only one exposure concentration
Hanks	Effect of metallic aluminum particles on oysters and clams	1965	Soft-shell clam, *Mya arenaria* American oyster, *Crassostrea virginica*	-	Dilution water not characterized, inappropriate form of Al
Harper et al.	In vivo biodistribution and toxicity depends on nanomaterial composition, size, surface functionalisation and route of exposure	2008	Zebrafish, *Danio rerio*	-	Inappropriate form of toxicant (Al-oxide)
Harry and Aldrich	The distress syndrome in *Taphtus glabratus* (Say) as a reaction to toxic concentrations of inorganic ions	1963	Snail, *Taphius glabratus*	24 hr LOEC (distress, inability to move)=5,000	Dilution water is distilled water
Havas	Effects of aluminum on aquatic biota	1986a	-	-	Review
Havas and Hutchinson	Aquatic invertebrates from the Smoking Hills, N.W.T.: effect of pH and metals on mortality	1982	-	-	Mixture
Havas and Hutchinson	Effect of low pH on the chemical composition of aquatic invertebrates from tundra ponds at the Smoking Hills, N.W.T., Canada	1983	-	-	Pre-exposure to pollutant
Havens	Aluminum binding to ion exchange sites in acid-sensitive versus acid tolerant cladocerans	1990	Cladoceran, *Daphnia galeata mendotae* Cladoceran, *Daphnia retrocurva* Cladoceran, *Bosmina longirostris*	24 hr 98% mortality at 200; 94% mortality at 200; 6% mortality at 200	Only one exposure concentration
Havens	Littoral zooplankton response to acid and aluminum stress during short-term laboratory bioassays	1991	-	-	Only one exposure concentration; mixture; low pH and Al
Havens	Acid and aluminum effects on sodium homeostasis and survival of acid-sensitive and acid-tolerant cladocera	1992	Cladoceran, *Daphnia galeata mendotae* Cladoceran, *Bosmina longirostris*	24 hr NOEC (survival)=100; NOEC=200	Only two exposure concentrations
Havens	Acid and aluminum effects on the survival of littoral macro-invertebrates during acute bioassays	1993a	-	-	Only one exposure concentration; control survival issues or mixed species exposure

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Havens	Acid and aluminum effects on osmoregulation and survival of the freshwater copepod *Skistodiaptomus oregonensis*	1993b	Copepod, *Skistodiaptomus oregonensis*	48 hr NOEC (survival)=200 at pH=7.5; LOEC=100 at pH=6.0	Only two exposure concentrations
Havens and Decosta	The role of aluminum contamination in determining phytoplankton and zooplankton responses to acidification	1987	-	-	Mixture; exposure concentration varied over time; Dilution water is lake water
Havens and Heath	Acid and aluminum effects on freshwater zooplankton: and in situ mesocosm study	1989	Zooplankton community	-	Mixture (low pH and Al); only one exposure concentration
Havens and Heath	Phytoplankton succession during acidification with and without increasing aluminum levels	1990	Phytoplankton community	-	Mixture (low pH and Al); only one exposure concentration
Heier et al.	Sublethal effects in Atlantic salmon (*Salmo salar*) exposed to mixtures of copper, aluminum and gamma radiation	2012	Atlantic salmon, *Salmo salar*	48 hr No mortality, but increase plasma glucose and decrease plasma sodium at 267	Only one exposure concentration, too few animals per concentration
Helliwell	Speciation and toxicity of aluminum in a model fresh water	1983	-	-	Lack of details; cannot determine effect concentration
Heming and Blumhagen	Plasma acid-base and electrolyte states of rainbow trout exposed to alum (aluminum sulphate) in acidic and alkaline environments	1988	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered fish
Herkovits et al.	Identification of aluminum toxicity and aluminum-zinc interaction in amphibian *Bufo arenarum* embryos	1997	Toad, *Bufo arenarum*	96 hr LC50=460	Not North American Species
Herrmann and Andersson	Aluminum impact on respiration of lotic mayflies at low pH	1986	-	-	Mixture; dilution water is stream water
Herrmann and Frick	Do stream invertebrates accumulate aluminum at low pH conditions?	1995	-	-	Survey
Hesse	Phosphorus relationships in a mangrove-swamp mud with particular reference to aluminum toxicity	1963	-	-	Sediment
Hill et al.	Zebrafish as a model vertebrate for investigating chemical toxicity	2005	Zebrafish, *Danio rerio*	-	Review
Hockett and Mount	Use of metal chelating agents to differentiate among sources of acute aquatic toxicity	1996	Cladoceran, *Ceriodaphnia dubia*	-	Mixture; EDTA, thiosulfate and Al
Hofler	Action of aluminum salts on Spirogyra and Zygnema	1958	-	-	Text in foreign language

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Horne and Dunson	Exclusion of the Jefferson salamander, *Ambystoma jeffersonianum*, from some potential breeding ponds in Pennsylvania: effects of pH, temperature, and metals on embryonic development	1994	Jefferson salamander, *Ambystoma jeffersonianum*	-	Lack of details; mixture; low pH and AL; duration not reported
Horne and Dunson	Toxicity of metals and low pH to embryos and larvae of the Jefferson salamander, Ambystoma jeffersonianum	1995a	Jefferson salamander, *Ambystoma jeffersonianum*	No effect values presented	No effect values presented
Horne and Dunson	Effects of low pH, metals, and water hardness on larval amphibians	1995b	Wood frog, *Rana sylvatica* Jefferson salamander, *Ambystoma jeffersonianum*	Percent survival depended on hardness, duration and species	Only one exposure concentration
Hornstrom et al.	Effects of pH and different levels of aluminum on lake plankton in the Swedish west coast area	1984	-	-	Survey; mixture; dilution water is lake water
Howells et al.	Effects of acidity, calcium, and aluminum on fish survival and productivity - a review	1983	-	-	Review; results of previously published papers
Howells et al.	EIFAC water quality criteria for European freshwater fish: Report on aluminum	1990	-	-	Review
Huebner and Pynnonen	Viability of glochidia of two species of *Anodonta* exposed to low pH and selected metals	1992	Swan mussel, *Anodonta cygnea*	24 hr glochidia EC50=18,000 at pH 4.5	Not North American species
Hunn et al.	Influence of pH and aluminum on developing brook trout in a low calcium water	1987	Brook trout, *Salvelinus fontinalis*	45 d Reduced growth and some behaviors at 283	Only one exposure concentration
Husaini and Rai	pH dependent aluminum toxicity to *Nostoc linckia*: Studies on phosphate uptake, alkaline and acid phosphatase activity, ATP content, and photosynthesis and carbon fixation	1992	Blue-green alga, *Nostoc linckia*	14 d Reduce photosynthetic O_2 evolution at 53,336	Only three exposure concentrations
Husaini et al.	Impact of aluminum, fluoride and flouroaluminate on ATPase activity og *Nostoc linckia* and *Chlorella vulgaris*	1996	Blue-green alga, *Nostoc linckia* Green alga, *Chlorella vulgaris*	-	Mixture
Hutchinson and Sprague	Toxicity of trace metal mixtures to American flagfish (*Jordanella floridae*) in soft, acidic water and implications for cultural acidification	1986	American flagfish, *Jordanella floridae*	-	Mixture; heavy metals
Hutchinson et al.	Lethal responses of salmonid early life stages to H+ and Al in dilute waters	1987	-	-	Review
Hwang	Lysosomal responses to environmental contaminants in bivalves	2001	American oyster, *Crassostrea virginica*	-	Exposure concentration not known; field accumulation study

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Hyne and Wilson	Toxicity of acid-sulphate soil leachate and aluminum to the embryos and larvae of Australian bass (*Macquaria novemaculeata*) in estuarine water	1997	Australian bass, *Macquaria novemaculeata*	No effect on survival at 1,000 and pH=1,000; Reduce survival by 63% at 500 and pH=4.0	Not North American species; dilution water not characterized
Ingersoll	The effects of pH, aluminum, and calcium on survival and growth of brook trout (*Salvelinus fontinalis*) early life stages	1986	Brook trout, *Salvelinus fontinalis*	-	Survival problems; low fertility success
Ingersoll et al.	Epidermal response to pH, aluminum, and calcium exposure in brook trout (*Salvelinus fontinalis*) fry	1990b	Brook trout, *Salvelinus fontinalis*	-	Only two exposure concentrations; too few test organisms per concentration
Jagoe and Haines	Changes in gill morphology of Atlantic salmon (*Salmo salar*) smolts due to addition of acid and aluminum to stream water	1997	Atlantic salmon, *Salmo salar*	-	Only one exposure concentration, increasing Al concentration over time
Jain et al.	Acute and chronic toxicity of aluminium fluoride to flora and fauna in a microcosm	2012	Duckweed, *Lemna aequinoctialis* Cladoceran, *Daphnia similis* Western mosquitofish, *Gambusis affinis*	-	Inapporiate form of toxicant (Aluminum floride)
Jan and Matsumoto	Early effects of aluminium on nutrient (K, Ca, and Mg) status of different root zones of two rice cultivars	1999	Rice, *Oryza sativa*	-	No control group; only one exposure concentration
Jan and Pettersson	Effects of low aluminium levels on growth and nutrient relations in three rice cultivars with different tolerances to aluminium	1993	Rice, *Oryza sativa*	-	Bioaccumulation study: exposure concentrations not measured
Jancula et al.	Effects of polyaluminium chloride on the freshwater invertebrate Daphnia magna	2011	-	-	Inappropriate form of toxicant; PAX-18 (9% Al)
Jaworska and Tomasik	Metal-metal interactions in biological systems. Part VI. Effects of some metal ions on mortality, pathogenicity and reproductivity of Steinernema carpocapsae and Heterohabditis bacteriophora entomopathogenic nematodes under laboratory conditions	1999	Nematode, *Steinernema carpocapsae*	-	Distilled water without proper salts added
Jaworska et al.	Effect of metal ions under laboratory conditions on the entomopathogenic Steinernema carpocapsae (Rhabditida: sterinernematidae)	1996	Nematode, *Steinernema carpocapsae*	-	Distilled water without proper salts added; infected test organism

Author	**Title**	**Date**	**Organism(s)**	**Concentration (μg/L)**	**Reason Unused**
Jaworska et al.	Effect of metal ions on the entomopathogenic nematode *Heterorhabditis bacteriophora* Poinar (Nematode: Heterohabditidae) under laboratory conditions	1997	Nematode, *Heterorhabditis bacteriophora*	-	Distilled water without proper salts added
Jay and Muncy	Toxicity to channel catfish of wastewater from an Iowa coal beneficiation plant	1979	-	-	Effluent
Jensen and Malte	Acid-base and electrolyte regulation, and haemolymph gas transport in crayfish, *Astacus astacus*, exposed to soft, acid water with and without aluminum	1990	Crayfish, *Astacus astacus*	21 d No effect on haemolymph haemocyanin concentration at 675	Not North American species, only one exposure concentration
Jensen and Weber	Internal hypoxia-hypercapnia in tench exposed to aluminum in acid water: Effects on blood gas transport, acid-base status and electrolyte composition in arterial blood	1987	Tench, *Tinca tinca*	-	Surgically altered test species
Ji et al.	Toxicity of oxide nanoparticles to the green algae *Chlorella sp.*	2011	Green alga, *Chlorella sp.*	-	Inappropriate form of toxicant (aluminum oxide)
Jones	The relation between the electrolytic solution pressures on the metals and their toxicity to the stickleback (*Gasterosteus aculeatus* L.)	1939	Threespine stickleback, *Gasterosteus aculeatus*	-	Lack of details; review
Jones	A further study of the relation between toxicity and solution prssure, with *Polycelis nigra* as test animals	1940	Planarian, *Polycelis nigra*	48 hr Survival time affected at 100,000	Not North American species; distilled water without proper salts
Jones et al.	Comparison of observed and calculated concentrations of dissolved Al and Fe in stream water	1974	-	-	Not applicable; no aluminum toxicity data
Jonsson et al.	Metals and linear alkylbenzene sulphonate as inhibitors of the algae *Pseudokirchneriella subcapitata* acid phosphatase activity	2009	Green alga, *Pseudokirchneriella subcapitata*	7 d Decrease relative activity at 53,960	Only two exposure concentrations
Juhel et al.	Alumina nanoparticles enhance growth of Lemna minor	2011	Duckweed, *Lemna minor*	-	Inappropriate form of toxicant; nanoparticles
Kadar et al.	Avoidance responses to aluminum in the freshwater bivalve, *Anodonta cygnea*	2001	Swan mussel, *Anodonta cygnea*	15 d Decrease in duration of shell gape at 516.3	Not North American species
Kadar et al.	Effect of sub-lethal concentrations of aluminum on the filtration activity of the freshwater mussel *Anodonta cygnea* L. At Neutral Ph	2002	Swan mussel, *Anodonta cygnea*	15 d Duration of siphon activity at 241.3	Not North American species, only two exposure concentrations

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Kaiser	Correlation and prediction of metal toxicity to aquatic biota	1980	-	-	Review; results of previously published papers
Karlsson-Norrgren et al.	Acid water and aluminum exposure: experimentally induced gill lesions in brown trout, *Salmo trutta* L	1986a	Brown trout, *Salmo trutta*	21 d Alteration in secondary gill lamellae at 200	Too few exposure concentrations, atypical endpoint
Karlsson-Norrgren et al.	Acid water and aluminum exposure: Gill lesions and aluminum accumulation in farmed brown trout, *Salmo trutta* L.	1986b	Brown trout, *Salmo trutta*	-	Bioaccumulation: survey; exposure concentration not measured over time
Keinanen et al.	Ion regulation in whitefish (*Coregonus lavaretus* L.) yolk-sac fry exposed to low pH and aluminum at low and moderate ionic strength	1998	Whitefish, *Coregonus lavaretus*	-	Not North American species; cannot determine effect concentration
Keinanen et al.	Comparison of the responses of the yolk-sac fry of pike (*Esox lucius*) and roach (*Rutilus rutilus*) to low pH and aluminum: sodium influx, development and activity	2000	Pike, *Esox lucius* Roach, *Rutilus rutilus*	10 d NOEC (growth)=600 at pH=5.0; 9 d LOEC (survival)=100 at pH=5.25	Too few exposure concentrations
Keinanen et al.	Fertilization and embryonic development of whitefish (*Coregonus lavaretus lavaretus*) in acidic low-ionic strength water with aluminum	2003	Whitefish, *Coregonus lavaretus lavaretus*	Decrease fertilization % and fertilization rate at 250	Not North American species; only one exposure concentration, duration, exposure methods unknown
Keinanen et al.	The susceptibility of early developmental phases of an acid-tolerant and acid-sensitive fish species to acidity and aluminum	2004	Pike, *Esox lucius*	-	Mixture; dilution water is lake water
Khangarot and Das	Acute toxicity of metals and reference toxicants to a freshwater ostracod, *Cypris subglobosa* Sowerby, 1840 and correlation to EC50 values of other test models	2009	Ostracod, *Cypris subglobosa*	-	Inappropriate form of toxicant (aluminum ammonia sulfate)
Kinross et al.	The influence of pH and aluminum on the growth of filamentous algae in artificial streams	2000	Alga (various species)	~3 d Decrease growth rate at 199.6	Only one exposure concentration
Kitamura	Relation between the toxicity of some toxicants to the aquatic animals (*Tanichthys albonubes* and *Neocaridina denticulata*) and the hardness of the test solution	1990	White cloud mountain minnow, *Tanichthys albonubes*	48 hr LC50=>100,000	Not North American species; text in foreign language
Klaprat et al.	The effect of low pH and aluminum on the olfactory organ of rainbow trout, *Salmo gairdneri*	1988	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Klauda and Palmer	Responses of bluback herring eggs and larvae to pulses of aluminum	1987	Blueback herring, *Alosa aestivalis*	-	Pulsed exposures to pollutant

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Klauda et al.	Sensitivity of early life stages of blueback herring to moderate acidity and aluminum in soft freshwater	1987	Blueback herring, *Alosa aestivalis*	-	Poor control survival (>10%)
Klimek et al.	The toxicity of aluminium salts to *Lecane inermis* rotifers: Are chemical and biological methods used to overcome activated sludge bulking mutually exclusive?	2013	Rotifer, *Lecane inermis*	24 hr EC50=12	Dilution water not characterized
Kline	The effects of organic complexation on aluminum toxicity to rainbow trout (*Oncorhynchus mykiss*)	1992	Rainbow trout, *Oncorhynchus mykiss*	-	Only two exposure concentrations; effect for inorganic Al not total Al
Klusek et al.	Trace element concentrations in the soft tissue of transplanted freshwater mussels near a coal-fired power plant	1993	Eastern lampmussel, *Lampsilis radiata*	-	Field exposure, exposure concentrations not measured
Knapp and Soltero	Trout-zooplankton relationships in Medical Lake, WA following restoration by aluminum sulfate treatment	1983	-	-	Field study, exposure concentration unknown
Kobbia et al.	Studies on the effects of some heavy metals in the biological activities of some phytoplankton species. I. differential tolerance of some Nile phytoplanktonic populations in cultures to the effects of some heavy metals	1986	-	-	Mixed species exposure
Kovacevic et al.	The effect of aluminum on the planarian *Polycelis felina* (Daly.)	2009a	Planarian, *Polycelis felina*	5 d No mortality at 200,000 and pH=6.14	Not North American species
Kovacevic et al.	Aluminum deposition in hydras	2009b	Hydra	-	Bioaccumulation: steady state not reached; static, unmeasured exposure
Krishnasamy and Seshu	Phosphine fumigation influence on rice seed germination and vigor	1990	Rice, *Oryza sativa*	-	Not applicable; no aluminum toxicity data
Kroglund et al.	Exposure to moderate acid water and aluminum reduces Atlantic salmon post-smolt survival	2007	Atlantic salmon, *Salmo salar*	-	Dilution water not characterized; mixture
Kroglund et al.	Water quality limits for Atlantic salmon (*Salmo salar* L.) exposed to short term reductions in pH and increased aluminum simulating episodes	2008	Atlantic salmon, *Salmo salar*	-	Review; results of previously published papers
Kroglund et al.	Recovery of Atlantic salmon smolts following aluminum exposure defined by changes in blood physiology and seawater tolerance	2012	Atlantic salmon, *Salmo salar*	-	Only one exposure concentration; no control group

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Kudlak et al.	Determination of EC50 in toxicity data of selected heavy metals toward *Heterocypris incongruens* and their comparison to "direct-contact" and microbiotests	2011	Ostracod, *Heterocypris incongruens*	-	Sediment contact test; dilution water is distilled water
Kure et al.	Molecular responses to toxicological stressors: Profiling microRNAs in wild Atlantic salmon (*Salmo salar*) exposed to acidic aluminum-rich water	2013	Atlantic salmon, *Salmo salar*	72 hr Decrease sodium and chloride and increase glucose in blood plasma at 123-128	Only one exposure concentration; no true control group
Lacroix et al.	Aluminum dynamics on gills of Atlantic salmon fry in the presence of citrate and effects on integrity of gill structures	1993	Atlantic salmon, *Salmo salar*	-	Mixture; Al and citrate
Laitinen and Valtonen	Cardiovascular, ventilatory and haematological responses of brown trout (*Salmo trutta* L.), to the combined effects of acidity and aluminum in humic water at winter temperatures	1995	Brown trout, *Salmo trutta*	-	Mixture; dilution water is river water
Lange	Toxicity of aluminum to selected freshwater invertebrates in water of pH 7.5	1985	Fingernail clam, *Sphaerium sp.*	4 d LC50=2,360	High control mortality (26.7%)
Lee and Hughes	A plant bioassay protocol for sediment heavy metal toxicity studies using wild rice as an indicator species	1998	Rice, *Oryza sativa*	-	Exposure medium not defined; hard to determine effect concentration
Lee et al.	Zebrafish transgenic line huORFZ is an effective living bioindicator for detecting environmental toxicants	2014	Zebrafish, *Danio rerio*	-	Distilled water without proper salts added
Leino and McCormick	Response of juvenile largemouth bass to different pH and aluminum levels at overwintering temperatures: effects on gill morphology, electrolyte balance, scale calcium, liver glycogen, and depot fat	1993	Largemouth bass, *Micropterus salmoides*	84 d Increase respiratory barrier thickness and interlamellar epithelial thickness in gills at 29.2	Only one exposure concentration; too few animals per concentration
Leino et al.	Effects of acid and aluminum on swim bladder development and yolk absorption in the fathead minnow, *Pimephales promelas*	1988	Fathead minnow, *Pimephales promelas*	38 % hatching success at 25	Only two exposure concentrations, lack of details
Leino et al.	Multiple effects of acid and aluminum on brood stock and progeny of fathead minnows, with emphasis on histopathology	1990	Fathead minnow, *Pimephales promelas*	-	Repeat of used paper (Leino et al. 1989)
Li and Zhang	Toxic effects of low pH and elevated Al concentration on early life stages of several species of freshwater fishes	1992	Grass carp, *Ctenopharingodon idella*	4 d LC50=260	Lack of exposure details; text in foreign language

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Li et al.	Responses of *Ceriodaphnia dubia* to TiO_2 and Al_2O_3 nanoparticles: A dynamic nano-toxicity assessment of energy budget distribution	2011	Cladoceran, *Ceriodaphnia dubia*	-	Inappropriate form of toxicant (nanoparticles)
Li et al.	Surface interactions affect the toxicity of engineered metal oxide nanoparticles toward *Paramecium*	2012	Protozoa, *Paramecium micronucleatum*	-	Inappropriate form of toxicant (nanoparticles)
Lincoln et al.	Quality-assurance data for routine water analyses by the U.S. Geological Survey laboratory in Troy, New York - July 2005 through June 2007	2009	-	-	Not applicable; no aluminum toxicity data
Lindemann et al.	The impact of aluminum on green algae isolated from two hydrochemically different headwater streams, Bavaria, Germany	1990	Green alga, *Chlorella sp.* Green alga, *Scenedesmus sp.*	-	Exposure concentration varied over time
Linnik	Aluminum in natural waters: content, forms of migration, toxicity	2007	-	-	Review; results of previously published papers
Lithner et al.	Bioconcentration factors for metals in humic waters at different pH in the Ronnskar area (N. Sweden)	1995	-	-	Exposure concentration not known; field accumulation study
Lockard and McWalter	Effects of toxic levels of sodium, arsenic, iron and aluminium on the rice plant	1956	Rice	-	Scientific name not provided
Macova et al.	Polyaluminium chloride (PAX-18) - acute toxicity and toxicity for early development stages of common carp (*Cyprinus carpio*)	2009	Common carp, *Cyprinus carpio*	-	Inappropriate form of toxicant, PAX-18 (9% Al)
Macova et al.	Acute toxicity of the preparation PAX-18 for juvenile and embryonic stages of zebrafish (*Danio rerio*)	2010	Zebrafish, *Danio rerio*	-	Inappropriate form of toxicant, PAX-18 (9% Al)
Madigosky et al.	Concentrations of aluminum in gut tissue of crayfish (*Procambarus clarkii*), purged in sodium chloride	1992	Crayfish, *Procambarus clarkii*	-	Exposure concentration not known; field accumulation study
Maessen et al.	The effects of aluminum/calcium and pH on aquatic plants from poorly buffered environments	1992	-	-	Only one exposure concentration; sediment
Malcolm et al.	Relationships between hydrochemistry and the presence of juvenile brown trout (*Salmo trutta*) in headwater streams recovering from acidification	2012	Brown trout, *Salmo trutta*	-	Survey
Malecki-Brown et al.	Alum application to improve water quality in a municipal wastewater treatment wetland: Effects on macrophyte growth and nutrient uptake	2010	Aquatic vegatation	-	Only one exposure concentration; dilution water not characterized; mixture
Malley and Chang	Effects of aluminum and acid on calcium uptake by the crayfish *Orconectes virilis*	1985	Crayfish, *Orconectes virilis*	-	No aluminum toxicity data; calcium uptake with Al treatment

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Malley et al.	Changes in the aluminum content of tissues of crayfish held in the laboratory and in experimental field enclosures	1986	Crayfish, *Orconectes virilis*	-	Mixture; sediment
Malley et al.	Effects on ionic composition of blood tissues of *Anodonta grandis grandis* (Bivalvia) of an addition of aluminum and acid to a lake	1988	Mussel, *Anodonta grandis grandis*	-	Exposure concentrations not known; Al dosed in a lake
Malte	Effects of aluminum in hard, acid water on metabolic rate, blood gas tensions and ionic status in the rainbow trout	1986	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Malte and Weber	Respiratory stress in rainbow trout dying from aluminum exposure in soft, acid water, with or without added sodium chloride	1988	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Mao et al.	Assessment of sacrificial anode impact by aluminum accumulation in mussel *Mytilus edulis*: a large-scale laboratory test	2011	Bay mussel, *Mytilus edulis*	-	Inappropriate form of toxicant; Al anode
Markarian et al.	Toxicity of nickel, copper, zinc and aluminum mixtures to the white sucker (*Catostomus commersoni*)	1980	White sucker, *Catostomus commersoni*	-	Mixture; industrial effluent streams
Marquis	Aluminum neurotoxicity: An experimental perspective	1982	-	-	Cannot determine effect concentration
Martin et al.	Relationships between physiological stress and trace toxic substances in the bay mussel, *Mytilus edulis*, from San Fransico Bay, California	1984	Bay mussel, *Mytilus edulis*	-	Exposure concentration not known; field accumulation study
Mayer and Ellersieck	Manual of acute toxicity: interpretation and data base for 410 chemicals and 66 species of freshwater animals	1986	-	-	Review; results of previously published papers
McCahon and Pascoe	Short-term experimental acidification of a Welsh stream: Toxicity of different forms of aluminum at low pH to fish and invertebrates	1989	-	-	Mixture; dilution water is stream water
McComick and Jensen	Osmoregulatory failure and death of first-year largemouth bass (*Micropterus salmoides*) exposed to low pH and elevated aluminum at low temperature in soft water	1992	Largemouth bass, *Micropterus salmoides*	84 d 56% survival at 53.9	Only one exposure concentration; duration too short
McCormick et al.	Chronic effects of low pH and elevated aluminum on survival, maturation, spawning and embryo-larval development of the fathead minnow in soft water	1989	Fathead minnow, *Pimephales promelas*	4 d 38% hatch at 49 and pH=5.5; 94% hatch at 66 and pH=7.5	Only two exposure concentrations

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
McCormick et al.	Thresholds for short-term acid and aluminum impacts on Atlantic salmon smolts	2012	Atlantic salmon, *Salmo salar*	48 hr No mortality at 169 and pH=6.0; 100% mortality at 184 and pH=5.3	Too few exposure concentrations; duration too short
McCrohan et al.	Bioaccumulation and toxicity of aluminum in the pond snail at neutral pH	2000	Snail, *Lymnaea stagnalis*	-	Dilution water not characterized; lack of exposure details
McDonald and Milligan	Sodium transport in the brook trout, Salvelinus fontinalis: effects of prolonged low pH exposure in the presence and absence of aluminum	1988	Brook trout, *Salvelinus fontinalis*	-	Only one exposure concentration; pre-exposure to pollutant
McDonald et al.	Nature and time course of acclimation to aluminum in juvenile brook trout (*Salvelinus fontinalis*). I. Physiology	1991	Brook trout, *Salvelinus fontinalis*	-	Exposure concentration varied over time; changed dose mid experiment
McKee and Wolf	Water quality criteria. 2nd Edition	1963	-	-	Review; results of previously published papers
McLeish et al.	Skin exposure to micro- and nano-particles can cause haemostasis in zebrafish larvae	2010	Zebrafish, *Danio rerio*	-	Inappropriate form of toxicant (nanoparticles)
Mehta et al.	Relative toxicity of some non-insecticidal chemicals to the free living larvae guinea-worm (*Dracunuculus medinensis*)	1982	Guinea worm (larvae), *Dracunculus medinensis*	24 hr LC50=16,218	Lack of details; dilution water not characterized; exposure methods unknown
Meili and Wills	Seasonal concentration changes of Hg, Cd, Cu and Al in a population of roach	1985	Roach, *Rutilus rutilus*	-	Not North American species; exposure concentration not known; field accumulation study
Meland et al.	Exposure of brown trout (Salmo trutta L.) to tunnel wash water runoff -- Chemical characterisation and biological impact	2010	Brown trout, *Salmo trutta*	-	Mixture; run-off
Mendez	Water-quality data from storm runoff after the 2007 fires, San Diego County, California	2010	-	-	Survey; occurrence
Merrett et al.	The response of macroinvertebrates to low pH and increased aluminum concentrations in Welsh streams: Multiple episodes and chronic exposure	1991	-	-	Mixture; exposure concentration varied over time; dilution water is stream water
Mersch et al.	Transplanted aquatic mosses for monitoring trace metal mobilization in acidified streams of the Vosges Mountains, France	1993	Moss, *Amblystegium riparium*	-	Field exposure, exposure concentrations not measured
Michailova et al.	Functional and structural rearrangements of salivary gland polytene chromosomes of *Chironomus riparius* Mg. (Diptera, Chironomidae) in response to freshly neutralized aluminum	2003	Midge, *Chironomus riparius*	24-25 d Higher frequency of numerous somatic aberrations at 500	Only one exposure concentration

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Minzoni	Effects of aluminum on different forms of phosphorus and freshwater plankton	1984	Zooplankton community	-	Only one exposure concentration
Mitchell	The effects of aluminum and acidity on algal productivity: a study of an effect of acid deposition	1982	Green alga, *Selenastrum capricornutum*	4 hr Productivity drops at 5,000	Lack of details; abstract only
Mo et al.	A study of the uptake by duckweed of aluminum, copper, and lead from aqueous solution	1988	Duckweed	-	No scientific name of test species provided
Mohanty et al.	Effect of a low dose of aluminum on mitotic and meiotic activity, 4C DNA content, and pollen sterility in rice, *Oryza sativa* L	2004	Rice, *Oryza sativa*	-	Only one exposure concentration; distilled water without proper salts added
Monette	Impacts of episodic acid and aluminum exposure on the physiology of Atlantic salmon, *Salmo salar*, smolt development	2007	Atlantic salmon, *Salmo salar*	-	Only one exposure concentration; pulse exposures
Monette and McCormick	Impacts of short-term acid and aluminum exposure on Atlantic salmon (*Salmo salar*) physiology: a direct comparison of parr and smolts	2008	Atlantic salmon, *Salmo salar*	-	Review of Monette 2007
Monette et al.	Effects of short-term acid and aluminum exposure on the parr-smolt transformation in the Atlantic slamon (*Salmo salar*): disruption of seawater tolerance and endocrine status	2008	Atlantic salmon, *Salmo salar*	-	Review of Monette 2007
Monette et al.	Physiological, molecular, and cellular mechanisms of impaired seawater tolerance following exposure of Atlantic salmon, *Salmo salar*, smolts to acid and aluminum	2010	Atlantic salmon, *Salmo salar*	6 d NOEC (mortality)=43; LOEC=71	Only two exposure concentrations;
Morgan et al.	A plant toxicity test with the moss *Physcomitrella patens* (Hedw.) B.S.G.	1990	Moss, *Physcomitrella patens*	-	Lack of details; toxicity information not discernible
Morgan et al.	An aquatic toxicity test using the moss *Physcomitrella patens* (Hedw) B.S.G.	1993	Moss, *Physcomitrella patens*	-	Lack of details; toxicity information not discernible
Mothersill et al.	Multiple stressor effects of radiation and metals in salmon (*Salmo salar*)	2007	Atlantic salmon, *Salmo salar*	-	Only one exposure concentration; too few fish per exposure concentration (3 per treatment)
Mount et al.	Effect of long-term exposure to acid, aluminum, and low calcium in adult brook trout (*Salvelinus fontinalis*). 1. survival, growth, fecundity, and progeny survival	1988a	Brook trout, *Salvelinus fontinalis*	-	Mixture; low pH and Al
Mount et al.	Effect of long-term exposure to acid, aluminum, and low calcium in adult brook trout (*Salvelinus fontinalis*). 2. vitellogenesis and osmoregulation	1988b	Brook trout, *Salvelinus fontinalis*	-	Mixture; low pH and Al

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Mount et al.	Response of brook trout (*Salvelinus fontinalis*) fry to fluctuating acid, aluminum, and low calcium exposures	1990	Brook trout, *Salvelinus fontinalis*	-	Pre-exposure to pollutant; only two exposure concentrations
Mueller et al.	Nature and time course of acclimation to aluminum in juvenile brook trout (*Salvelinus fontinalis*). II. Gill histology	1991	Brook trout, *Salvelinus fontinalis*	-	Only one exposure concentration; exposure concentration varied over time
Mukai	Effects of chemical pretreatment on the germination of statoblasts of the freshwater bryozoan, *Pectinatella gelatinosa*	1977	Bryozoa, *Pectinatella gelatinosa*	-	Not applicable; no aluminum toxicity data
Mulvey et al.	Effects of potassium aluminium sulphate (alum) used in an *Aeromonas salmonicida* bacterin on Atlantic salmon, *Salmo salar*	1995	Atlantic salmon, *Salmo salar*	-	Inject toxicant; inappropriate form of toxicant (potassium aluminum sulphate)
Muniz and Leivestad	Toxic effects of aluminum on the brown trout, *Salmo trutta* L.	1980b	Brown trout, *Salmo trutta*	-	Mixture; dilution water is breakwater
Muniz et al.	Physiological response of brown trout (*Salmo trutta*) spawners and postspawners to acidic alminum-rich stream water	1987	Brown trout, *Salmo trutta*	-	Field exposure, exposure concentrations not measured
Muramoto	Influence of complexans (NTA, EDTA) on the toxicity of aluminum chloride and sulfate to fish at high concentrations	1981	Common carp, *Cyprinus carpio*	48 hr 30% mortality at 8,000 and pH=6.3	Dilution water not characterized
Murungi and Robinson	Synergistic effects of pH and aluminum concentrations on the life expectancy of tilapia (Mozambica) fingerlings	1987	-	-	Scientific name not given
Murungi and Robinson	Uptake and accumulation of aluminum by fish - the modifying effect of added ions	1992	Shiners, *Notropis sp.*	96 hr Whole fish tissue = 0.78 mg/g (dry weight) at 5,000	Lack of details, exposure methods unknown
Musibono and Day	Active uptake of aluminum, copper, and manganese by the freshwater amphipod *Paramelita nigroculus* in acidic waters	2000	Amphipod, *Paramelita nigroculus*	-	Not North American species; mixture
Nagasaka et al.	Novel iron-storage particles may play a role in aluminum tolerance of *Cyanidium caldarium*	2002	Red alga, *Cyanidium caldarium*	-	Only one exposure concentration; mixture (low pH and Al)
Naskar et al.	Aluminum toxicity induced poikilocytosis in an air-breathing telost, *Clarias batrachus* (Linn.)	2006	Catfish, *Clarias batrachus*	5 d Some membrane abnormalities with red blood cells at 165,000	Only two exposure concentrations; non-wild population test animals

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Neave et al.	The transcriptome and proteome are altered in marine polychaetes (Annelida) exposed to elevated metal levels	2012	Polychaete, *Ophelina sp.*	-	Mixture; field study: exposure concentration not known
Negri et al.	Effects of alumina refinery wastewater and signature metal constituents at the upper thermal tolerance of: 2. The early life stages of the coral *Acropora tenuis*	2011	Coral, *Acropora tenuis*	-	Not North American species
Neville	Physiological response of juvenile rainbow trout, Salmo gairdneri, to acid and aluminum - prediction of field responses from laboratory data	1985	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Neville and Campbell	Possible mechanisms of aluminum toxicity in a dilute, acidic environment to fingerlings and older life stages of salmonids	1988	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Nilsen et al.	Effects of acidic water and aluminum exposure on gill Na+, K+ -ATPase α-subunit isoforms, enzyme activity, physiology and return rates in Atlantic salmon (*Salmo salar* L.)	2010	Atlantic salmon, *Salmo salar*	-	Only one exposure concentration; dilution water not characterized
Nilsen et al.	Atlantic salmon (*Salmo salar* L.) smolts require more than two weeks to recover from acidic water and aluminum exposure	2013	Atlantic salmon, *Salmo salar*	7 d, 86 Gill content=26.6 µg/g dw at pH=5.7	Only one exposure concentration; not whole body or muscle
Norrgren and Degerman	Effects of different water qualities on the early development of Atlantic salmon and brown trout exposed in situ	1993	-	-	Mixture; no control group; dilution water is river water
Norrgren et al.	Accumulation and effects of aluminum in the minnow (*Phoxinus phoxinus* L.) at different pH levels	1991	Minnow, *Phoxinus phoxinus*	48 d No effect on mortality at 174 and pH=7.1; Increase mortality at 168 and pH=5.9	Only one exposure concentration
Nyberg et al.	Labile inorganic manganese - An overlooked reason for fish mortality in acidified streams?	1995	Brown trout, *Salmo trutta*	-	Field exposure, exposure concentrations not measured
Odonnell et al.	A review of the toxicity of aluminum in fresh water	1984	-	-	Review
Olaveson and Nalewajko	Effects of acidity on the growth of two *Euglena* species	2000	Alga, *Euglena mutabilis* Alga, *Euglena gracilis*	-	Mixture (low pH and Al)
Ormerod et al.	Short-term experimental acidification of Welsh stream: Comparing the biological effects of hydrogen ions and aluminum	1987	-	-	Mixture; dilution water is river water

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
OSU (Oregon State University)	Chronic toxicity of aluminum, at pH6, to the freshwater duckweed, *Lemna minor*	2012d	Duckweed, *Lemna minor*	-	Excessive EDTA used
Pagano et al.	Use of sea urchin sperm and embryo bioassay in testing the sublethal toxicity of realistic pollutant levels	1989	-	-	Mixture; effluent
Pagano et al.	Cytogenetic, developmental, and biochemical effects of aluminum, iron, and their mixture in sea urchins and mussels	1996	-	-	Lack of details; exposure duration not reported; cannot determine effect concentration
Pakrashi et al.	Cytotoxicity of aluminium oxide nanoparticles towards fresh water algal isolate at low exposure concentrations	2013a	Alga, *Chlorella ellipsoids*	-	Inappropriate form of toxicant (nanoparticles)
Pakrashi et al.	*Ceriodaphnia dubia* as a potential bio-indicator for assessing acute aluminum oxide nanoparticle toxicity in fresh water environment	2013b	Cladoceran, *Ceriodaphnia dubia*	-	Inappropriate form of toxicant (nanoparticles)
Paladino and Swartz	Interactive and synergistic effects of temperature, acid and aluminum toxicity on fish critical thermal tolerance	1984	-	-	Scientific name not given; lack of exposure details; abstract only
Palmer et al.	Comparative sensitivities of bluegill, channel catfish and fathead minnow to pH and aluminum	1988	Bluegill, *Lepomis macrochirus* Fathead minnow, *Pimephales promelas* Channel catfish, *Ictalurus punctatus*	Exposure concentrations overlapped (all over the place)	Exposure concentrations overlapped
Panda and Khan	Lipid peroxidation and oxidative damage in aquatic duckweed (*Lemna minor* L.) in response to aluminum toxicity	2004	Duckweed, *Lemna minor*	-	Cannot determine effect concentration, dilution media not defined; no statistical analysis
Pandey et al.	Salicylic acid alleviates aluminum toxicity in rice seedlings better than magnesium and calcium by reducing aluminum uptake, suppressing oxidative damage and increasing antioxidative defense	2013	Rice, *Oryza sativa*	12 d Reduced root and shoot length at 13,494	Only one exposure concentration
Papathanasiou et al.	Toxicity of aluminium in natural waters controlled by type rather than quantity of natural organic matter	2011	Snail, *Lymnaea stagnalis*	24 d Decrease mean eggs/day at 500	Only one exposure concentration
Parent et al.	Influences of natural dissolved organic matter on the interaction of aluminum with the microalga Chlorella: a test of free-ion model of trace metal toxicity	1996	Green alga, *Chlorella pyrenoidosa*	-	Mixture; Al and soil fluvic acid

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Parkhurst et al.	Inorganic monomeric aluminum and pH as predictors of acidic water toxicity to brook trout (Salvelinus fontinalis)	1990	Brook trout, *Salvelinus fontinalis*	-	Only three exposure concentrations, difficult to determine effect concentration
Parsons Engineering Science, Inc.	Aluminum water-effect ratio study for the calculation of a site-specific water quality standard in Welsh reservoir	1997	Cladoceran, *Ceriodaphnia dubia* Fathead minnow, *Pimephales promela*	-	Mixture; power plant effluent
Pauwels	Some effects of exposure to acid and aluminum on several lifestages of the Atlantic salmon (*Salmo salar*)	1990	Atlantic salmon, *Salmo salar*	24 d Mortality increased faster at 106 and pH=5.25	Only one exposure concentration
Payton and Greene	A comparison of the effect of aluminum on a single species algal assay and indigenous community algal toxicity bioassay	1980	Green alga, *Scenedesmus bijgua*	-	Lack of details; duration and exposure methods not provided
Peterson et al.	Responses of Atlantic salmon (*Salmo salar*) alevins to dissolved organic carbon and dissolved aluminum at low pH	1989	Atlantic salmon, *Salmo salar*	-	Poor control survival; only two exposure concentrations
Pettersson et al.	Physiological and structural responses of the cyanobacterium *Anabaena cylindrica* to aluminum	1985a	Blue-green alga, *Anabaena cylindrica*	-	Excessive EDTA used (672.52 µg/L)
Pettersson et al.	Accumulation of aluminum by *Anabaena cylindrica* into polyphosphate granules and cell walls: an X-ray energy-dispersive microanalysis study	1985b	Blue-green alga, *Anabaena cylindrica*	-	Bioaccumulation: not renewal or flow-through
Pettersson et al.	Aluminum uptake by A*nabaena cylindrica*	1986	Blue-green alga, *Anabaena cylindrica*	-	Bioaccumulation: not renewal or flow-through; steady state not reached
Pettersson et al.	Aluminum effects on uptake and metabolism of phosphorus by the cyanobacterium *Anabaena cylindrica*	1988	Blue-green alga, *Anabaena cylindrica*	-	Only two exposure concentrations; cannot determine effect concentration; no statistical analysis
Peuranen et al.	Effects of acidity and aluminum on fish gills in laboratory experiments and in the field	1993	Whitefish, *Coregonus lavaretus*	143 d Decrease of respiratory diffusing capacity at 150 and pH=4.75	Not North American species; dilution water not characterized; only one exposure concentration
Phillips and Russo	Metal bioaccumulation in fishes and aquatic invertebrates: A literature review	1978	-	-	Review
Piasecki and Zacharzewski	Influence of coagulants used for lake restoration on *Daphnia magna* Straus (Crustacea, Cladocera)	2010	Cladoceran, *Daphnia magna*	-	Inappropriate form of toxicant, PIX 113 and PAX 18

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Playle	Physiological effects of aluminum on rainbow trout in acidic soft water, with emphasis on the gill micro-environment	1989	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Playle and Wood	Water pH and aluminum chemistry in the gill micro-environment of rainbow trout during acid and aluminum exposures	1989	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Playle and Wood	Mechanisms of aluminum extraction and accumulation at the gills of rainbow trout, *Oncorhynchus mykiss* (Walbaum), in acidic soft water	1991	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Playle et al.	Physiological disturbances in rainbow trout during acid and aluminum exposures	1988	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Playle et al.	Physiological disturbances in rainbow trout (*Salmo gairdneri*) during acid and aluminum exposures in soft water of two calcium concentrations	1989	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Poleo	Temperature as a major factor concerning fish mortality in acidic Al-rich waters: Experiments with young stage Atlantic salmon (*Salmo salar* L.)	1992	Atlantic salmon, *Salmo salar*	-	Text in foreign language
Poleo	Aluminum polymerization: a mechanism of acute toxicity of aqueous aluminum to fish	1995	-	-	Review
Poleo and Muniz	Effect of aluminum in soft water at low pH and different temperatures on mortality, ventilation frequency and water balance in smoltifying Atlantic salmon, *Salmo salar*	1993	Atlantic salmon, *Salmo salar*	LT50=49 hr at 271 (1˚C); LT50=21 hr at 272 (10˚C)	Only one exposure concentration; no control group
Poleo et al.	The influence of temperature on aqueous aluminum chemistry and survival of Atlantic salmon (*Salmo salar* L.) fingerlings	1991	Atlantic salmon, *Salmo salar*	LT50=170 hr at 403 (1˚C); LT50=46 hr at 402 (10˚C)	Only one exposure concentration; no control group
Poleo et al.	Survival of crucian carp, *Carassius carassius*, exposed to a high low-molecular weight inorganic aluminum challenge	1995	Crucian carp, *Carassius carassius*	-	Not North American species; only two exposure concentrations; no true control group
Poleo et al.	Toxicity of acid aluminum-rich water to seven freshwater fish species: a comparative laboratory study	1997	-	-	Too few organisms per treatment, 1-2 fish per treatment
Poleo et al.	The effect of various metals on *Gyrodactylus salaris* (Plathyrlminthes, Monogenea) infections in Atlantic salmon (*Salmo salar*)	2004	Parasite, *Gyrodactylus salaris* Atlantic salmon, *Salmo salar*	-	Two species tested with one exposure; not sure how much exposure to the parasite

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Pond et al.	Downstream effects of mountaintop coal mining: comparing biological conditions using family- and genus-level macroinvertebrate bioassessment tools	2008	-	-	Field survey, mixture
Poor	Effect of lake management efforts on the trophic state of a subtropical shallow lake in Lakeland, Florida, USA	2010	-	-	Survey
Poston	Effects of dietary aluminum on growth and composition of young Atlantic salmon	1991	Atlantic salmon, *Salmo salar*	-	Fed pollutant
Prange and Dennison	Physiological responses of five seagrass species to trace metals	2000	Seagrass	-	Exposure concentration not known; field accumulation study
Pribyl et al.	Cytoskeletal alterations in interphase cells of the green alga Spirogyra decimina in response to heavy metals exposure: I. the effect of cadmium	2005	Green alga, *Spirogyra decimina*	-	Not applicable; cadmium study
Pynnonen	Aluminum accumulation and distribution in the freshwater clams (Unionidae)	1990	Mussel, *Anodonta anatina* Mussel, *Unio pictorum*	-	Not North American species; exposure concentrations varied too much over time
Quiroz-Vazquez et al.	Bioavailability and toxicity of aluminum in a model planktonic food chain (*Chlamydomonas-Daphnia*) at neutral pH	2010	-	-	Bioaccumulation: not renewal or flow-through; steady state not reached
Radic et al.	Ecotoxicological effects of aluminum and zinc on growth and antioxidants in *Lemna minor* L.	2010	Duckweed, *Lemna minor*	15 d NOEC (relative growth rate)=4,047; LOEC=8,094	
Rahman et al.	Varietal differences in the growth of rice plants in response to aluminum and silicon	1998	Rice	-	Scientific name not given
Rai et al.	Physiological and biochemical responses of *Nostoc linckia* to combined effects of aluminium, fluoride and acidification	1996	Cyanobacteria, *Nostoc linckia*	15 d pH 7.5 LC50=121.4, pH 6.0 LC50=11.13, pH4.5 LC50=3.643	Only three exposure concentrations
Rajesh	Toxic effect of aluminum in *Oreochromis mossambicus* (Peters)	2010	Mozambique tilapia, *Oreochromis mossambicus*	4 d LC50=8,000	Dilution water not characterized
Ramamoorthy	Effect of pH on speciation and toxicity of aluminum to rainbow trout (*Salmo gairdneri*)	1988	Rainbow trout, *Oncorhynchus mykiss*	-	Mixture
Razo-Estrada et al.	Aluminum-induced oxidative stress and apoptosis in liver of the common carp, *Cyprinus carpio*	2013	Common carp, *Cyprinus carpio*	96 hr Increase lipid peroxidation at 50	Only three exposure concentrations

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Reader and Morris	Effects of aluminium and pH on calcium fluxes, and effects of cadmium and manganese on calcium and sodium fluxes in brown trout (*Salmo trutta* L.)	1988	Brown trout, *Salmo trutta*	-	Only one exposure concentration; too few fish per exposure concentration
Reader et al.	Growth, mineral uptake and skeletal calcium deposition in brown trout, *Salmo trutta* L., yolk-sac fry exposed to aluminum and manganese in soft acid water	1988	Brown trout, *Salmo trutta*	-	Mixture, Al, NH_3, NH_4
Reader et al.	The effects of eight trace metals in acid soft water on survival, mineral uptake and skeletal calcium deposition in yolk-sac fry of brown trout, *Salmo trutta* L.	1989	Brown trout, *Salmo trutta*	30 d 0% survival at 178.1 and pH=4.5; No effect on survival at 170.0 at pH=6.5	Only one exposure concentration
Reader et al.	Episodic exposure to acid and aluminum in soft water: survival and recovery of brown trout, *Salmo trutta* L.	1991	Brown trout, *Salmo trutta*	-	No control group
Reid et al.	Acclimation to sublethal aluminum: modification of metal - gill surface interactions of juvenile rainbow trout (*Oncorhynchus mykiss*)	1991	Rainbow trout, *Oncorhynchus mykiss*	-	Only two exposure concentrations; pre-exposure to pollutant
Reznikoff	Micrurgical studies in cell physiology. II. The action of chlorides of lead, mercury, copper, iron, and aluminum on the protoplasm of Amoeba proteus	1926	-	-	Lack of exposure details; dilution water not characterized
Riseng et al.	The effect of pH, aluminum, and chelator manipulations on the growth of acidic and circumneutral species of *Asterionella*	1991	Diatom, *Asterionella ralfsii* Diatom, *Asterionella formosa*	-	Mixture; EDTA and Al
Rizzo et al.	Removal of THM precursors from a high-alkaline surface water by enhanced coagulation and behaviour of THMFP toxicity on *D. magna*	2005	Cladoceran, *Daphnia magna*	-	Not applicable; no aluminum toxicity data
Robertson and Liber	Bioassays with caged *Hyalella azteca* to determine in situ toxicity downstream of two Saskatchewan, Canada, uranium operations	2007	Amphipod, *Hyalella azteca*	-	Mixture; downstream exposure of uranium mining operation
Robertson et al.	Survival of *Cryptosporidium parvum* oocysts under various environmental pressures	1992	Parasite, *Cryptosporidium parvum*	-	Poor control survival; only two exposure concentrations
Robinson and Deano	The synergistic effects of acidity and aluminum on fish (Golden shiners) in Louisiana	1985	Golden shiner, *Notemigonus crystoleucas*	-	Dilution water not characterized; high control mortality (10-20%)

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Robinson and Deano	Acid rain: the effect of pH, aluminum, and leaf decomposition products on fish survival	1986	Golden shiner, *Notemigonus crystoleucas*	-	Only two exposure concentrations
Rosemond et al.	Comparative analysis of regional water quality in Canada using the water quality index	2009	-	-	Survey; no aluminum toxicity data
Rosseland and Skogheim	Comparative study on salmonid fish species in acid aluminum-rich water II. Physiological stress and mortality of one- and two-year-old fish	1984	-	-	Mixture; dilution water is lake water
Rosseland et al.	Mortality and physiological stress of year-classes of landlocked and migratory Atlantic salmon, brown trout and brook trout in acidic aluminium-rich soft water	1986	Atlantic salmon, *Salmo salar* Brown trout, *Salmo trutta* Brook trout, *Salvelinus fontinalis*	83 hr, pH=5.14, 228 100% mortality; 0% mortality; 0% mortality	Dilution water not characterized; only one exposure concentration
Rosseland et al.	Environmental effects of aluminum	1990	-	-	Review of previously published literature
Rosseland et al.	The mixing zone between limed and acidic river waters: Complex aluminum and extreme toxicity for salmonids	1992	-	-	Mixture; exposure concentration varied over time; dilution water is river water
Roy and Bhadra	Hematoxylin staining of seedling roots is a potential phenotypic index for screening of aluminium tolerance in rice (*Oryza sativa* L.)	2013	Rice, *Oryza sativa*	-	Not applicable, no aluminum toxicity information
Royset et al.	Diffusive gradients in thin films sampler predicts stress in brown trout (*Salmo trutta* L.) exposed to aluminum in acid fresh waters	2005	Brown trout, *Salmo trutta*	-	Mixture; dilution water is river water
Rueter et al.	Indirect aluminum toxicity to the green alga *Scenedesmus* through increased cupric ion activity	1987	Green alga, *Scenedesmus quadricauda*	-	Mixture; Al and Cu
Sacan and Balcioglu	Bioaccumulation of aluminium in *Dunaliella tertiolecta* in natural sewater: Aluminium-metal (Cu, Pb, Se) interactions and influence of pH	2001	Phytoplankton, *Dunaliella tertiolecta*	-	Bioaccumulation, steady state not documented
Sadler and Lynam	Some effects on the growth of brown trout from exposure to aluminum at different pH levels	1987	Brown trout, *Salmo trutta*	7 d NOEC (specific growth rate)=18.87 at pH=5.5; LOEC=30.04 at pH=5.5	Too few exposure concentrations; duration

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Sadler and Lynam	The influence of calcium on aluminum-induced changes in the growth rate and mortality of brown trout, *Salmo trutta* L.	1988	Brown trout, *Salmo trutta*	42 d Increase mortality at 54 and hardness from 3-6 mg/L as $CaCO_3$, but not greater than 9 mg/L	Only one exposure concentration
Salbu et al.	Environmentally relevant mixed exposures to radiation and heavy metals induce measurable stress responses in Atlantic salmon	2008	Atlantic salmon, *Salmo salar*	-	Only one exposure concentration; mixture
Sauer	Heavy metals in fish scales: accumulation and effects on cadmium regulation in the mummichog, *Fundulus heteroclitus* L.	1986	Mummichog, *Fundulus heteroclitus*	-	Not applicable; no aluminum toxicity data
Sayer	Survival and subsequent development of brown trout, *Salmo trutta* L., subjected to episodic exposures of acid, aluminum and copper in soft water during embryonic and larval stages	1991	Brown trout, *Salmo trutta*	-	Only one exposure concentration; mixture; low pH and Al
Sayer et al.	Embryonic and larval development of brown trout, Salmo trutta L.: exposure to aluminum, copper, lead or zinc in soft, acid water	1991a	Brown trout, *Salmo trutta*	700 d 13% mortality at 161.8	Only one exposure concentration
Sayer et al.	Embryonic and larval development of brown trout, *Salmo trutta* L.: exposure to trace metal mixtures in soft water	1991b	Brown trout, *Salmo trutta*	-	Only two exposure concentrations; mixture
Sayer et al.	Effects of six trace metals on calcium fluxes in brown trout (*Salmo trutta* L.) in soft water	1991c	Brown trout, *Salmo trutta*	-	Only two exposure concentrations; mixture
Sayer et al.	Mineral content and blood parameters of dying brown trout (*Salmo trutta* L.) exposed to acid and aluminum in soft water	1991d	Brown trout, *Salmo trutta*	4 d Increase haematocrit and decrease plasma sodium levels and whole body sodium and potassium content at 273.6	Only one exposure concentration; too few organisms per concentration
Schindler and Turner	Biological, chemical and physical responses of lakes to experimental acidification	1982	-	-	Mixture, Al and low pH
Schofield and Trojnar	Aluminum toxicity to brook trout (*Salvelinus fontinalis*) in acidified waters	1980	Brook trout, *Salvelinus fontinalis*	-	Mixture; dilution water not characterized
Schumaker et al.	Zooplankton responses to aluminum sulfate treatment of Newman Lake, Washington	1993	-	-	Exposure concentrations not known
Segner et al.	Growth, aluminum uptake and mucous cell morphometrics of early life stages of brown trout, *Salmo trutta*, in low pH water	1988	Brown trout, *Salmo trutta*	5d Decrease weight and length at 230	Only one exposure concentration

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Senger et al.	Aluminum exposure alters behavioral parameters and increases acetylcholinesterase activity in zebrafish (*Danio rerio*) brain	2011	Zebrafish, *Danio rerio*	4 d Increase AChE activity in brain at 10.12 at pH=5.8 but not pH=6.8	Only one exposure concentration
Shabana et al.	Studies on the effects of some heavy metals on the biological activities of some phytoplankton species. II. The effects of some metallic ions on the growth criteria and morphology of *Anabaena oryzae* and *Aulosira fertilissima*	1986a	-	-	Lack of details; cannot determine effect concentration
Shabana et al.	Studies on the effects of some heavy metals on the biological activities os some phytoplankton species. III. Effects Al3+, Cr3+, Pb2+ and Zn 2+ on heterocyst frequency, nitrogen and phosphorus metabolism of *Anabaena oryzae* and *Aulosira fertilissima*	1986b	-	-	Lack of details; cannot determine effect concentration
Sharma et al.	Protective effect of *Spirulina* and tamarind fruit pulp diet supplement in fish (*Gambusia affinis* Baird & Girard) exposed to sublethal concentration of fluoride, aluminum and aluminum fluoride	2012	Western mosquitofish, *Gambusia affinis*	-	Only one exposure concentration; poor control survival
Shuhaimi-Othman et al.	Toxicity of eight metals to Malaysian freshwater midge larvae *Chironomus javanus* (Diptera, Chironomidae)	2011b	Midge, *Chironomus javanus*	4 d LC50=1,430	Not North American species
Shuhaimi-Othman et al.	Toxicity of metals to tadpoles of the commone Sunda toad, *Duttaphrynus melanostictus*	2012c	Sunda toad, *Duttaphrynus melanostictus*	4 d LC50=1,900	Not North American species
Siebers and Ehlers	Heavy metal action on transintegumentary absorption of glycine in two annelid species	1979	-	-	Not applicable; no aluminum toxicity data
Simon	Sediment and interstitial water toxicity to freshwater mussels and the ecotoxicological recovery of remediated acrid mine drainage streams	2005	-	-	Sediment exposure
Sivakumar and Sivasubramanian	FT-IR study of the effect of aluminum on the muscle tissue of *Cirrhinus mrigala*	2011	Carp hawk, *Cirrhinus mrigala*	4 d LC50=8,200	Not North American species; dilution water not characterized
Skogheim and Rosseland	A comparative study on salmonid fish species in acid aluminum-rich water I. Mortality of eggs and alevins	1984	Trout	-	Mixture; dilution water is lake water
Skogheim and Rosseland	Mortality of smolt of Atlantic salmon, *Salmo salar* L., at low levels of aluminum in acidic softwater	1986	Atlantic salmon, *Salmo salar*	-	Mixture; dilution water is lake water

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Skogheim et al.	Addition of NaOH, limestone slurry and finegrained limestone to acidified lake water and the effects on smolts of Atlantic salmon (*Salmo salar* L.)	1987	Atlantic salmon, *Salmo salar*	-	Prior exposure; stressed organisms
Soleng et al.	Toxicity of aqueous aluminum to the ectoparasitic monogenean *Gyrodactylus salaris*	2005	-	-	Only two exposure concentrations; two species tested with one exposure; not sure how much exposure to the parasite
Sonnichsen	Toxicity of a phosphate-reducing agent (aluminum sulphate) on the zooplankton in the lake Lyngby So	1978	-	-	Not applicable; no aluminum toxicity data
Sparling	Conditioned aversion of aluminum sulfate in black ducks	1990	Black ducks, *Anas rubripes*	-	Dietary exposure
Sparling and Lowe	Environmental hazards of aluminum to plants, invertebrates, fish and wildlife	1996a	-	-	Review; results of previously published papers
Sparling and Lowe	Metal concentrations of tadpoles in experimental ponds	1996b	-	-	Exposed through soil
Sparling and Lowe	Metal concentrations in aquatic macrophytes as influenced by soil and acidification	1998	Macrophytes	-	Exposed through soil
Sparling et al.	Responses of amphibian populations to water and soil factors in experimentally-treated aquatic macrocosms	1995	-	-	Exposed through soil
Sparling et al.	Ecotoxicology of aluminum to fish and wildlife	1997	-	-	Review
Staurnes et al.	Reduced carbonic anhydrase and Na-K-ATPase activity in gills of salmonids exposed to aluminium-containing acid water	1984	-	-	Mixture, Al and low pH
Staurnes et al.	Effects of acid water and aluminum on parr-smolt transformation and seawater tolerance in Atlantic salmon, *Salmo salar*	1993	Atlantic salmon, *Salmo salar*	-	Only one exposure concentration; high control mortality (>40%)
Stearns et al.	Occurrence of cyanide-resistant respiration and of increased concentrations of cytochromes in Tetrahymena cells grown with various metals	1978	-	-	Cannot determine effect concentration
Storey et al.	An appraisal of some effects of simulated acid rain and aluminum ions on *Cyclops viridis* (Crustacea, Copepoda) and *Gammarus pulex* (Crustacea, Amphipoda)	1992	Copepod, *Cyclops viridis* Amphipod, *Gammarus pulex*	168 hr LC50=>26,980; LC50=>26,980	Dilution water not characterized
Strigul et al.	Acute toxicity of boron, titanium dioxide, and aluminum nanoparticles to Daphnia magna and Vibrio fischeri	2009	Cladoceran, *Daphnia magna*	-	Inappropriate form of toxicant, nanoparticles

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Sudo and Aiba	Effect of some metals on the specific growth rate of Ciliata isolated from activated sludge	1975	-	-	Pre-exposure to pollutant; isolated from activated sludge
Tabak and Gibbs	Effects of aluminum, calcium and low pH on egg hatching and nymphal survival of *Cloeon triangulifer* McDunnough (Ephemeroptera: Baetidae)	1991	Mayfly, *Cloeon triangulifer*	No effect on hatch success at 100 and pH=5.5	Only two exposure concentrations
Takano and Shimmen	Effects of aluminum on plasma membrane as revealed by analysis of alkaline band formation in internodal cells of *Chara corallina*	1999	Alga, *Chara corallina*	-	Excised cells
Tanaka and Navasero	Aluminum toxicity of the rice plant under water culture conditions	1966	-	-	Species not given
Taneeva	Toxicity of some heavy metals for hydrobionts	1973	Barnacle, *Balanus eburneus*	LC50=240	Text in foreign language
Taskinen et al.	Effect of pH, iron and aluminum on survival of early life history stages of the endangered freshwater pearl mussel, *Margaritifera margaritifera*	2011	Pearl mussel, *Margaritifera margaritifera*	-	Mixture; dilution water is river water
Tease and Coler	The effect of mineral acids and aluminum from coal leachate on substrate periphyton composition and productivity	1984	-	-	Mixture, Al and low pH
Teien et al.	Sodium silicate as alternative to liming-reduced aluminium toxicity for Atlantic salmon (*Salmo salar* L.) in unstable mixing zones	2006b	Atlantic salmon, *Salmo salar*	-	Only one exposure concentration; dilution water not characterized
Terhaar et al.	Toxicity of photographic processing chemicals to fish	1972	-	-	Mixture; no aluminum toxicity data
Thawornwong and Van Diest	Influences of high acidity and aluminum on the growth of lowland rice	1974	Rice	-	Scientific name not provided
Thomas	Effects of certain metallic salts upon fishes	1915	Mummichog, *Fundulus heteroclitus*	36 hr 100% mortality at 2,208; 120 hr 100% mortality at 1,104	Dilution water not characterized; lack of exposure details
Thompson et al.	Concentration factors of chemical elements in edible aquatic organisms	1972	-	-	Review

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Thomsen et al.	Effect of aluminum and calcium ions on survival and physiology of rainbow trout *Salmo gairdneri* (Richardson) eggs and larvae exposed to acid stress	1988	Rainbow trout, *Oncorhynchus mykiss*	25 d LC50=3,800 (soft water); LC50=71,000 (hard water)	Dilution water not characterized; unmeasured chronic exposure
Thorstad et al.	Reduced marine survival of hatchery-reared Atlantic salmon post-smolts exposed to aluminium and moderate acidification in freshwater	2013	Atlantic salmon, *Salmo salar*	-	Only two exposure concentrations; surgically altered test species (outfitted with acoustic transmitters)
Tietge et al.	Morphometric changes in gill secondary lamellae of brook trout (Salvelinus fontinalis) after long-term exposure to acid and aluminum	1988	Brook trout, *Salvelinus fontinalis*	147 d No effect on survival, but decrease growth at 393	Only one exposure concentration
Tipping et al.	Metal accumulation by stream bryophytes, related to chemical speciation	2008	Bryophytes	-	Exposure concentration not known; field accumulation study
Tomasik et al.	The metal-metal interactions in biological systems. Part III. *Daphnia magna*	1995a	Cladoceran, *Daphnia magna*	24 hr 10% mortality at 7,500	High control mortality (10-20%)
Tomasik et al.	The metal-metal interactions in biological systems. Part IV. Freshwater snail *Bulinus globosus*	1995b	Snail, *Bulinus globosus*	96 hr 100% mortality at 10,000; 1% mortality at 3,000	Not North American species
Troilo et al.	Biochemical responses of *Prochilodus lineatus* after 24-h exposure to aluminum	2007	Sabalo, *Prochilodus lineatus*	24 hr Increase in liver GST and increase in gill CAT at 100	Not North American species; lack of details; exposure methods unknown; abstract only
Truscott et al.	Effect of aluminum and lead on activity in the freshwater pond snail *Lymnaea stagnalis*	1995	Snail, *Lymnaea stagnalis*	45 hr Reduce activity at 500	Only two exposure concentrations
Tunca et al.	Tissue distribution and correlation profiles of heavy-metal accumulation in the freshwater crayfish *Astacus leptodactylus*	2013	Crayfish, *Astacus leptodactylus*	-	Field bioaccumulation study: exposure concentration not know; not North American species
Tyler-Jones et al.	The effects of acid water and aluminium on the embryonic development of the common frog, *Rana temporaria*	1989	Common frog, *Rana temporaria*	-	Not North American species; only three exposure concentrations
Umebese and Motajo	Accumulation, tolerance and impact of aluminium, copper and zinc on growth and nitrate reductase activity of *Ceratophyllum demersum* (Hornwort)	2008	Hornwort, *Ceratophyllum demersum*	15 d Decrease dry biomass at 3,000	Only two exposure concentrations

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Upreti et al.	Toxic effects of aluminium and fluoride on planktonic community of the microcosms	2013	Microcosms	-	Only one exposure concentration; dilution water not characterized
van Coillie and Rousseau	Mineral composition of the scales of *Catostomus commersoni* from two different waters: Studies using electron microprobe analysis	1974	White sucker, *Catostomus commersoni*	-	Exposure concentration not known; field accumulation study
van Dam et al.	Impact of acidification on diatoms and chemistry of Dutch moorland pools	1981	-	-	Mixture, Al and low pH
Van Hoecke et al.	Influence of alumina coating on characteristics and effects of SiO2 nanoparticles in algal growth inhibition assays at various pH and organic matter contents	2011	Alga	-	Inappropriate form of toxicant (nanoparticles)
Vazquez et al.	Effects of water acidity and metal concentrations on accumulation and within-plant distribution of metals in the aquatic bryophyte *Fontinalis antipyretica*	2000	Bryophyte, *Fontinalis antipyretica*	-	Exposure concentration not known; field accumulation study
Velzeboer et al.	Release of geosmin by *Anabaena circinalis* following treatment with aluminium sulphate	1995	Cyanobacteria, *Anabaena circinalis*	-	Only two exposure concentrations; dilution water not characterized
Velzeboer et al.	Aquatic ecotoxicity tests of some nanomaterials	2008	-	-	Inappropriate form of toxicant, nanoparticles
Verbost et al.	The toxic mixing zone of neutral and acidic river water: acute aluminum toxicity in brown trout (*Salmo trutta* L.)	1995	Brown trout, *Salmo trutta*	-	Mixture; dilution water is lake water
Vieira et al.	Effects of aluminum on the energetic substrates in neotropical freshwater *Astyanax bimaculatus* (Teleostei: Characidae) females	2013	Two spot astyanax, *Astyanax bimaculatus*	96 hr Decrease T_4 levels and increase T_3 levels at 600	Not North American species; only one exposure concentration
Vinay et al.	Toxicity and dose determination of quillaja saponin, aluminum hydroxide and squalene in olive flounder (*Paralichthys olivaceus*)	2013	Olive flounder, *Paralichthys olivaceus*	-	Injected toxicant
Vincent et al.	Accumulation of Al, Mn, Fe, Cu, Zn, Cd, and Pb by the bryophyte *Scapania undulata* in three upland waters of different pH	2001	Bryophyte, *Scapania undulata*	-	Exposure concentration not known; field accumulation study
Vuorinen et al.	The sensitivity to acidity and aluminum of newly-hatched perch (*Perca fluviatilis*) originating from strains from four lakes with different degrees	1994a	Perch, *Perca fluviatilis*	7 d LC50=>1,000	Not North American species

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Vuorinen et al.	The sensitivity to acidification of pike (*Esox lucius*), whitefish (*Coregonus lavaretus*) and roach (*Rutilus rutilus*): a comparison of field and laboratory studies	1994b	-	-	Review of Vuorineu et al. 1993
Vuorinen et al.	Reproduction, blood and plasma parameters and gill histology of vendace (*Coregonus albula* L.) in long-term exposure to acidity to aluminum	2003	Vendace, *Coregonus albula*	60 d Decrease growth at 168 and pH=5.25; Decrease growth at 213 and pH=4.75	Not North American species; only one exposure concentration
Wakabayashi et al.	Relative lethal sensitivity of two Daphnia species to chemicals	1988	-	-	Text in foreign language
Walker et al.	Effects of low pH and aluminum on ventilation in the brook trout (*Salvelinus fontinalis*)	1988	Brook trout, *Salvelinus fontinalis*	-	Surgically altered fish; only one exposure concentration
Walker et al.	Effects of long-term preexposure to sublethal concentrations of acid and aluminum on the ventilatory response to aluminum challenge in brook trout (*Salvelinus fontinalis*)	1991	Brook trout, *Salvelinus fontinalis*	-	Pre-exposure to pollutant
Wallen et al.	Toxicity to *Gambusia affinis* of certain pure chemicals in turbid waters	1957	Western mosquitofish, *Gambusia affinis*	96 hr LC50=26,919 ($AlCl_3$); LC50=37,062 ($Al_2(SO_4)_3$	Dilution water not characterized; farm pond with high turbidity and poor fish population
Walton et al.	Tissue accumulation of aluminum is not a predictor of toxicity in the freshwater snail, *Lymnaea stagnalis*	2009	Snail, *Lymnaea stagnalis*	steady state not reached	Lack of details; steady state not reached
Walton et al.	Trophic transfer of aluminium through an aquatic grazer-omnivore food chain	2010a	Snail, *Lymnaea stagnalis* Crayfish, *Pacifasticus leniusculus*	-	Bioaccumulation: steady state not reached
Walton et al.	The suitability of gallium as a substitute for aluminum in tracing experiments	2010b	Snail, *Lymnaea stagnalis*	-	Bioaccumulation: steady state not reached
Wang et al.	Optimising indoor phosphine fumigation of paddy rice bag-stacks under sheeting for control of resistant insects	2006	-	-	Not applicable, no aluminum toxicity information
Wang et al.	Toxicity of nanoparticulate and bulk ZnO, Al2O3 and TiO2 to the nematode *Caenorhabditis elegans*	2009	Nematode, *Caenorhabditis elegans*	-	Inappropriate form of toxicant (nanoparticles)
Wang et al.	Synergistic toxic effect of nano-Al2O3 and As(V) on *Ceriodaphnia dubia*	2011	Cladoceran, *Ceriodaphnia dubia*	-	Inappropriate form of toxicant (nanoparticles)

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Ward et al.	Influences of aqueous aluminum on the immune system of the freshwater crayfish Pacifasticus leniusculus	2006	Crayfish, *Pacifasticus leniusculus*	-	Only one exposure concentration; test organism injected with bacteria
Waring and Brown	Ionoregulatory and respiratory responses of brown trout, *Salmo trutta*, exposed to lethal and sublethal aluminum in acidic soft waters	1995	Brown trout, *Salmo trutta*	5 d NOEC (survival)=12.5; LOEC=25	Too few exposure concentrations
Waring et al.	Plasma prolactin, cortisol, and thyroid response of the brown trout (*Salmo trutta*) exposed to lethal and sublethal aluminum in acidic soft waters	1996	Brown trout, *Salmo trutta*	-	Surgically altered test species
Waterman	Effect of salts of heavy meatls on development of the sea urchin, *Arbacia punctulata*	1937	Sea urchin, *Arbacia punctulata*	-	Dilution water not characterized; cannot determine effect concentration
Wauer and Teien	Risk of acute toxicity for fish during aluminum application to hardwater lakes	2010	-	-	Survey
Weatherley et al.	The response of macroinvertebrates to experimental episodes of low pH with different forms of aluminum, during a natural spate	1988	-	-	Mixture; dilution water is stream water
Weatherley et al.	The survival of early life stages of brown trout (*Salmo trutta* L.) in relation to aluminum speciation in upland Welsh streams	1990	Brown trout, *Salmo trutta*	-	Mixture; dilution water is stream water
Weatherley et al.	Liming acid streams: aluminum toxicity to fish in mixing zones	1991	-	-	Mixture; dilution water is stream water
White et al.	Avoidance of aluminum toxicity on freshwater snails involves intracellular silicon-aluminum biointeraction	2008	Snail, *Lymnaea stagnalis*	-	Mixture, Al and Si
Whitehead and Brown	Endocrine responses of brown trout, Salmo trutta L., to acid, aluminum and lime dosing in a Welsh hill stream	1989	Brown trout, *Salmo trutta*	-	Mixture, field experiment-dosed stream
Wilkinson and Campbell	Aluminum bioconcentration at the gill surface of juvenile Atlantic salmon in acidic media	1993	Atlantic salmon, *Salmo salar*	-	Bioaccumulation: steady state not reached
Wilkinson et al.	Surface complexation of aluminum on isolated fish gill cells	1993	Largemouth bass, *Micropterus salmoides*	-	Exposed cells only
Williams et al.	Assessment of surface-water quantity and quality, Eagle River Watershed, Colorado, 1947-2007	2011	-	-	Not applicable; no aluminum toxicity data
Wilson	Physiological and metabolic costs of acclimation to chronic sub-lethal acid and aluminum exposure in rainbow trout	1996	-	-	Review

Author	**Title**	**Date**	**Organism(s)**	**Concentration (µg/L)**	**Reason Unused**
Wilson and Hyne	Toxicity of acid-sulfate soil leachate and aluminum to embryos of the Sydney Rock Oyster	1997	Sydney rock oyster, *Accostrea commercialis*	48 hr EC50 (development)=222; EC50=227	Not North American species
Wilson and Wood	Swimming performance, whole body ions, and gill A1 accumulation during acclimation to sublethal aluminum in juvenile rainbow trout (*Oncorhynchus mykiss*)	1992	Rainbow trout, *Oncorhynchus mykiss*	22 d No effect on mortality, but decrease weight at 31.4	Only one exposure concentration
Wilson et al.	Metabolic costs and physiological consequences of acclimation to aluminum in juvenile rainbow trout (*Oncorhynchus mykiss*). 1: Acclimation specificity, resting physiology, feeding, and growth	1994a	Rainbow trout, *Oncorhynchus mykiss*	34 d 5.5% mortality at 38.1	Only one exposure concentration
Wilson et al.	Metabolic costs and physiological consequences of acclimation to aluminum in juvenile rainbow trout (*Oncorhynchus mykiss*). 2: Gill morphology, swimming performance, and aerobic scope	1994b	Rainbow trout, *Oncorhynchus mykiss*	34 d Decrease # of mucous cells in gills, oxygen consumption rates, swimming performance at 38	Only one exposure concentration
Wilson et al.	Growth and protein turnover during acclimation to acid and aluminum in juvenile rainbow trout (*Oncorhynchus mykiss*)	1996	Rainbow trout, *Oncorhynchus mykiss*	-	Only one exposure concentration; pre-exposure to pollutant
Winter et al.	Influences of acidic to basic water pH and natural organic matter on aluminum accumulation by gills of rainbow trout (*Oncorhynchus mykiss*)	2005	Rainbow trout, *Oncorhynchus mykiss*	-	Bioaccumulation: not renewal or flow-through exposure; high control mortality
Witters	Acute acid exposure of rainbow trout, S*almo gairdneri* Richardson: effects of aluminum and calcium on ion balance and haematology	1986	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species; only one exposure concentration
Witters et al.	Interference of aluminum and pH on the Na-influx in an aquatic insect *Corixa punctata* (Illig.)	1984	Waterbug, *Corixa punctata*	-	Mixture; low pH and Al
Witters et al.	Ionoregulatory and haematological responses of rainbow trout *Salmo gairdneri* Richardson to chronic acid and aluminum stress	1987a	Rainbow trout, *Oncorhynchus mykiss*	48 hr ~50% mortality at 200	Only one exposure concentration
Witters et al.	Physiological study on the recovery of rainbow trout (*Salmo gairdneri* Richardson) from acid and Al stress	1987b	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species; only one exposure concentration
Witters et al.	Haematological disturbances and osmotic shifts in rainbow trout, *Oncorhynchus mykiss* (Walbaum) under acid and aluminum exposure	1990a	Rainbow trout, *Oncorhynchus mykiss*	2.5 d ~53% mortality at 200	Only one exposure concentration

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Witters et al.	The effect of humic substances on the toxicity of aluminum to adult rainbow trout, *Oncorhynchus mykiss* (Walbaum)	1990b	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Witters et al.	Adrenergic response to physiological disturbances in rainbow trout, Oncorhynchus mykiss, exposed to aluminum at acid pH	1991	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Witters et al.	Physicochemical changes of aluminum in mixing zones: Mortality and physiological disturbances in brown trout (*Salmo trutta* L.)	1996	Brown trout, *Salmo trutta*	48 hr 60% mortality at 184.0	Only one exposure concentration
Wold	Some effects of aluminum sulfate and arsenic sulfide on *Daphnia pulex* and *Chironomus tentans*	2001	Cladoceran, *Daphnia pulex* Midge, *Chironomus tentans*	-	Inadequate exposure methods; chronic was a static, unmeasured exposure; pre-exposure to pollutant
Wold et al.	Life-history responses of *Daphnia pulex* with exposure to aluminum sulfate	2005	Cladoceran, *Daphnia pulex*	Increased survivorship in clones that were prior-exposed to alum treated lakes	Only three exposure concentrations; dilution water not characterized
Wood and McDonald	The physiology of acid/aluminum stress in trout	1987	Trout	-	Too few exposure concentrations, cannot determine effect concentration
Wood et al.	Blood gases, acid-base status, ions, and hematology in adult brook trout (*Salvelinus fontinalis*) under acid/aluminum exposure	1988a	Brook trout, *Salvelinus fontinalis*	-	Only one exposure concentration; surgically altered test species
Wood et al.	Physiological evidence of acclimation to acid/aluminum stress in adult brook trout (*Salvelinus fontinalis*). 1. Blood composition and net sodium fluxes	1988b	Brook trout, *Salvelinus fontinalis*	10 wk 28% mortality at 77	Only two exposure concentrations
Wood et al.	Physiological evidence of acclimation to acid/aluminum stress in adult brook trout (*Salvelinus fontinalis*). 2. Blood parameters by cannulation	1988c	Brook trout, *Salvelinus fontinalis*	-	Only one exposure concentration; surgically altered test species
Wood et al.	Whole body ions of brook trout (*Salvelinus fontinalis*) alevins: responses of yolk-sac and swim-up stages to water acidity, calcium, and aluminum, and recovery effects	1990a	Brook trout, *Salvelinus fontinalis*	-	Lack of details; cannot determine effect concentration

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Wood et al.	Effects of water acidity, calcium, and aluminum on whole body ions of brook trout (*Salvelinus fontinalis*) continuously exposed from fertilization to swim-up: a study by instrumental neutron activation analysis	1990b	Brook trout, *Salvelinus fontinalis*	-	Lack of details; cannot determine effect concentration
Woodburn et al.	Accumulation and toxicity of aluminium-contaminated food in the freshwater crayfish, *Pacifastacus leniusculus*	2011	Crayfish, *Pacifastacus leniusculus*	-	Dietary exposure
Wooldridge and Wooldridge	Internal damage in an aquatic beetle exposed to sublethal concentrations of inorganic ions	1969	Aquatic beetle, *Tropistermus lateralis nimbatus*	14 d Change the body fat at 26,981	Only one exposure concentration
Wren et al.	Examination of bioaccumulation and biomagnification of metlas in a Precambrian Shield Lake	1983	-	-	Field exposure, exposure concentrations not measured adequately
Wu et al.	QTLs and epistasis for aluminum tolerance in rice (*Oryza sativa* L.) at different seedling stages	2000	Rice, *Oryza sativa*	-	Only one exposure concentration; difficult to determine effect concentration
Wu et al.	Aluminum nanoparticle exposure in L1 larvae results in more severe lethality toxicity than in L4 larvae or young adults by strengthening the formation of stress response and intestinal lipofuscin accumulation in nematodes	2011	-	-	Inappropriate form of toxicant, nanoparticles
Yang and van den Berg	Metal complexation by humic substances in seawater	2009	-	-	Not applicable; no aluminum toxicity data
Yang et al.	Identification of aluminum-responsive proteins in rice roots by a proteomic approach: Cysteine synthase as a key player in Al response	2007	Rice, *Oryza sativa*	3 d Decreased root length at 53,960	Only two exposure concentrations
Youson and Neville	Deposition of aluminum in the gill epithelium of rainbow trout (*Salmo gairdneri* Richardson) subjected to sublethal concentrations of the metal	1987	Rainbow trout, *Oncorhynchus mykiss*	-	Surgically altered test species
Ytrestoyl et al.	Swimming performance and blood chemistry in Atlantic salmon spawners exposed to acid river water with elevated aluminium concentrations	2001	Atlantic salmon, *Salmo salar*	-	Only one exposure concentrations; dilution water not characterized; no true control group
Zaifnejad et al.	Aluminum and water stress effects on growth and proline of sorghum	1997	Sorghum, *Sorghum bicolor*	-	Inappropriate form of toxicant (aluminum potassium sulfate)
Zaini and Mercado	Calcium-aluminum interaction on the growth of two rice cultivars in culture solution	1984	Rice	-	Scientific name not provided

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Zarini et al.	Effects produced by aluminum in freshwater communities studied by "enclosure" method	1983	-	-	Mixed species exposure; no species names provided; dilution water not characterized
Zhou and Yokel	The chemical species of aluminum influences its paracellular flux across and uptake into Caco-2 cells, a model of gastrointestinal absorption	2005	-	-	Excised cells, in vitro
Zhu et al.	Comparative toxicity of several metal oxide nanoparticle aqueous suspensions to Zebrafish (*Danio rerio*) early developmental stage	2008	Zebrafish, *Danio rerio*	-	Inappropriate form of toxicant, nanoparticles
Zhu et al.	Acute toxicities of six manufactured nanomaterial suspensions to *Daphnia magna*	2009	Cladoceran, *Daphnia magna*	-	Inappropriate form of toxicant (nanoparticles)

Appendix K RECOMMENDED CRITERIA FOR VARIOUS WATER CHEMISTRY CONDITIONS

Table K-1. Freshwater CMC at DOC of 0.1 mg/L and Various Water Total Hardness Levels and pHs.

Total Hardness	**Acute Criterion (CMC) (µg/L total aluminum) (DOC=0.1 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*1.0*	a	*4.8*	b	18	d	**51**	d	**120**	b	**210**	a	**290**	a	**310**	a	***320***	a	***270***	a	*180*	a	*95*	a	*39*	a
25	*2.4*	a	*10*	h	32	d	**84**	d	**180**	d	**290**	a	**370**	a	**380**	a	***360***	a	***280***	a	*170*	a	*78*	a	*29*	a
50	*4.6*	a	*17*	d	50	d	**120**	d	**240**	d	**380**	a	**440**	a	**430**	a	***400***	a	***280***	a	*160*	a	*67*	a	*23*	a
75	*6.7*	b	*24*	d	64	d	**150**	d	**290**	d	**440**	b	**480**	a	**470**	a	***420***	a	***280***	a	*150*	a	*62*	a	*20*	a
100	*8.8*	b	*30*	d	76	d	**170**	d	**320**	d	**490**	i	**520**	a	**500**	a	***430***	a	***280***	a	*150*	a	*58*	a	*18*	a
150	*13*	c	*40*	d	96	d	**200**	d	**380**	d	**560**	h	**580**	a	**540**	a	***460***	a	***290***	a	*140*	a	*53*	a	*16*	a
200	*17*	c	*49*	d	110	d	**230**	d	**420**	d	**610**	d	**620**	a	**570**	a	***480***	a	***290***	a	*140*	a	*50*	a	*15*	a
250	*20*	d	*58*	d	130	d	**250**	d	**460**	d	**660**	d	**650**	a	**600**	a	***490***	a	***290***	a	*130*	a	*48*	a	*14*	a
300	*24*	d	*66*	d	140	d	**270**	d	**490**	d	**700**	d	**680**	a	**620**	a	***500***	a	***290***	a	*130*	a	*46*	a	*13*	a
350	*28*	d	*73*	d	150	d	**290**	d	**510**	d	**730**	d	**710**	a	**640**	a	***510***	a	***290***	a	*130*	a	*45*	a	*12*	a
400	*31*	d	*80*	d	160	d	**310**	d	**540**	d	760	d	**730**	a	**660**	a	***520***	a	***290***	a	*130*	a	*43*	a	*12*	a
430	*33*	d	*84*	d	170	d	**320**	d	**550**	d	780	d	750	a	**670**	a	***530***	a	***290***	a	*130*	a	*43*	a	*11*	a

Bolded values indicate where the 2018 criteria are lower than the 1988 criteria magnitude within the 1988 pH range applied of 6.5-9.0.

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Daphnia, Ceriodaphnia, Stenocypris, Nais
b Daphnia, Ceriodaphnia, Stenocypris, Micropterus
c Daphnia, Micropterus, Ceriodaphnia, Stenocypris
d Daphnia, Micropterus, Oncorhynchus, Ceriodaphnia
e Daphnia, Micropterus, Oncorhynchus, Salmo
f Micropterus, Daphnia, Oncorhynchus, Salmo
g Micropterus, Oncorhynchus, Daphnia, Salmo
h Daphnia, Micropterus, Ceriodaphnia, Oncorhynchus
i Daphnia, Ceriodaphnia, Micropterus, Stenocypris

Table K-2. Freshwater CCC at DOC of 0.1 mg/L and Various Water Hardness Levels and pHs.

Total Hardness	**Chronic Criterion (CCC) (µg/L total aluminum) (DOC=0.1 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*0.63*	a	*3.1*	b	12	d	**33**	e	**77**	b	130	a	180	a	200	a	*200*	a	*170*	a	*110*	a	*59*	a	*24*	a
25	*1.5*	a	*6.7*	c	19	f	**48**	f	120	d	180	a	230	a	240	a	*230*	a	*170*	a	*100*	a	*49*	a	*18*	a
50	*2.9*	a	*11*	e	26	h	**63**	g	140	e	240	b	270	a	270	a	*250*	a	*180*	a	*97*	a	*42*	a	*14*	a
75	*4.3*	b	*14*	f	31	g	**71**	g	160	f	290	b	300	a	290	a	*260*	a	*180*	a	*94*	a	*39*	a	*13*	a
100	*5.8*	b	*17*	f	35	g	**77**	g	180	f	320	c	330	a	310	a	*270*	a	*180*	a	*91*	a	*36*	a	*11*	a
150	*8.6*	c	*21*	h	42	g	87	g	190	g	370	c	360	a	340	a	*290*	a	*180*	a	*88*	a	*33*	a	*10*	a
200	*11*	c	*25*	g	47	g	94	g	200	g	400	e	390	a	360	a	*300*	a	*180*	a	*85*	a	*31*	a	*9.1*	a
250	*13*	d	*28*	g	51	g	100	g	210	g	420	e	410	a	380	a	*310*	a	*180*	a	*83*	a	*30*	a	*8.5*	a
300	*16*	e	*31*	g	55	g	100	g	220	g	430	e	430	a	390	a	*320*	a	*180*	a	*82*	a	*29*	a	*8.0*	a
350	*17*	e	*33*	g	58	g	110	g	220	g	440	e	440	a	400	a	*320*	a	*180*	a	*81*	a	*28*	a	*7.6*	a
400	*19*	e	*36*	g	61	g	110	g	230	g	450	e	460	a	410	a	*330*	a	*180*	a	*80*	a	*27*	a	*7.3*	a
430	*20*	e	*37*	g	63	g	120	g	230	g	450	e	470	a	420	a	*330*	a	*180*	a	*79*	a	*27*	a	*7.1*	a

Bolded values indicate where the 2018 criteria are lower than the 1988 criteria magnitude within the 1988 pH range applied of 6.5-9.0.

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4)

a Daphnia, Lampsilis, Ceriodaphnia, Hyalella
b Daphnia, Lampsilis, Ceriodaphnia, Salmo
c Daphnia, Lampsilis, Salmo, Ceriodaphnia
d Daphnia, Salmo, Lampsilis, Ceriodaphnia
e Salmo, Daphnia, Lampsilis, Ceriodaphnia
f Salmo, Daphnia, Lampsilis, Salvelinus
g Salmo, Salvelinus, Daphnia, Lampsilis
h Salmo, Daphnia, Salvelinus, Lampsilis
i Salmo, Salvelinus, Daphnia, Danio
j Salmo, Salvelinus, Danio, Daphnia
k Salmo, Salvelinus, Danio, Pimephales

Table K-3. Freshwater CMC at DOC of 0.5 mg/L and Various Water Total Hardness Levels and pHs.

Total Hardness	**Acute Criterion (CMC) (µg/L total aluminum) (DOC=0.5 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*2.6*	a	*13*	a	46	c	**130**	d	**300**	d	**550**	i	770	a	820	a	*830*	a	***710***	a	*470*	a	*250*	a	*100*	a
25	*6.3*	a	*27*	a	86	d	**210**	d	**430**	d	750	d	960	a	980	a	*940*	a	***720***	a	*430*	a	*200*	a	*75*	a
50	*12*	a	*47*	b	130	d	**300**	d	**560**	d	920	d	1,100	b	1,100	a	*1,000*	a	***730***	a	*410*	a	*180*	a	*60*	a
75	*18*	a	*66*	c	170	d	**360**	d	**650**	d	1,000	d	1,300	b	1,200	a	*1,100*	a	***740***	a	*390*	a	*160*	a	*52*	a
100	*23*	a	*82*	d	210	d	**410**	d	**720**	d	1,100	d	1,400	c	1,300	a	*1,100*	a	***740***	a	*380*	a	*150*	a	*48*	a
150	*34*	a	*110*	d	260	d	**480**	d	820	d	1,200	d	1,500	d	1,400	b	*1,200*	a	*750*	a	*370*	a	*140*	a	*42*	a
200	*44*	a	*140*	d	310	d	**550**	d	890	d	1,300	d	1,600	d	1,500	b	*1,200*	a	*750*	a	*360*	a	*130*	a	*38*	a
250	*54*	a	*170*	d	350	d	**600**	d	950	d	1,400	d	1,600	d	1,600	i	*1,300*	a	*760*	a	*350*	a	*130*	a	*35*	a
300	*65*	a	*190*	d	390	d	**650**	e	1,000	e	1,500	d	1,700	d	1,600	c	*1,300*	a	*760*	a	*340*	a	*120*	a	*33*	a
350	*75*	a	*220*	d	420	d	**700**	e	1,100	e	1,500	d	1,800	d	1,700	c	*1,300*	a	*760*	a	*340*	a	*120*	a	*32*	a
400	*85*	a	*240*	d	450	d	**740**	e	1,100	e	1,500	d	1,800	d	1,700	h	*1,400*	a	*760*	a	*330*	a	*110*	a	*30*	a
430	*90*	a	*250*	d	470	d	770	e	1,100	e	1,600	d	1,800	d	1,700	d	*1,400*	a	*760*	a	*330*	a	*110*	a	*30*	a

Bolded values indicate where the 2018 criteria are lower than the 1988 criteria magnitude within the 1988 pH range applied of 6.5-9.0.
(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Daphnia, Ceriodaphnia, Stenocypris, Nais
b Daphnia, Ceriodaphnia, Stenocypris, Micropterus
c Daphnia, Micropterus, Ceriodaphnia, Stenocypris
d Daphnia, Micropterus, Oncorhynchus, Ceriodaphnia
e Daphnia, Micropterus, Oncorhynchus, Salmo
f Micropterus, Daphnia, Oncorhynchus, Salmo
g Micropterus, Oncorhynchus, Daphnia, Salmo
h Daphnia, Micropterus, Ceriodaphnia, Oncorhynchus
i Daphnia, Ceriodaphnia, Micropterus, Stenocypris

Table K-4. Freshwater CCC at DOC of 0.5 mg/L and Various Water Hardness Levels and pHs.

Total Hardness	**Chronic Criterion (CCC) (µg/L total aluminum) (DOC=0.5 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*1.7*	a	*7.9*	a	31	c	**78**	e	180	e	370	c	480	a	510	a	*520*	a	*440*	a	*300*	a	*150*	a	*63*	a
25	*3.9*	a	*17*	b	52	e	110	h	230	f	470	e	600	a	620	a	*590*	a	*450*	a	*270*	a	*130*	a	*47*	a
50	*7.5*	a	*31*	c	74	f	140	g	270	g	520	f	740	b	710	a	*650*	a	*460*	a	*250*	a	*110*	a	*37*	a
75	*11*	a	*44*	c	89	g	160	g	290	g	560	f	840	c	770	a	*680*	a	*460*	a	*240*	a	*100*	a	*33*	a
100	*14*	a	*54*	d	100	g	170	g	300	g	580	g	910	c	820	a	*710*	a	*460*	a	*240*	a	*95*	a	*30*	a
150	*21*	a	*70*	e	120	g	190	g	320	g	600	g	970	d	910	b	*750*	a	*470*	a	*230*	a	*87*	a	*26*	a
200	*28*	a	*84*	e	130	g	200	g	340	g	610	g	990	e	990	b	*780*	a	*470*	a	*220*	a	*82*	a	*24*	a
250	*34*	a	*96*	f	150	g	220	g	350	g	610	g	1,000	e	1,000	c	*800*	a	*470*	a	*220*	a	*78*	a	*22*	a
300	*40*	a	*110*	f	160	g	230	g	360	g	620	g	1,000	e	1,100	c	*820*	a	*470*	a	*210*	a	*75*	a	*21*	a
350	*47*	a	*120*	f	170	g	240	g	370	g	620	g	1,000	e	1,100	c	*840*	a	*480*	a	*210*	a	*73*	a	*20*	a
400	*53*	a	*130*	f	180	g	250	g	370	g	630	g	1,000	f	1,100	c	*860*	a	*480*	a	*210*	a	*71*	a	*19*	a
430	*57*	a	*140*	f	180	g	250	g	380	g	630	g	1,000	f	1,100	d	*860*	a	*480*	a	*210*	a	*70*	a	*19*	a

Bolded values indicate where the 2018 criteria are lower than the 1988 criteria magnitude within the 1988 pH range applied of 6.5-9.0.

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4)

a Daphnia, Lampsilis, Ceriodaphnia, Hyalella
b Daphnia, Lampsilis, Ceriodaphnia, Salmo
c Daphnia, Lampsilis, Salmo, Ceriodaphnia
d Daphnia, Salmo, Lampsilis, Ceriodaphnia
e Salmo, Daphnia, Lampsilis, Ceriodaphnia
f Salmo, Daphnia, Lampsilis, Salvelinus
g Salmo, Salvelinus, Daphnia, Lampsilis
h Salmo, Daphnia, Salvelinus, Lampsilis
i Salmo, Salvelinus, Daphnia, Danio
j Salmo, Salvelinus, Danio, Daphnia
k Salmo, Salvelinus, Danio, Pimephales

Table K-5. Freshwater CMC at DOC of 1.0 mg/L and Various Water Total Hardness Levels and pHs.

Total Hardness	**Acute Criterion (CMC) (µg/L total aluminum) (DOC=1.0 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*4.0*	a	*19*	a	70	c	**190**	d	**430**	d	810	d	1,200	a	1,200	a	*1,300*	a	*1,100*	a	*720*	a	*370*	a	*150*	a
25	*9.5*	a	*40*	a	130	d	**310**	d	**620**	d	1,100	d	1,400	c	1,500	a	*1,400*	a	*1,100*	a	*660*	a	*310*	a	*110*	a
50	*18*	a	*72*	b	210	d	**430**	d	790	d	1,300	d	1,700	d	1,700	b	*1,600*	a	*1,100*	a	*610*	a	*270*	a	*90*	a
75	*27*	a	*100*	b	260	d	**520**	d	900	d	1,400	d	1,800	d	1,800	c	*1,700*	a	*1,100*	a	*590*	a	*240*	a	*79*	a
100	*35*	a	*130*	c	320	d	**590**	d	980	d	1,500	d	1,900	d	1,900	d	*1,700*	a	*1,100*	a	*570*	a	*230*	a	*72*	a
150	*51*	a	*170*	d	400	d	**700**	d	1,100	d	1,600	d	2,100	d	2,100	d	*1,800*	a	*1,100*	a	*550*	a	*210*	a	*63*	a
200	*67*	a	*220*	d	470	d	790	d	1,200	e	1,700	d	2,200	d	2,200	d	*1,900*	b	*1,100*	a	*540*	a	*200*	a	*57*	a
250	*82*	a	*260*	d	540	d	870	e	1,300	e	1,800	d	2,200	d	2,200	d	*1,900*	b	*1,100*	a	*530*	a	*190*	a	*53*	a
300	*98*	a	*300*	d	600	d	950	e	1,400	f	1,900	d	2,300	d	2,300	d	*2,000*	b	*1,100*	a	*520*	a	*180*	a	*50*	a
350	*110*	a	*340*	d	650	d	1,000	e	1,500	f	1,900	e	2,300	d	2,300	d	*2,000*	c	*1,200*	a	*510*	a	*180*	a	*48*	a
400	*130*	a	*380*	d	700	d	1,100	f	1,600	f	2,000	e	2,400	d	2,400	d	*2,100*	c	*1,200*	a	*500*	a	*170*	a	*46*	a
430	*140*	a	*400*	d	730	d	1,100	f	1,600	f	2,000	e	2,400	d	2,400	d	*2,100*	c	*1,200*	a	*500*	a	*170*	a	*45*	a

Bolded values indicate where the 2018 criteria are lower than the 1988 criteria magnitude within the 1988 pH range applied of 6.5-9.0.

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Daphnia, Ceriodaphnia, Stenocypris, Nais
b Daphnia, Ceriodaphnia, Stenocypris, Micropterus
c Daphnia, Micropterus, Ceriodaphnia, Stenocypris
d Daphnia, Micropterus, Oncorhynchus, Ceriodaphnia
e Daphnia, Micropterus, Oncorhynchus, Salmo
f Micropterus, Daphnia, Oncorhynchus, Salmo
g Micropterus, Oncorhynchus, Daphnia, Salmo
h Daphnia, Micropterus, Ceriodaphnia, Oncorhynchus
i Daphnia, Ceriodaphnia, Micropterus, Stenocypris

Table K-6. Freshwater CCC at DOC of 1.0 mg/L and Various Water Hardness Levels and pHs.

Total Hardness	**Chronic Criterion (CCC) (µg/L total aluminum) (DOC=1.0 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*2.5*	a	*12*	a	47	c	110	e	240	f	500	e	730	b	770	a	*790*	a	*670*	a	*450*	a	*230*	a	*95*	a
25	*5.9*	a	*25*	a	81	e	160	g	300	g	580	f	970	c	930	a	*890*	a	*680*	a	*410*	a	*190*	a	*71*	a
50	*11*	a	*46*	b	110	f	200	g	340	g	620	g	1,100	e	1,100	c	*980*	a	*690*	a	*380*	a	*170*	a	*56*	a
75	*17*	a	*66*	b	140	h	220	g	360	g	640	g	1,100	e	1,200	c	*1,000*	a	*700*	a	*370*	a	*150*	a	*49*	a
100	*22*	a	*85*	c	160	g	240	g	380	g	650	g	1,100	f	1,300	d	*1,100*	a	*700*	a	*360*	a	*140*	a	*45*	a
150	*32*	a	*120*	d	190	g	260	g	400	g	660	g	1,100	f	1,300	e	*1,100*	a	*710*	a	*350*	a	*130*	a	*39*	a
200	*42*	a	*140*	e	210	g	290	g	420	g	670	g	1,100	g	1,300	e	*1,200*	b	*710*	a	*340*	a	*120*	a	*36*	a
250	*51*	a	*160*	e	230	g	300	g	430	g	670	g	1,100	g	1,300	f	*1,300*	b	*720*	a	*330*	a	*120*	a	*33*	a
300	*61*	a	*180*	e	250	g	320	g	440	g	680	g	1,100	g	1,300	f	*1,300*	c	*720*	a	*320*	a	*110*	a	*31*	a
350	*71*	a	*200*	e	260	g	330	g	450	i	680	g	1,100	g	1,300	f	*1,400*	c	*720*	a	*320*	a	*110*	a	*30*	a
400	*80*	a	*220*	e	280	g	340	g	470	j	680	g	1,100	g	1,300	f	*1,400*	c	*720*	a	*310*	a	*110*	a	*29*	a
430	*86*	a	*230*	f	290	g	350	i	470	j	680	g	1,100	g	1,300	f	*1,400*	c	*720*	a	*310*	a	*110*	a	*28*	a

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4)

a Daphnia, Lampsilis, Ceriodaphnia, Hyalella
b Daphnia, Lampsilis, Ceriodaphnia, Salmo
c Daphnia, Lampsilis, Salmo, Ceriodaphnia
d Daphnia, Salmo, Lampsilis, Ceriodaphnia
e Salmo, Daphnia, Lampsilis, Ceriodaphnia
f Salmo, Daphnia, Lampsilis, Salvelinus
g Salmo, Salvelinus, Daphnia, Lampsilis
h Salmo, Daphnia, Salvelinus, Lampsilis
i Salmo, Salvelinus, Daphnia, Danio
j Salmo, Salvelinus, Danio, Daphnia
k Salmo, Salvelinus, Danio, Pimephales

Table K-7. Freshwater CMC at DOC of 2.5 mg/L and Various Water Total Hardness Levels and pHs.

Total Hardness	**Acute Criterion (CMC) (µg/L total aluminum) (DOC=2.5 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*6.9*	a	*33*	a	120	i	**330**	d	**700**	d	1,300	d	1,900	d	2,100	c	*2,200*	a	*1,900*	a	*1,200*	a	*650*	a	*260*	a
25	*16*	a	*70*	a	230	d	**520**	d	960	d	1,600	d	2,300	d	2,500	d	*2,500*	b	*1,900*	a	*1,100*	a	*530*	a	*200*	a
50	*31*	a	*120*	a	360	d	**720**	d	1,200	d	1,800	d	2,500	d	2,700	d	*2,700*	h	*1,900*	a	*1,100*	a	*460*	a	*160*	a
75	*46*	a	*170*	a	460	d	850	d	1,300	e	2,000	d	2,700	d	2,800	d	*2,800*	d	*1,900*	a	*1,000*	a	*420*	a	*140*	a
100	*60*	a	*220*	b	550	d	970	d	1,500	e	2,100	e	2,700	d	2,900	d	*2,900*	d	*1,900*	a	*990*	a	*400*	a	*120*	a
150	*88*	a	*310*	b	710	d	1,100	d	1,700	f	2,300	e	2,900	d	3,000	d	*3,000*	d	*2,000*	a	*960*	a	*360*	a	*110*	a
200	*120*	a	*390*	c	840	d	1,300	e	1,900	g	2,500	f	2,900	d	3,100	d	*3,000*	d	*2,000*	a	*930*	a	*340*	a	*99*	a
250	*140*	a	*460*	c	960	d	1,500	e	2,100	g	2,600	g	3,000	d	3,100	d	*3,000*	d	*2,000*	a	*910*	a	*330*	a	*92*	a
300	*170*	a	*530*	d	1,100	d	1,600	f	2,200	g	2,700	g	3,000	e	3,100	d	*3,100*	d	*2,000*	a	*890*	a	*320*	a	*87*	a
350	*190*	a	*600*	d	1,200	d	1,700	f	2,300	g	2,800	g	3,100	e	3,200	d	*3,100*	d	*2,000*	a	*880*	a	*310*	a	*83*	a
400	*220*	a	*670*	d	1,200	d	1,800	f	2,400	g	2,900	g	3,100	e	3,200	d	*3,100*	d	*2,000*	a	*870*	a	*300*	a	*79*	a
430	*240*	a	*710*	d	1,300	d	1,900	g	2,400	g	2,900	g	3,100	e	3,200	d	*3,100*	d	*2,000*	a	*860*	a	*290*	a	*77*	a

Bolded values indicate where the 2018 criteria are lower than the 1988 criteria magnitude within the 1988 pH range applied of 6.5-9.0.

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Daphnia, Ceriodaphnia, Stenocypris, Nais
b Daphnia, Ceriodaphnia, Stenocypris, Micropterus
c Daphnia, Micropterus, Ceriodaphnia, Stenocypris
d Daphnia, Micropterus, Oncorhynchus, Ceriodaphnia
e Daphnia, Micropterus, Oncorhynchus, Salmo
f Micropterus, Daphnia, Oncorhynchus, Salmo
g Micropterus, Oncorhynchus, Daphnia, Salmo
h Daphnia, Micropterus, Ceriodaphnia, Oncorhynchus
i Daphnia, Ceriodaphnia, Micropterus, Stenocypris

Table K-8. Freshwater CCC at DOC of 2.5 mg/L and Various Water Hardness Levels and pHs.

Total Hardness	**Chronic Criterion (CCC) (µg/L total aluminum) (DOC=2.5 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*4.3*	a	*21*	a	81	c	180	f	340	g	650	g	1,200	e	1,400	c	*1,400*	a	*1,200*	a	*780*	a	*400*	a	*160*	a
25	*10*	a	*44*	a	140	e	250	g	400	g	690	g	1,200	f	1,500	e	*1,600*	b	*1,200*	a	*710*	a	*330*	a	*120*	a
50	*20*	a	*77*	a	200	f	310	g	450	g	710	g	1,200	g	1,500	f	*1,800*	c	*1,200*	a	*660*	a	*290*	a	*98*	a
75	*29*	a	*110*	a	250	f	340	g	480	g	720	g	1,200	g	1,500	g	*1,800*	e	*1,200*	a	*640*	a	*260*	a	*86*	a
100	*38*	a	*140*	b	290	g	370	g	500	g	730	g	1,200	g	1,400	g	*1,700*	e	*1,200*	a	*620*	a	*250*	a	*78*	a
150	*55*	a	*200*	b	340	g	410	g	530	i	740	g	1,100	g	1,400	g	*1,700*	f	*1,200*	a	*600*	a	*230*	a	*68*	a
200	*72*	a	*260*	c	390	g	440	g	560	j	750	j	1,100	g	1,300	g	*1,700*	f	*1,200*	a	*580*	a	*210*	a	*62*	a
250	*89*	a	*310*	c	420	g	470	g	580	j	760	j	1,100	g	1,300	g	*1,600*	f	*1,200*	a	*570*	a	*210*	a	*58*	a
300	*110*	a	*350*	d	460	g	490	i	600	j	770	j	1,100	g	1,300	g	*1,600*	h	*1,200*	a	*560*	a	*200*	a	*54*	a
350	*120*	a	*390*	e	480	g	520	i	610	j	780	j	1,100	g	1,200	g	*1,600*	g	*1,200*	a	*550*	a	*190*	a	*52*	a
400	*140*	a	*430*	e	510	g	540	j	630	j	780	j	1,000	g	1,200	g	*1,500*	g	*1,300*	b	*540*	a	*190*	a	*50*	a
430	*150*	a	*450*	e	520	g	550	j	640	j	790	j	1,000	g	1,200	g	*1,500*	g	*1,300*	b	*540*	a	*180*	a	*48*	a

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4)

a Daphnia, Lampsilis, Ceriodaphnia, Hyalella
b Daphnia, Lampsilis, Ceriodaphnia, Salmo
c Daphnia, Lampsilis, Salmo, Ceriodaphnia
d Daphnia, Salmo, Lampsilis, Ceriodaphnia
e Salmo, Daphnia, Lampsilis, Ceriodaphnia
f Salmo, Daphnia, Lampsilis, Salvelinus
g Salmo, Salvelinus, Daphnia, Lampsilis
h Salmo, Daphnia, Salvelinus, Lampsilis
i Salmo, Salvelinus, Daphnia, Danio
j Salmo, Salvelinus, Danio, Daphnia
k Salmo, Salvelinus, Danio, Pimephales

Table K-9. Freshwater CMC at DOC of 5.0 mg/L and Various Water Total Hardness Levels and pHs.

Total Hardness	Acute Criterion (CMC) (µg/L total aluminum) (DOC=5.0 mg/L)																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*10*	a	*50*	a	180	b	**490**	d	970	d	1,700	d	2,600	d	3,000	d	*3,300*	d	*2,800*	a	*1900*	a	*980*	a	*400*	a
25	*25*	a	*110*	a	350	d	760	d	1,300	d	2,000	d	3,000	d	3,300	d	*3,500*	d	*2,900*	a	*1,700*	a	*810*	a	*300*	a
50	*47*	a	*190*	a	550	d	1,000	d	1,600	e	2,400	e	3,100	d	3,400	d	*3,700*	d	*2,900*	a	*1,600*	a	*700*	a	*240*	a
75	*69*	a	*260*	a	710	d	1,200	d	1,900	f	2,600	f	3,200	d	3,500	d	*3,700*	d	*2,900*	b	*1,500*	a	*640*	a	*210*	a
100	*91*	a	*330*	a	850	d	1,400	d	2,100	f	2,800	g	3,300	e	3,500	d	*3,700*	d	*2,900*	b	*1,500*	a	*600*	a	*190*	a
150	*130*	a	*460*	a	1,100	d	1,700	e	2,400	g	3,000	g	3,500	f	3,600	e	*3,700*	d	*2,900*	c	*1,400*	a	*550*	a	*160*	a
200	*170*	a	*590*	b	1,300	d	1,900	e	2,600	g	3,200	g	3,600	f	3,700	e	*3,700*	d	*2,900*	d	*1,400*	a	*520*	a	*150*	a
250	*210*	a	*700*	b	1,500	d	2,100	f	2,800	g	3,400	g	3,700	g	3,700	e	*3,700*	d	*2,900*	d	*1,400*	a	*500*	a	*140*	a
300	*260*	a	*820*	i	1,600	d	2,300	f	3,000	g	3,500	g	3,800	g	3,800	f	*3,700*	d	*2,900*	d	*1,400*	a	*480*	a	*130*	a
350	*290*	a	*930*	c	1,800	d	2,500	g	3,100	g	3,600	g	3,800	g	3,800	f	*3,600*	d	*2,900*	d	*1,300*	a	*460*	a	*130*	a
400	*330*	a	*1,000*	c	1,900	d	2,600	g	3,200	g	3,700	g	3,900	g	3,800	g	*3,600*	d	*2,900*	d	*1,300*	a	*450*	a	*120*	a
430	*360*	a	*1,100*	c	2,000	d	2,700	g	3,300	g	3,700	g	3,900	g	3,900	g	*3,600*	d	*2,900*	d	*1,300*	a	*440*	a	*120*	a

Bolded values indicate where the 2018 criteria are lower than the 1988 criteria magnitude within the 1988 pH range applied of 6.5-9.0.

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Daphnia, Ceriodaphnia, Stenocypris, Nais
b Daphnia, Ceriodaphnia, Stenocypris, Micropterus
c Daphnia, Micropterus, Ceriodaphnia, Stenocypris
d Daphnia, Micropterus, Oncorhynchus, Ceriodaphnia
e Daphnia, Micropterus, Oncorhynchus, Salmo
f Micropterus, Daphnia, Oncorhynchus, Salmo
g Micropterus, Oncorhynchus, Daphnia, Salmo
h Daphnia, Micropterus, Ceriodaphnia, Oncorhynchus
i Daphnia, Ceriodaphnia, Micropterus, Stenocypris

Table K-10. Freshwater CCC at DOC of 5.0 mg/L and Various Water Hardness Levels and pHs.

Total Hardness	**Chronic Criterion (CCC) (µg/L total aluminum) (DOC=5.0 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*6.5*	a	*31*	a	120	b	260	f	430	g	740	g	1,300	g	1,700	f	*2,200*	d	*1,800*	a	*1200*	a	*610*	a	*250*	a
25	*15*	a	*66*	a	220	e	350	g	500	g	760	g	1,300	g	1,600	g	*2,000*	e	*1,800*	a	*1,100*	a	*500*	a	*190*	a
50	*30*	a	*120*	a	320	e	430	g	550	g	780	g	1,200	g	1,500	g	*1,900*	h	*1,800*	b	*1,000*	a	*440*	a	*150*	a
75	*43*	a	*160*	a	390	f	480	g	590	i	790	j	1,200	g	1,400	g	*1,800*	g	*1,900*	b	*970*	a	*400*	a	*130*	a
100	*57*	a	*210*	a	450	h	520	g	620	j	810	j	1,100	g	1,300	g	*1,700*	g	*2,000*	c	*940*	a	*380*	a	*120*	a
150	*83*	a	*290*	b	540	g	570	g	660	j	830	j	1,100	i	1,300	g	*1,600*	g	*2,000*	c	*900*	a	*350*	a	*100*	a
200	*110*	a	*380*	b	610	g	620	g	700	j	840	j	1,100	j	1,200	g	*1,500*	g	*1,900*	e	*880*	a	*330*	a	*94*	a
250	*130*	a	*470*	b	670	g	660	i	720	j	850	j	1,100	j	1,200	g	*1,500*	g	*1,800*	e	*860*	a	*310*	a	*87*	a
300	*160*	a	*550*	c	720	g	690	j	750	j	860	j	1,100	j	1,200	i	*1,400*	g	*1,800*	e	*850*	a	*300*	a	*82*	a
350	*180*	a	*620*	c	760	g	730	j	770	j	860	j	1,000	j	1,100	j	*1,400*	g	*1,700*	e	*830*	a	*290*	a	*78*	a
400	*210*	a	*690*	c	800	g	760	j	780	j	870	j	1,000	j	1,100	j	*1,300*	g	*1,700*	e	*820*	a	*280*	a	*75*	a
430	*220*	a	*730*	c	830	g	770	j	790	j	870	j	1,000	j	1,100	j	*1,300*	g	*1,700*	e	*820*	a	*280*	a	*73*	a

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4)

a Daphnia, Lampsilis, Ceriodaphnia, Hyalella
b Daphnia, Lampsilis, Ceriodaphnia, Salmo
c Daphnia, Lampsilis, Salmo, Ceriodaphnia
d Daphnia, Salmo, Lampsilis, Ceriodaphnia
e Salmo, Daphnia, Lampsilis, Ceriodaphnia
f Salmo, Daphnia, Lampsilis, Salvelinus
g Salmo, Salvelinus, Daphnia, Lampsilis
h Salmo, Daphnia, Salvelinus, Lampsilis
i Salmo, Salvelinus, Daphnia, Danio
j Salmo, Salvelinus, Danio, Daphnia
k Salmo, Salvelinus, Danio, Pimephales

Table K-11. Freshwater CMC at DOC of 10.0 mg/L and Various Water Total Hardness Levels and pHs.

Total Hardness	**Acute Criterion (CMC) (µg/L total aluminum) (DOC=10.0 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*16*	a	*75*	a	280	b	**720**	d	1,300	d	2,200	d	3,300	d	3,800	d	*4,400*	d	*4,300*	b	*2,800*	a	*1,500*	a	*600*	a
25	*37*	a	*160*	a	530	d	1,100	d	1,800	e	2,700	f	3,600	e	4,000	d	*4,500*	d	*4,300*	d	*2,600*	a	*1,200*	a	*450*	a
50	*72*	a	*280*	a	830	d	1,500	d	2,300	f	3,100	g	3,900	f	4,100	e	*4,400*	d	*4,200*	d	*2,400*	a	*1,100*	a	*360*	a
75	*100*	a	*400*	a	1,100	d	1,800	d	2,600	g	3,400	g	4,100	g	4,200	f	*4,300*	d	*4,100*	d	*2,300*	a	*970*	a	*310*	a
100	*140*	a	*500*	a	1,300	d	2,000	e	2,900	g	3,600	g	4,200	g	4,300	g	*4,300*	e	*4,000*	d	*2,300*	a	*910*	a	*280*	a
150	*200*	a	*700*	a	1,700	d	2,500	e	3,300	g	3,900	g	4,300	g	4,400	g	*4,300*	e	*3,900*	d	*2,200*	a	*840*	a	*250*	a
200	*260*	a	*890*	a	2,000	d	2,800	f	3,600	g	4,100	g	4,400	g	4,500	g	*4,300*	f	*3,800*	d	*2,100*	a	*790*	a	*230*	a
250	*330*	a	*1,100*	a	2,300	d	3,100	f	3,800	g	4,200	g	4,500	g	4,500	g	*4,300*	g	*3,700*	d	*2,100*	b	*750*	a	*210*	a
300	*390*	a	*1,200*	b	2,500	d	3,400	g	4,000	g	4,300	g	4,500	g	4,500	g	*4,300*	g	*3,600*	d	*2,000*	b	*720*	a	*200*	a
350	*450*	a	*1,400*	b	2,700	d	3,600	g	4,200	g	4,400	g	4,500	g	4,500	g	*4,300*	g	*3,500*	d	*2,000*	b	*700*	a	*190*	a
400	*510*	a	*1,600*	b	3,000	d	3,900	g	4,300	g	4,500	g	4,600	g	4,500	g	*4,300*	g	*3,500*	d	*2,000*	b	*680*	a	*180*	a
430	*540*	a	*1,700*	b	3,100	d	4,000	g	4,400	g	4,500	g	4,600	g	4,500	g	*4,300*	g	*3,400*	d	*2,000*	i	*670*	a	*180*	a

Bolded values indicate where the 2018 criteria are lower than the 1988 criteria magnitude within the 1988 pH range applied of 6.5-9.0.

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Daphnia, Ceriodaphnia, Stenocypris, Nais
b Daphnia, Ceriodaphnia, Stenocypris, Micropterus
c Daphnia, Micropterus, Ceriodaphnia, Stenocypris
d Daphnia, Micropterus, Oncorhynchus, Ceriodaphnia
e Daphnia, Micropterus, Oncorhynchus, Salmo
f Micropterus, Daphnia, Oncorhynchus, Salmo
g Micropterus, Oncorhynchus, Daphnia, Salmo
h Daphnia, Micropterus, Ceriodaphnia, Oncorhynchus
i Daphnia, Ceriodaphnia, Micropterus, Stenocypris

Table K-12. Freshwater CCC at DOC of 10.0 mg/L and Various Water Hardness Levels and pHs.

Total Hardness	**Chronic Criterion (CCC) (µg/L total aluminum) (DOC=10.0 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*9.9*	a	*47*	a	180	b	370	g	540	g	810	g	1,300	g	1,700	g	*2,300*	g	*2,800*	b	*1,800*	a	*930*	a	*380*	a
25	*23*	a	*100*	a	340	d	490	g	610	g	830	i	1,200	g	1,500	g	*2,000*	g	*2,800*	e	*1,600*	a	*760*	a	*280*	a
50	*45*	a	*180*	a	490	e	600	g	690	j	870	j	1,200	j	1,300	g	*1,700*	g	*2,400*	e	*1,500*	a	*660*	a	*220*	a
75	*66*	a	*250*	a	610	f	670	g	740	j	890	j	1,100	j	1,300	j	*1,600*	g	*2,300*	f	*1,500*	a	*600*	a	*200*	a
100	*86*	a	*310*	a	700	f	720	g	780	j	900	j	1,100	j	1,200	j	*1,500*	g	*2,100*	h	*1,400*	a	*570*	a	*180*	a
150	*130*	a	*440*	a	850	g	800	g	830	j	910	j	1,100	j	1,200	j	*1,400*	g	*1,900*	g	*1,400*	a	*520*	a	*160*	a
200	*160*	a	*560*	a	960	g	860	i	870	j	920	j	1,100	j	1,200	j	*1,300*	i	*1,800*	g	*1,300*	b	*490*	a	*140*	a
250	*200*	a	*670*	b	1,100	g	930	j	900	j	930	j	1,100	j	1,100	j	*1,300*	j	*1,700*	g	*1,300*	b	*470*	a	*130*	a
300	*240*	a	*800*	b	1,100	g	980	j	920	j	930	j	1,000	j	1,100	j	*1,200*	j	*1,600*	g	*1,300*	b	*450*	a	*120*	a
350	*280*	a	*920*	b	1,200	g	1,000	j	950	j	950	k	1,000	j	1,100	j	*1,200*	j	*1,500*	g	*1,300*	b	*440*	a	*120*	a
400	*320*	a	*1,000*	b	1,300	g	1,100	j	960	j	970	k	1,000	j	1,100	j	*1,200*	j	*1,500*	g	*1,300*	c	*420*	a	*110*	a
430	*340*	a	*1,100*	b	1,300	g	1,100	j	970	j	970	k	1,000	j	1,100	j	*1,200*	j	*1,400*	g	*1,300*	c	*420*	a	*110*	a

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4)

a Daphnia, Lampsilis, Ceriodaphnia, Hyalella
b Daphnia, Lampsilis, Ceriodaphnia, Salmo
c Daphnia, Lampsilis, Salmo, Ceriodaphnia
d Daphnia, Salmo, Lampsilis, Ceriodaphnia
e Salmo, Daphnia, Lampsilis, Ceriodaphnia
f Salmo, Daphnia, Lampsilis, Salvelinus
g Salmo, Salvelinus, Daphnia, Lampsilis
h Salmo, Daphnia, Salvelinus, Lampsilis
i Salmo, Salvelinus, Daphnia, Danio
j Salmo, Salvelinus, Danio, Daphnia
k Salmo, Salvelinus, Danio, Pimephales

Table K-13. Freshwater CMC at DOC of 12.0 mg/L and Various Water Total Hardness Levels and pHs.

Total Hardness	Acute Criterion (CMC) (µg/L total aluminum) (DOC=12.0 mg/L)																									
	pH 5.0		pH 5.5		pH 6.0		pH 6.5		pH 7.0		pH 7.5		pH 8.0		pH 8.2		pH 8.5		pH 9.0		pH 9.5		pH 10.0		pH 10.5	
10	*18*	a	*84*	a	310	b	800	d	1,500	d	2,300	e	3500	d	4,000	d	*4,700*	d	*4,700*	c	*3,200*	a	*1,600*	a	*670*	a
25	*42*	a	*180*	a	590	d	1,200	d	2,000	e	2,900	f	3,800	f	4,100	e	*4,700*	d	*4,600*	d	*2,900*	a	*1,400*	a	*500*	a
50	*80*	a	*320*	a	930	d	1,700	d	2,500	g	3,400	g	4,100	g	4,400	f	*4,500*	d	*4,500*	d	*2,700*	a	*1,200*	a	*400*	a
75	*120*	a	*440*	a	1,200	d	2,000	d	2,900	g	3,600	g	4,300	g	4,500	g	*4,500*	e	*4,300*	d	*2,600*	a	*1,100*	a	*350*	a
100	*150*	a	*560*	a	1,500	d	2,200	e	3,100	g	3,800	g	4,400	g	4,500	g	*4,500*	e	*4,200*	d	*2,500*	a	*1,000*	a	*320*	a
150	*220*	a	*780*	a	1,900	d	2,700	e	3,500	g	4,100	g	4,500	g	4,600	g	*4,500*	f	*4,100*	d	*2,400*	b	*930*	a	*280*	a
200	*290*	a	*990*	a	2,200	d	3,100	f	3,900	g	4,300	g	4,600	g	4,600	g	*4,500*	g	*3,900*	d	*2,400*	b	*880*	a	*250*	a
250	*360*	a	*1,200*	a	2,500	d	3,500	g	4,100	g	4,400	g	4,600	g	4,700	g	*4,500*	g	*3,800*	d	*2,300*	c	*840*	a	*240*	a
300	*430*	a	*1,400*	b	2,800	d	3,700	g	4,300	g	4,500	g	4,700	g	4,700	g	*4,500*	g	*3,700*	d	*2,300*	c	*800*	a	*220*	a
350	*500*	a	*1,600*	b	3,100	d	4,000	g	4,500	g	4,600	g	4,700	g	4,700	g	*4,500*	g	*3,600*	d	*2,200*	h	*780*	a	*210*	a
400	*560*	a	*1,800*	b	3,300	d	4,300	g	4,700	g	4,700	g	4,700	g	4,700	g	*4,400*	g	*3,500*	d	*2,200*	d	*760*	a	*200*	a
430	*600*	a	*1,900*	b	3,500	d	4,400	g	4,800	g	4,800	g	4,700	g	4,700	g	*4,400*	g	*3,500*	d	*2,200*	d	*750*	a	*200*	a

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Daphnia, Ceriodaphnia, Stenocypris, Nais
b Daphnia, Ceriodaphnia, Stenocypris, Micropterus
c Daphnia, Micropterus, Ceriodaphnia, Stenocypris
d Daphnia, Micropterus, Oncorhynchus, Ceriodaphnia
e Daphnia, Micropterus, Oncorhynchus, Salmo
f Micropterus, Daphnia, Oncorhynchus, Salmo
g Micropterus, Oncorhynchus, Daphnia, Salmo
h Daphnia, Micropterus, Ceriodaphnia, Oncorhynchus
i Daphnia, Ceriodaphnia, Micropterus, Stenocypris

Table K-14. Freshwater CCC at DOC of 12.0 mg/L and Various Water Hardness Levels and pHs.

Total Hardness	**Chronic Criterion (CCC) (µg/L total aluminum) (DOC=12.0 mg/L)**																									
	pH 5.0		**pH 5.5**		**pH 6.0**		**pH 6.5**		**pH 7.0**		**pH 7.5**		**pH 8.0**		**pH 8.2**		**pH 8.5**		**pH 9.0**		**pH 9.5**		**pH 10.0**		**pH 10.5**	
10	*11*	a	*52*	a	200	b	410	g	570	g	820	g	1,300	g	1,600	g	*2,200*	g	*3,200*	c	*2,000*	a	*1,000*	a	*420*	a
25	*26*	a	*110*	a	390	d	540	g	650	g	860	j	1,200	g	1,400	g	*1,900*	g	*2,800*	e	*1,800*	a	*850*	a	*310*	a
50	*50*	a	*200*	a	560	e	650	g	730	j	890	j	1,200	j	1,300	j	*1,700*	g	*2,400*	f	*1,700*	a	*730*	a	*250*	a
75	*73*	a	*280*	a	680	f	730	g	780	j	910	j	1,100	j	1,300	j	*1,500*	g	*2,200*	g	*1,600*	a	*670*	a	*220*	a
100	*96*	a	*350*	a	790	f	780	g	820	j	920	j	1,100	j	1,200	j	*1,400*	g	*2,100*	g	*1,600*	a	*630*	a	*200*	a
150	*140*	a	*490*	a	950	g	870	g	880	j	940	j	1,100	j	1,200	j	*1,300*	j	*1,800*	g	*1,600*	b	*580*	a	*170*	a
200	*180*	a	*620*	a	1,100	g	950	i	920	j	940	j	1,100	j	1,100	j	*1,300*	j	*1,700*	g	*1,600*	b	*550*	a	*160*	a
250	*230*	a	*740*	a	1,200	g	1,000	j	950	j	950	k	1,000	j	1,100	j	*1,200*	j	*1,600*	g	*1,500*	c	*520*	a	*150*	a
300	*270*	a	*880*	b	1,300	g	1,100	j	980	j	980	k	1,000	j	1,100	j	*1,200*	j	*1,500*	g	*1,500*	c	*500*	a	*140*	a
350	*310*	a	*1,000*	b	1,400	g	1,100	j	1,000	j	990	k	1,000	j	1,100	j	*1,200*	j	*1,400*	g	*1,500*	c	*490*	a	*130*	a
400	*350*	a	*1,100*	b	1,400	g	1,200	j	1,000	j	1,000	k	1,000	k	1,000	j	*1,100*	j	*1,400*	g	*1,400*	d	*470*	a	*130*	a
430	*380*	a	*1,200*	b	1,500	g	1,200	j	1,000	j	1,000	k	1,000	k	1,000	j	*1,100*	j	*1,300*	g	*1,400*	e	*470*	a	*120*	a

(Italicized and underlined values are outside the pH limits of the empirical data used to generate the MLR models and should be used with caution).

Ranking of four most sensitive genera (Rank 1-Rank 4)

a Daphnia, Lampsilis, Ceriodaphnia, Hyalella
b Daphnia, Lampsilis, Ceriodaphnia, Salmo
c Daphnia, Lampsilis, Salmo, Ceriodaphnia
d Daphnia, Salmo, Lampsilis, Ceriodaphnia
e Salmo, Daphnia, Lampsilis, Ceriodaphnia
f Salmo, Daphnia, Lampsilis, Salvelinus
g Salmo, Salvelinus, Daphnia, Lampsilis
h Salmo, Daphnia, Salvelinus, Lampsilis
i Salmo, Salvelinus, Daphnia, Danio
j Salmo, Salvelinus, Danio, Daphnia
k Salmo, Salvelinus, Danio, Pimephales

Appendix L EPA'S MLR MODEL COMPARISON OF DEFOREST ET AL. (2018B) POOLED AND INDIVIDUAL-SPECIES MODEL OPTIONS

Background

The EPA conducted a comparison of the DeForest et al. (2018b) pooled MLRs (fish and invertebrate data pooled) and individual-species MLRs (fish and invertebrates regressed separately) in order to determine which approach would be most appropriate for use in the Final 2018 Aluminum Aquatic Life AWQC. This appendix describes the EPA's analysis.

DeForest et al. (2018b) updated the individual-species MLR models to incorporate new toxicity data, with the addition of nine *Ceriodaphnia dubia* and nine *Pimephales promelas* toxicity tests under water chemistry conditions that were largely not addressed in the 2017 EPA Draft Aluminum AWQC or the DeForest et al. (2018a) publication. These toxicity tests were conducted by Oregon State University (OSU) and provided to the EPA and DeForest et al. as a courtesy in 2018. These new toxicity tests included fish and invertebrate testing under higher DOC concentration, higher hardness, and slightly higher pH conditions that were not included in the original publication and MLR database (DeForest et al. 2018a). DeForest et al. provided the MLR analyses, using both the new and older datasets in an memorandum to the EPA (DeForest et al. 2018b).

In addition to the analyses described in this appendix, the EPA subjected the DeForest et al. (2018b) memorandum to independent, external expert peer review in 2018. Several of the external peer reviewers noticed trends in the data and criteria derived using the pooled model. (See EPA's website for the Aluminum AWQC [https://www.epa.gov/wqc/aquatic-life-criteria-aluminum] for supporting documentation including the external peer review reports and EPA's responses to the external peer reviewer comments).

The conditions addressed in these new toxicity tests expanded the water quality conditions for model development (**Table L-1**). All conditions and effect concentrations for the 32 *Ceriodaphnia dubia* and 31 *Pimephales promelas* tests are presented in **Table L-2**.

Table L-1. Range of Water Quality Conditions Tested for MLR Model Development.

		Number of test	Range of Water Quality Conditions Tested		
			DOC (mg/L)	pH	Total Hardness (mg/L as $CaCO_3$)
Expanded database	*Ceriodaphnia dubia*	32	0.1-12.3	6.3-8.7	9.8-428
Former database	*Ceriodaphnia dubia*	23	0.1-4	6.3-8.1	9.8-123
Expanded database	*Pimephales promelas*	31	0.08-11.6	6.0-8.12	10.2-422
Former database	*Pimephales promelas*	22	0.08-5.0	6.0-8.0	10.2-127

Table L-2. Database Used for MLR Model Development.

Species	Endpoint	Duration	DOC (mg/L)	pH	Total Hardness (mg/L)	EC_{20} (µg Al/L)	Lower 95% CI	Upper 95% CI	Reference	
Ceriodaphnia dubia	Reproduction	7 d	0.1	6.92	9.8	124	12	1259	CIMM 2009	
Ceriodaphnia dubia	Reproduction	7 d	0.1	7.84	9.8	379	141	1020	CIMM 2009	
Ceriodaphnia dubia	Reproduction	7 d	0.1	6.34	25	37	22	62	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	0.1	6.4	60	160	123	209	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	0.1	6.38	121	222	105	466	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	2	6.34	25	377	159	895	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	2	6.38	61	631	362	1101	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	2	6.37	121	1012	692	1479	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	4	6.33	25	623	532	729	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	4	6.3	61	693	618	777	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	4	6.38	121	841	773	914	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	0.3	7.15	50	1780			Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	0.3	7.61	51	426	249	727	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	2	6.37	25	353	268	465	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	2	6.34	25	452	401	511	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	2	6.35	25	440	357	523	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	0.5	6.34	26	260	170	310	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	0.5	6.36	122	390	170	450	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	0.5	7	26	250	150	340	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	0.5	7.1	123	860	590	1090	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	0.5	8	25	700	510	830	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	0.5	8	62	1010	740	1180	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	0.5	8.1	123	870	710	1130	Gensemer et al. 2018	
Ceriodaphnia dubia	Reproduction	7 d	1.87	6.42	64	829	437	1572	OSU 2018a	new
Ceriodaphnia dubia	Reproduction	7 d	8.71	6.33	133	3829			OSU 2018a	new
Ceriodaphnia dubia	Reproduction	7 d	12.3	6.40	138	6224	3866	10022	OSU 2018a	new
Ceriodaphnia dubia	Reproduction	7 d	1.64	6.30	428	2011	1539	2628	OSU 2018a	new
Ceriodaphnia dubia	Reproduction	7 d	6.57	7.21	125	6401	4274	9588	OSU 2018a	new
Ceriodaphnia dubia	Reproduction	7 d	12.01	7.19	127	6612			OSU 2018a	new
Ceriodaphnia dubia	Reproduction	7 d	1.3	8.17	263	3749	2904	4838	OSU 2018a	new
Ceriodaphnia dubia	Reproduction	7 d	1.2	8.21	425	2852	1647	4939	OSU 2018a	new

Species	Endpoint	Duration	DOC (mg/L)	pH	Total Hardness (mg/L)	EC_{20} (µg Al/L)	Lower 95% CI	Upper 95% CI	Reference	
Ceriodaphnia dubia	Reproduction	7 d	1.04	8.7	125	1693			OSU 2018a	new
Pimephales promelas	Mean Dry Biomass	7 d	0.3	8	48	10753	1458	79301	Parametrix 2009	
Pimephales promelas	Mean Dry Biomass	7 d	0.08	6	10.6	127	-	-	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	0.19	6.1	25.8	136	98	188	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	0.22	6	60.8	314	200	495	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	0.09	6	123.9	624	410	951	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	0.92	6.1	10.2	426	402	451	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	0.86	6.1	61	634	338	1190	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	0.88	6.1	123.7	773	559	1070	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	1.73	6.1	10.6	633	497	805	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	1.74	6	59.9	1326	1119	1571	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	1.56	6	118.2	1494	1116	1999	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	3.35	6	11.8	829	691	995	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	3.51	6	64.8	2523	1971	3230	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	3.27	6	119.6	2938	2288	3772	Gensemer et al. 2018	
Pimephales promelas	Larval Survival	33 d	0.3	6	93.9	429			Cardwell et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	0.7	6.1	25.9	660	364	1197	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	0.9	6	116	824	393	1729	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	2.9	6.1	122	2210	1640	2978	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	0.8	7.1	26.5	1534	932	2522	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	2.5	7	123	5411	3144	9313	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	0.7	8	28.8	7262	4714	11187	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	5	7.9	127	6795	3161	14607	Gensemer et al. 2018	
Pimephales promelas	Mean Dry Biomass	7 d	7	6.04	134	4618	3281	6499	OSU 2018b	new
Pimephales promelas	Mean Dry Biomass	7 d	11.5	6.04	131	9511	7291	12408	OSU 2018b	new
Pimephales promelas	Mean Dry Biomass	7 d	1.1	6.82	422	2969	2010	4386	OSU 2018b	new
Pimephales promelas	Mean Dry Biomass	7 d	7.2	7.00	135	8047	6273	10322	OSU 2018b	new
Pimephales promelas	Mean Dry Biomass	7 d	11.6	6.96	125	12542	6598	23842	OSU 2018b	new
Pimephales promelas	Mean Dry Biomass	7 d	1.1	8.06	288	5634	1768	17957	OSU 2018b	new
Pimephales promelas	Mean Dry Biomass	7 d	1.6	8.12	396	13274	6674	26401	OSU 2018b	new
Pimephales promelas	Mean Dry Biomass	7 d	0.8	6.1	49	885	574	1365	OSU 2018d	new
Pimephales promelas	Mean Dry Biomass	7 d	1.6	6	94	1817	1444	2287	OSU 2018d	new

DeForest et al. (2018b) developed a pooled MLR model that combined the two datasets, fish and invertebrate, with common slopes for the multiple linear regression test parameters. Deforest et al. (2018b) provided the EPA with a memorandum that presented four new MLR models: 1) a *C. dubia* Individual-species MLR Model; 2) *C. dubia* Pooled MLR Model (*C. dubia* and *P. promelas* data pooled, but using *C. dubia* intercept); 3) *P. promelas* Individual-species MLR Model; and 4) *P. promelas* Pooled MLR Model (*C. dubia* and *P. promelas* data pooled, but using *P. promelas* intercept).

Note: the species-specific intercepts in the pooled model account for the difference in sensitivity of the two test organisms, but slopes for each test parameter are the same. To incorporate these models into AWQC, the EPA evaluated the most appropriate approach to normalize the freshwater aluminum toxicity data by comparing model performance. The DeForest et al. reported models from their 2018 memorandum were:

Invertebrate-focused models

C. dubia Individual-species MLR Model:

$$C.dubia\ EC_{20} = e^{\left[-32.523+[0.597\times\ln(DOC)]+[2.089\times\ln(hard)]+(8.802\times pH)-\left(0.491\times pH^{2}\right)-[0.230\times pH:\ln(hard)]\right]}$$

C. dubia Pooled MLR Model (*C. dubia* and *P. promelas* data pooled, but using *C. dubia* intercept):

$$C.dubia\ EC_{20} = e^{\left[-8.555+[0.592\times\ln(DOC)]+[2.188\times\ln(hard)]+(1.998\times pH)-[0.268\times pH:\ln(hard)]\right]}$$

Vertebrate-focused models

P. promelas Individual-species MLR Model:

$$P.promelas\ EC_{20} = e^{\left[-7.371+[2.209\times\ln(DOC)]+[1.862\times\ln(hard)]+(2.041\times pH)-[0.232\times pH:\ln(hard)]-[0.261\times pH:\ln(DOC)]\right]}$$

P. promelas Pooled MLR Model (*C. dubia* and *P. promelas* data pooled, but using *P. promelas* intercept):

$$P.promelas\ EC_{20} = e^{\left[-7.550+[0.592\times\ln(DOC)]+[2.188\times\ln(hard)]+(1.998\times pH)-[0.268\times pH:\ln(hard)]\right]}$$

The EPA Analysis of the DeForest et al. (2018b) MLR Models

The EPA analyzed model performance to determine if it was more appropriate to normalize the freshwater toxicity data using the two individual models applied to vertebrate and invertebrates separately or to use the common pooled slope model to normalize all the data regardless of taxonomy. As DeForest et al. (2018b) suggested in the memorandum, both the pooled model and the individual models performed similarly when comparing observed versus predicted values, with predicted values within a factor of two being a benchmark to determine performance. **Figure L-1** show that 31/32 (97%) of the predicted values for the *C. dubia* tests for both MLR models were within a factor of two (DeForest et al. 2018b). The individual model for *P. promelas* had a similar level of performance with 30/31 (97%) of the tests within a factor of two, while the pooled model was only slightly less with 29/31 (94%) of the predicted values within a factor of two of the observed values (**Figure L-2**) (DeForest et al. 2018b).

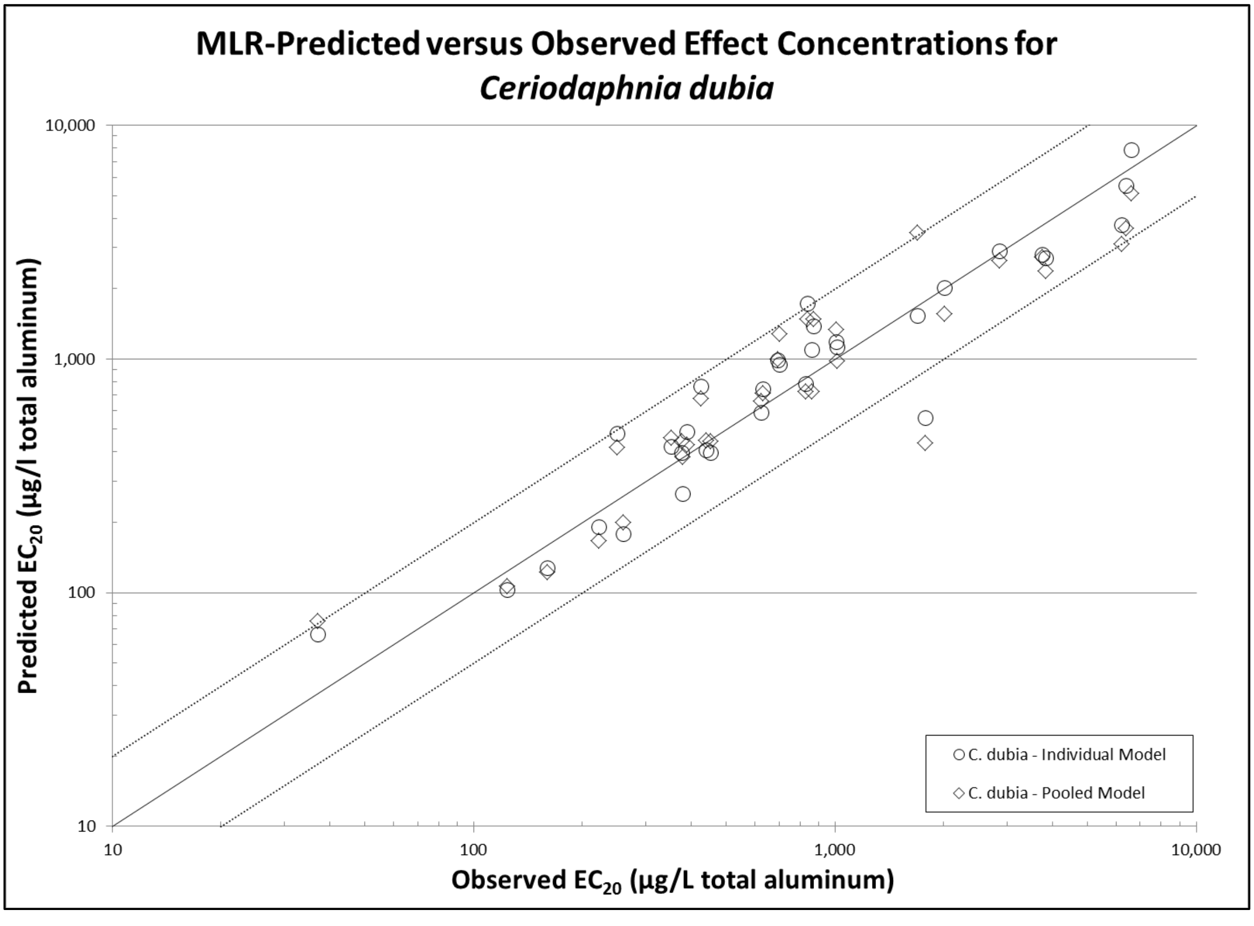

Figure L-1. Predicted versus Observed Values for the *C. dubia* MLR models.
(The solid diagonal line represents a 1:1 relationship while the dotted diagonal lines represent a factor of two).

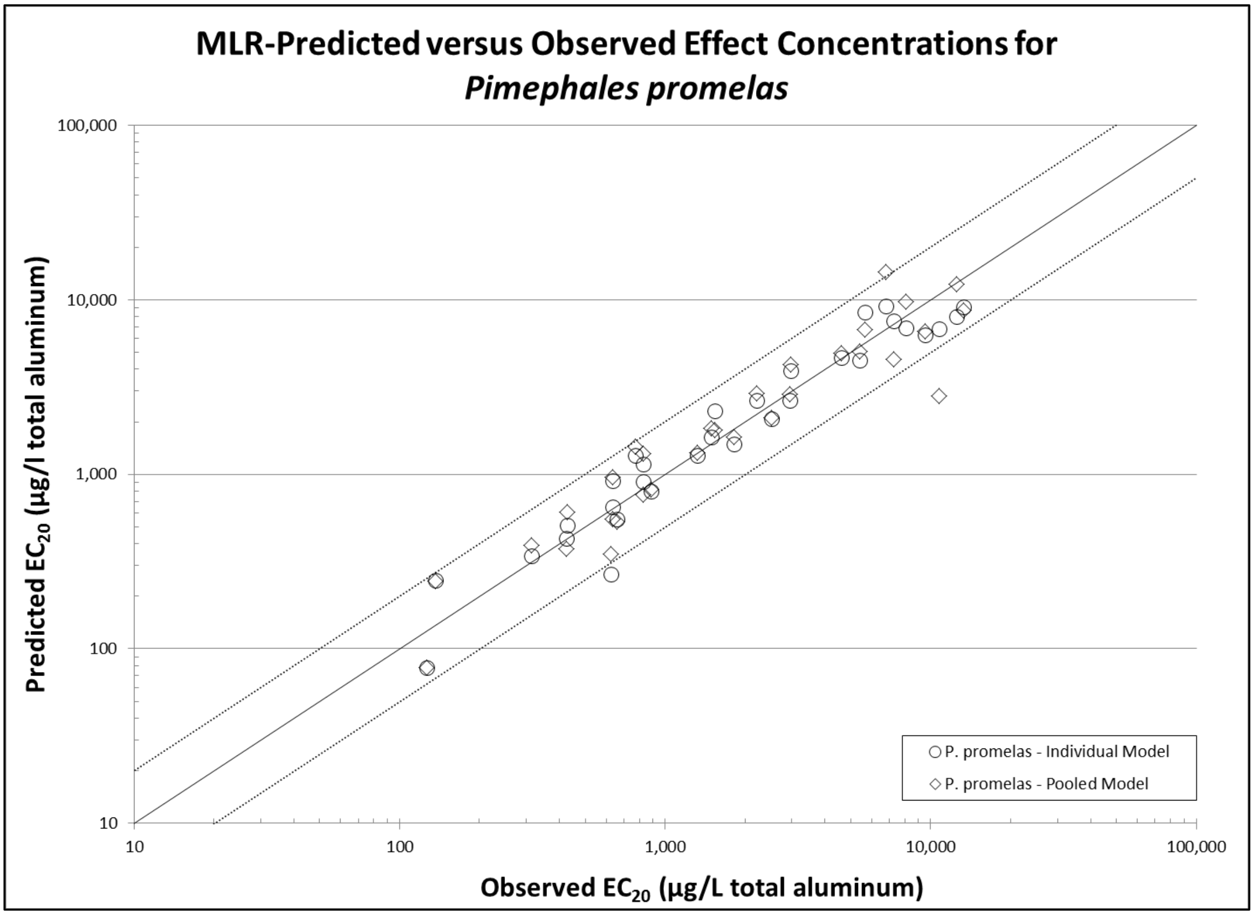

Figure L-2. Predicted versus Observed Values for the *P. promelas* MLR models.
(The solid diagonal line represents a 1:1 relationship while the dotted diagonal lines represent a factor of two).

In order to refine the analysis, the EPA looked at the residuals (observed value minus the predicted value) to determine if one model fit the data better. This analysis is similar to the approach in DeForest et al. (2018a). The residuals were plotted against each individual water quality parameter (pH, total hardness and DOC) to determine if either model generated a biased predicted value. All parameters were natural log transformed for clarity of presentation except pH.

The results of these plots revealed that the *C. dubia* pooled MLR model was over predicting test concentrations (higher predicted EC_{20}s than observed values) as pH increased, and under predicting test concentrations as DOC and total hardness increased (lower predicted EC_{20}s than observed values) (**Figure L-3**, **Figure L-4** and **Figure L-5**). Conversely, the *C. dubia* individual-species MLR model showed no trends in the residuals over any of the test parameters.

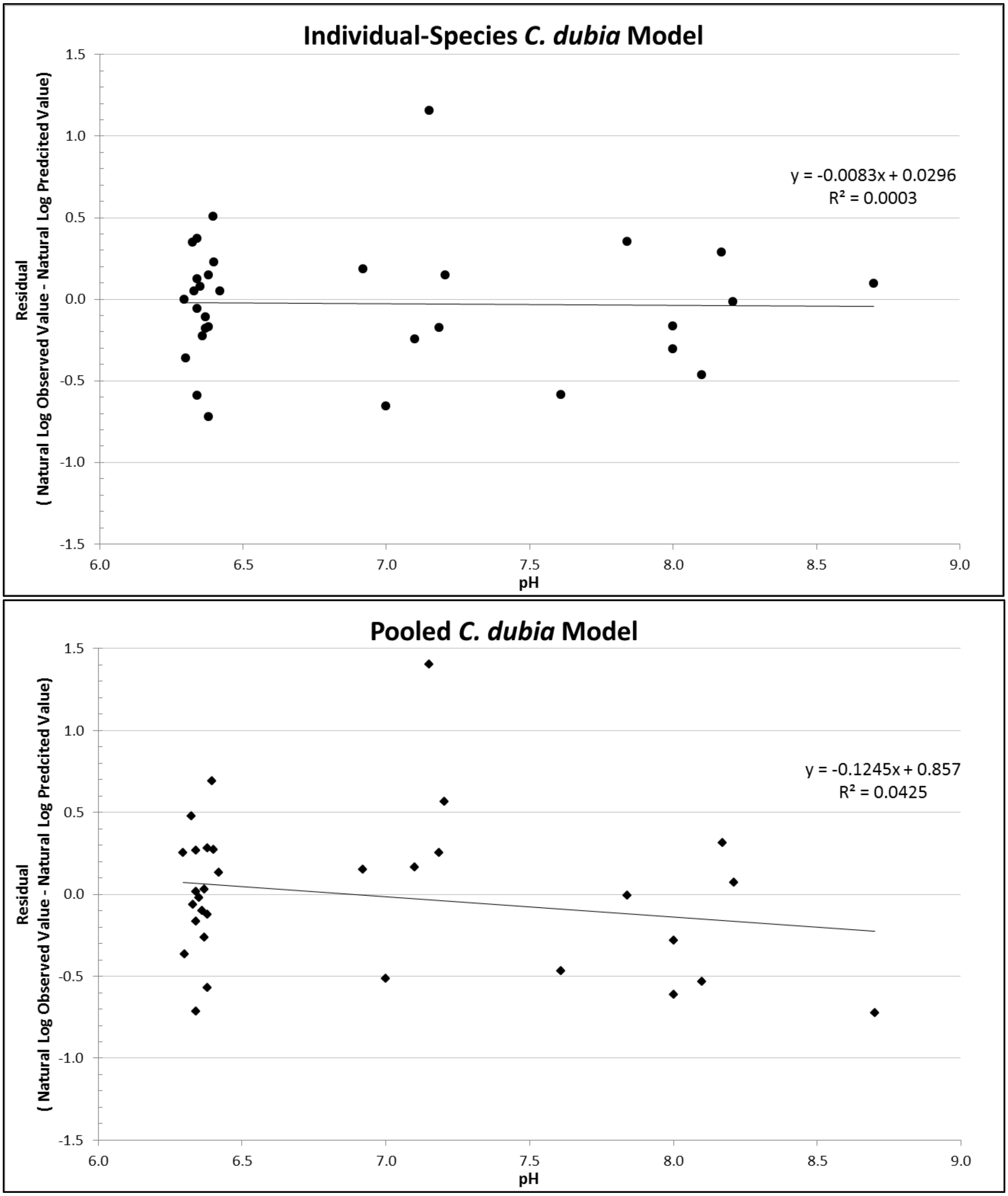

Figure L-3. Residual Plots for the *Ceriodaphnia dubia* models versus pH.

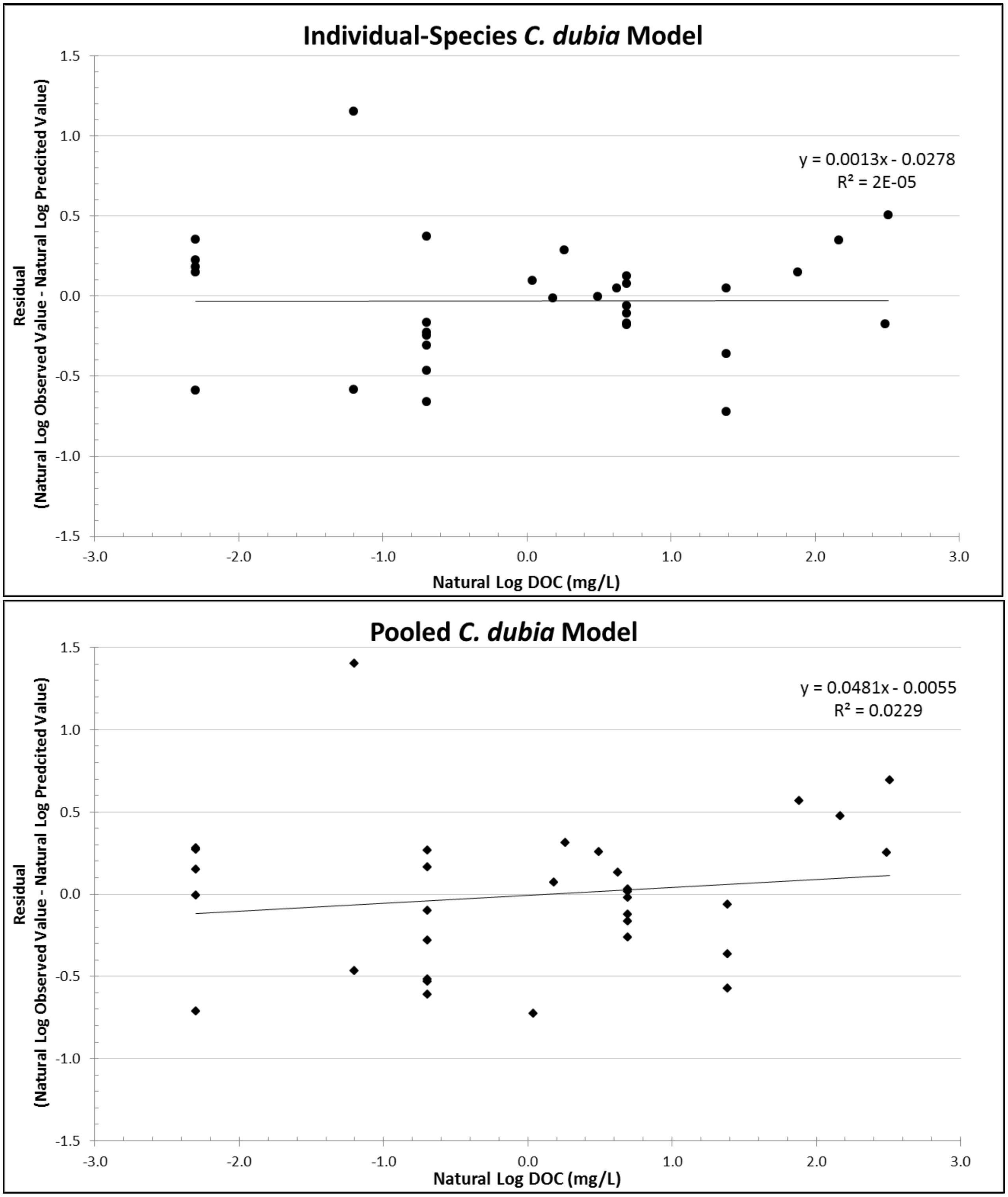

Figure L-4. Residual Plots for the *Ceriodaphnia dubia* models versus DOC

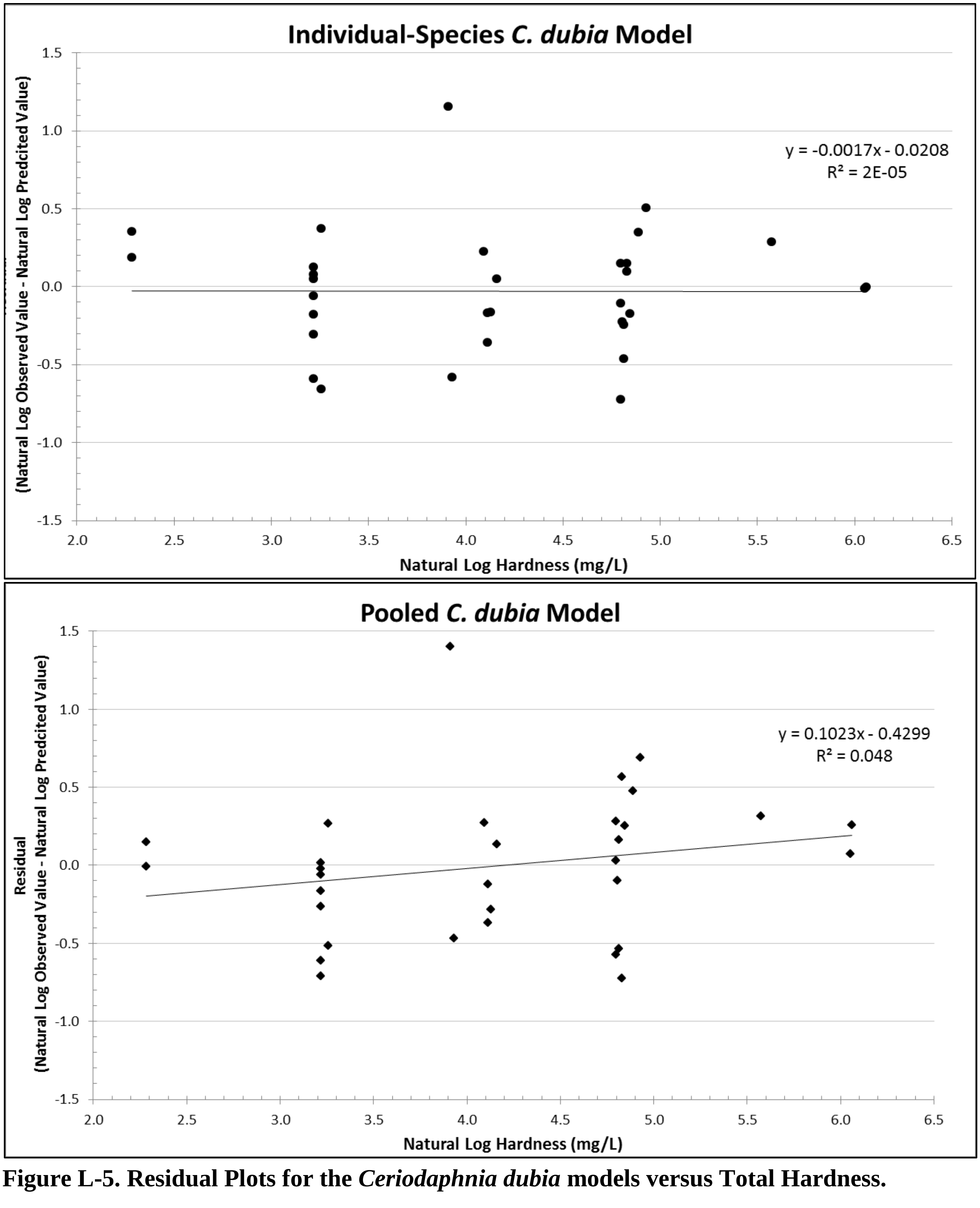

Figure L-5. Residual Plots for the *Ceriodaphnia dubia* models versus Total Hardness.

Similarly, a comparison of the residuals plots for the individual-species *P. promelas* showed no trends in the residuals over any of the test parameters (**Figure L-6**, **Figure L-7** and

Figure L-8). Likewise, there were also trends in the residuals for the pooled *P. promelas* MLR model. The predicted values were over predicting (higher predicted EC_{20}s than observed) as total hardness and DOC increased and under predicting (lower predicted EC_{20}s than observed) as pH increased.

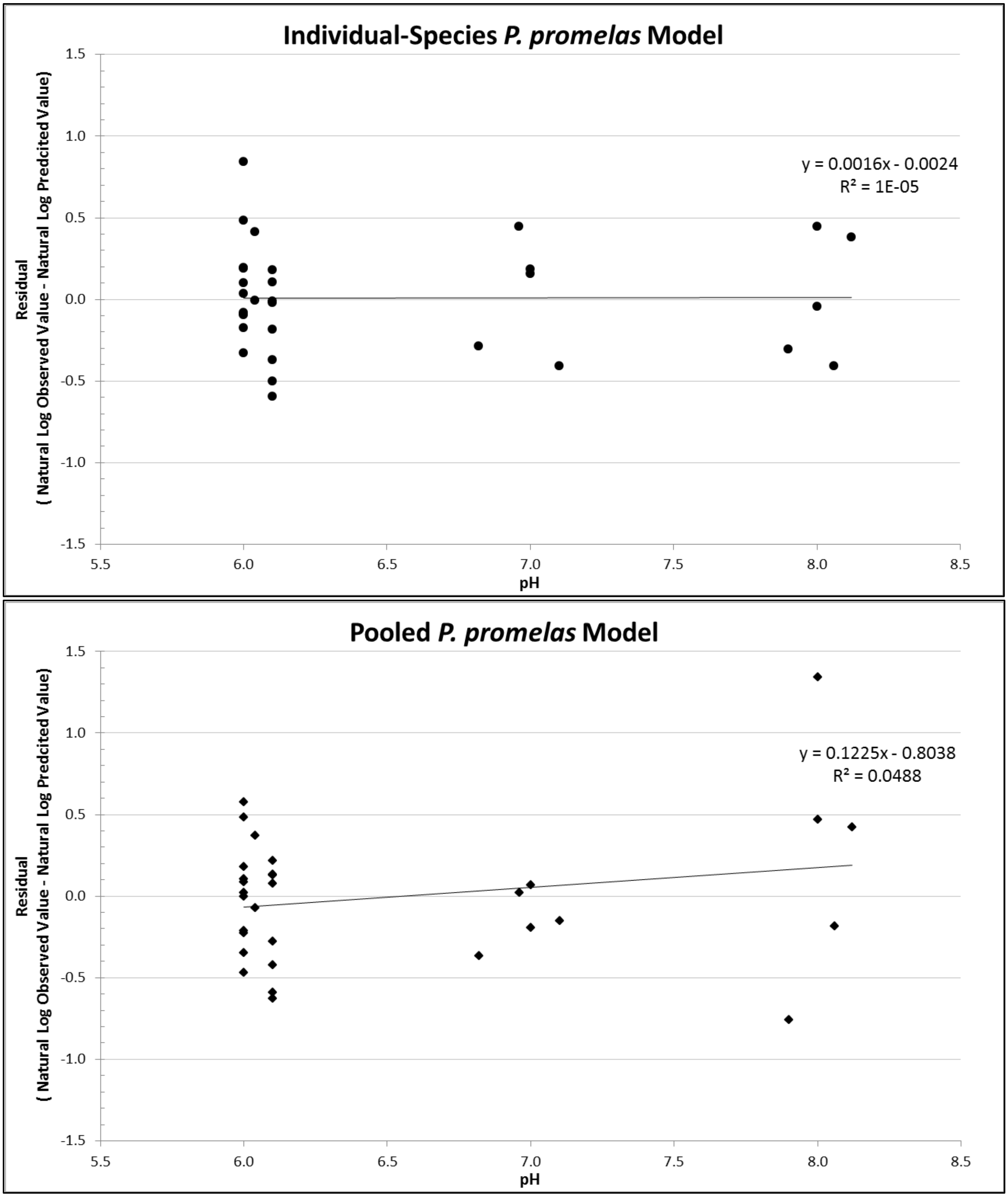

Figure L-6. Residual Plots for the *Pimephales promelas* models versus pH.

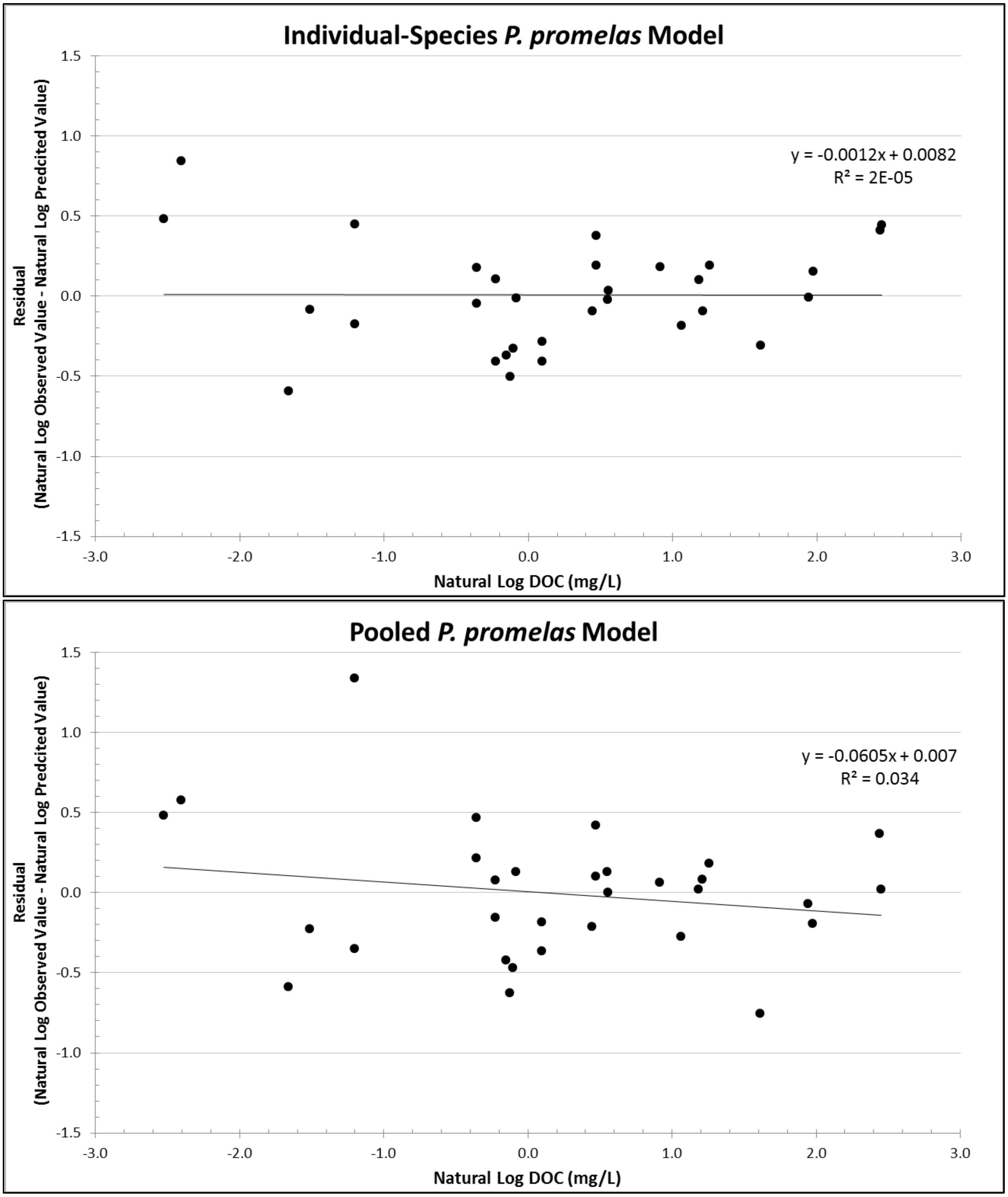

Figure L-7. Residual Plots for the *Pimephales promelas* models versus DOC.

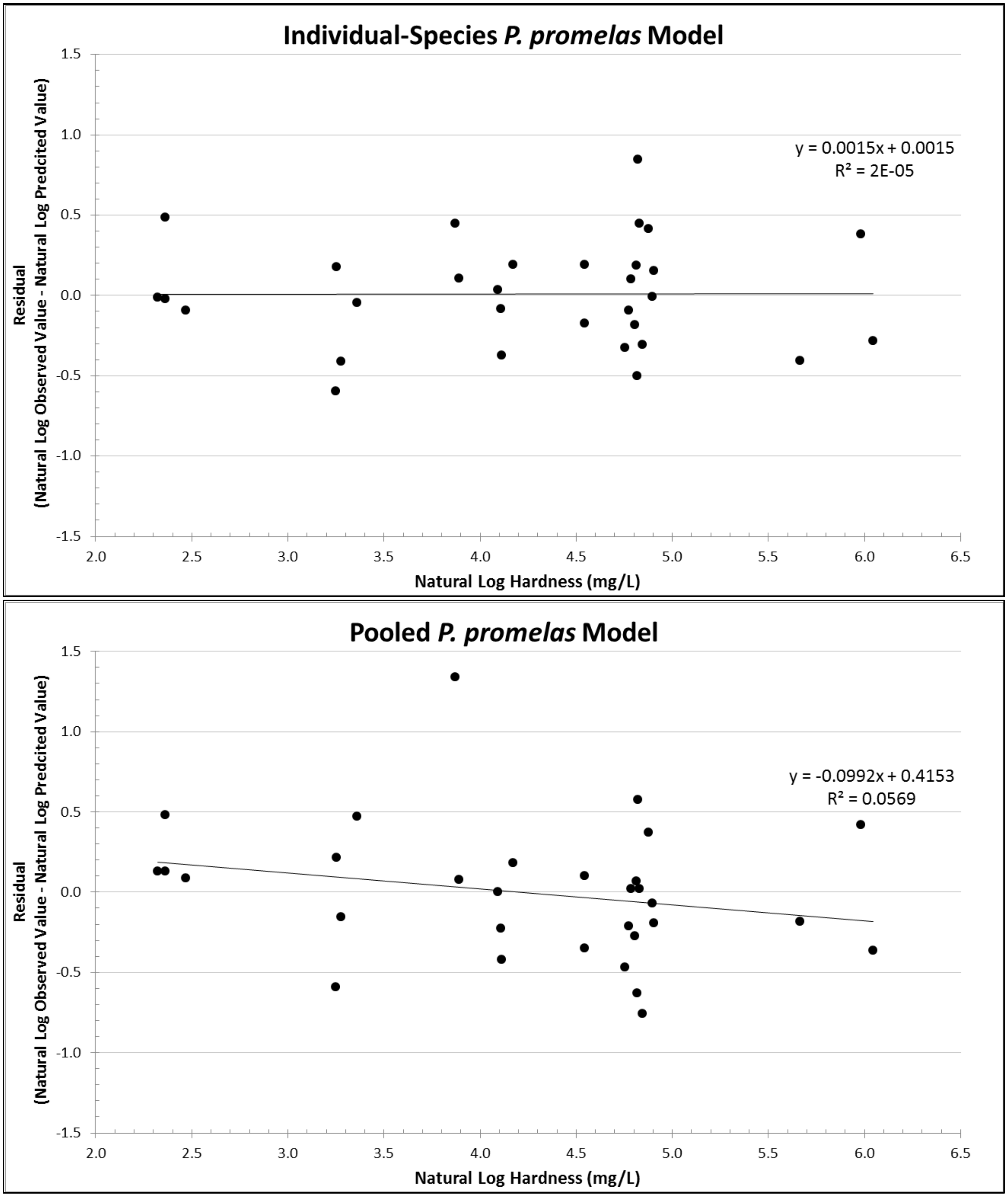

Figure L-8. Residual Plots for the *Pimephales promelas* models versus Total Hardness.

In addition to these residual trends for the pooled model, a poorer fit for the pooled model is indicated by higher standard deviations of the residuals than for the individual-species models.

For the natural logarithm transformed observed and predicted EC_{20}s, the residual standard deviation for the *C. dubia* dataset was 0.45 for the pooled model versus 0.38 for the individual-species model (18% higher). For *P. promelas*, the difference was 0.41 versus 0.32 (27% higher). The statistical significance of this poorer fit was evaluated using an F-test on the merged data across both species. The residual sum-of-squares for the pooled models (SS=11.618, df=57) was reduced 33% by applying the individual-species models (SS=7.814, df=51). For the null hypothesis of no improvement from applying the individual-species models, this translates into a F statistic of 4.14 with 6 and 51 degrees of freedom, rejecting the null hypothesis at $p<0.002$.

Based on these analyses, the EPA decided to use the updated individual-species MLR models presented in DeForest et al. (2018b) to normalize the freshwater aluminum toxicity data in developing the Final 2018 Aluminum Aquatic Life AWQC.