



DRAFT
AQUATIC LIFE AMBIENT WATER
QUALITY CRITERIA FOR
ALUMINUM
2017

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AMBIENT WATER QUALITY CRITERIA FOR
ALUMINUM - 2017

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U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF WATER
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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 on a case-by-case basis that differ from these criteria when appropriate. While this document contains EPA's scientific recommendations regarding ambient concentrations of aluminum that protect aquatic life, it does not substitute for the CWA or EPA's regulations; nor is it a regulation itself. Thus, it cannot impose legally binding requirements on EPA, states, tribes, or the regulated community, and might not apply to a particular situation based upon the circumstances. EPA may change 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.

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<https://www.epa.gov/wqc/aquatic-life-criteria-and-methods-toxics>.

FOREWORD

Section 304(a)(1) of the Clean Water Act of 1977 (P.L. 95-217) requires that the Administrator of the Environmental Protection Agency (EPA) publish water quality criteria that accurately reflect the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare that might be expected from the presence of pollutants in any body of water, including ground water. This document is a draft 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 Clean Water Act, section 304(a)(1) and section 303(c)(2). The term has a different program impact in each section. In section 304, the term represents a non-regulatory, scientific assessment of ecological effects. Criteria presented in this document are such scientific assessments. If water quality criteria associated with specific surface water uses are adopted by a state or EPA as water quality standards under section 303, they become applicable Clean Water Act water quality standards 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 criteria developed under section 304. However, in many situations states might want to adjust water quality criteria developed under section 304 to reflect local environmental conditions and human exposure patterns. Alternatively, states and authorized tribes may use derive 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 EPA, that criteria become Clean Water Act 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 handbook and additional guidance on the development of water quality standards and other water-related programs of this Agency have been developed by the Office of Water.

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

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ACRONYMS

ACR	Acute-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 Requirements
MLR	Multiple Linear Regression
NAWQA	National Water Quality Assessment
NOAA	National Oceanic and Atmospheric Administration
NOEC	No Observed Effect Concentration
NPDES	National Pollutant Discharge Elimination System
QA/QC	Quality Assurance/Quality Control
SD	Sensitivity Distribution
SMAV	Species Mean Acute Value
SMCV	Species Mean Chronic Value
TMDL	Total Maximum Daily Load
US	United States
USGS	United States Geological Survey
WQC	Water Quality Criteria
WQS	Water Quality Standards

EXECUTIVE SUMMARY

EPA is updating the aluminum aquatic life ambient water quality criteria recommendation in accordance with the provisions of §304(a) of the Clean Water Act to revise Ambient Water Quality Criteria (AWQC) from time to time to reflect the latest scientific knowledge. The aluminum aquatic life criteria were developed using peer reviewed methods and data that are acceptable for the derivation of criteria using the procedures described in 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 as "1985 Guidelines" in this document). Recommended 304(a) water quality criteria for aluminum were originally developed in 1988 (EPA 440/5-86-008). Literature searches for laboratory toxicity tests of aluminum on aquatic life published from 1988 to 2015 identified new studies containing acute and chronic toxicity data acceptable for criteria derivation. These were supplemented by additional data made available by researchers in 2016 and 2017. A full evaluation of available data was performed by 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. This update establishes a freshwater criteria magnitude that is affected by total hardness, pH and dissolved organic carbon (DOC) and expands on the toxicity database to include those studies below pH 6.5. The criteria durations are one-hour average for acute and 4-day average for chronic, respectively, and both criteria frequencies are once in 3 years on average, consistent with the 1985 Guidelines recommendations.

Multiple linear regression (MLR) models were developed to characterize the bioavailability of aluminum in aquatic systems based on the effects of pH, hardness and DOC (DeForest et al. 2017). The authors used 22 chronic tests with the fathead minnow (*Pimephales promelas*), and 23 chronic tests with *Ceriodaphnia dubia* to evaluate the ability of MLR models to predict chronic toxicity of aluminum as a function of multiple combinations of pH, hardness, and DOC conditions. These three parameters are thought to be the most influential for aluminum bioavailability and can be used to explain the magnitude of differences in the observed toxicity values. 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, hardness and DOC on aluminum

toxicity, and therefore allow the criteria magnitudes to be a function of the unique chemistry conditions at a given site. EPA reviewed these models, published by DeForest et al (2017), and verified the results. Thus, the aluminum criteria were derived using MLR models that incorporate pH, hardness and DOC as input parameters to normalize the freshwater acute and chronic toxicity data to a set of predetermined water quality conditions based on the models published (DeForest et al. 2017) in the peer-reviewed open literature.

Freshwater Criteria Update

The 1988 aluminum freshwater acute criterion was based on dissolved aluminum concentrations and data from 8 species of invertebrates and 7 species of fish for a total of 15 species grouped into 14 genera. This 2017 draft criteria update is based on total aluminum concentrations and includes 11 species of invertebrates, 8 species of fish, and one species of frog for a total of 20 species grouped into 18 genera. The freshwater acute criterion, known as the Criterion Maximum Concentration (CMC), expresses the concentration of total aluminum under which approximately 95% of genera in a freshwater aquatic ecosystem should be protected if the one-hour average concentration of total aluminum is not exceeded more than once in 3 years on average. Because the CMC depends on the set of water chemistry conditions at the site, the CMC is a function of the MLR models used to normalize the acute toxicity data. As a result, the CMC will vary with water chemistry conditions. For example, conditions of pH 7, total hardness of 100 mg/L as CaCO_3 and DOC of 1 mg/L would result in a CMC of 1,400 $\mu\text{g/L}$. At the same pH and hardness, but with a DOC of 2 mg/L, the CMC would be 2,000 $\mu\text{g/L}$. It should be noted that the MLR criteria outputs are bounded at a maximum of 150 mg/L total hardness, as CaCO_3 , and DOC of 5.0 mg/L, because the available toxicity data did not extend beyond these maxima (input data ranged from 9.8 to 127 mg/L for hardness and 0.08 to 5 mg/L for DOC). The user can input values for areas with hardness greater than 150 mg/L and DOC of 5 mg/L, but the criteria output for these parameters will be limited at the bounds stated due to underlying data limitations. The pH range of the model is from 5.0 to 9.0, extending beyond the range of empirical data used for model development (pH 6.0 to 8.1). This is provided to be protective of a broader range of natural waters; however, values estimated outside of the range of the data are more uncertain. The MLR equations applied to the acute toxicity data were those developed through chronic tests, with the assumption that the effect of water chemistry on bioavailability remains consistent

across exposure duration. **Appendix K** (*Criteria for Various Water Chemistry Conditions*) provides a series of look-up tables to determine the recommended CMC magnitude at various pH, total hardness and DOC values. The available freshwater toxicity data for aluminum indicate that freshwater aquatic life should be protected if the 1-hour average concentration of total aluminum does not exceed the magnitude specified by the output of the MLR model for acute criteria for the relevant water chemistry conditions. These values are recommended not to be exceeded more than once every three years on average.

The 1988 aluminum freshwater chronic dataset included 2 species of invertebrates and one fish species grouped into 3 genera. This 2017 draft criteria update includes new data for an additional 8 species, and consists of 7 invertebrate and 4 fish species grouped into 11 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. Like the acute criterion, the freshwater chronic criterion, known as the Criterion Continuous Concentration (CCC), is also dependent upon the set of water chemistry conditions at the site and is likewise a function of the MLR models used to normalize the chronic toxicity data. For example, the resulting recommended ambient water quality criteria indicate that freshwater aquatic organisms in ambient water would have an appropriate level of protection if the four-day average concentration of total aluminum does not exceed 390 µg/L at pH 7, total hardness of 100 mg/L as CaCO₃ and DOC of 1 mg/L; or the average concentration of total aluminum does not exceed 560 µg/L at pH 7, total hardness of 100 mg/L and DOC of 2 mg/L. Again, in the MLR equations defining the criteria magnitude, the total hardness was bounded at 150 mg/L as CaCO₃ and the DOC at 5.0 mg/L, to reflect the bounds of the underlying model data, whereas the pH covers the range of 5.0 to 9.0. Likewise, the user can apply the model in areas with hardness greater than 150 mg/L and DOC of 5 mg/L, but the model output for these parameters will be limited at the bounds stated due to underlying data limitations.

Appendix K provides a series of look-up tables to determine the recommended CCC magnitude at various pH, total hardness and DOC values. The available freshwater toxicity data for aluminum indicate that freshwater aquatic life should be protected if the 4-day average concentration of total aluminum does not exceed the magnitude specified by the output of the

MLR model for chronic criteria for the relevant water chemistry conditions. These values are recommended not to be exceeded more than once every three years on average.

2017 Draft Aluminum Aquatic Life Criteria Compared to Current 1988 Criteria^a

Version	Freshwater Acute (1 day, total aluminum)	Freshwater Chronic (4-day, total aluminum)
2017 Draft AWQC Criteria (MLR normalized to pH = 7, hardness = 100 mg/L, DOC = 1 mg/L)	1,400 µg/L	390 µg/L
1988 AWQC Criteria (pH 6.5 – 9.0, across all 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: Values will be different under differing water chemistry conditions as identified in this document.

Additionally, EPA created a user-friendly Aluminum Criteria Calculator V.1.0 (*Aluminum Criteria Calculator V.1.0.xlsx*) 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.

Estuarine/Marine Criteria Update

Like the 1988 AWQC for aluminum, there are still insufficient data to fulfill the MDRs as per the 1985 Guidelines, such that no estuarine/marine criteria can be recommended 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. New acute toxicity data for 5 families representing 5 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 LC₅₀ (SMAV) of 97.15 µg/L, and the most tolerant species was a copepod, (*Nitokra spinipes*) with a SMAV of 10,000 µg/L. No acceptable acute test data on fish species were available. There are no estuarine/marine chronic toxicity data that meet the test acceptability and quality assurance/control principles as outlined in the 1985 Guidelines. Aluminum toxicity data on estuarine/marine species remain a data gap.

1 INTRODUCTION AND BACKGROUND

National Recommended Ambient Water Quality Criteria (AWQC) are established by the United States Environmental Protection Agency (EPA) under 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. Aquatic life criteria address the CWA goals of providing for the protection and propagation of fish and shellfish. Once EPA publishes final §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 also modify these criteria to reflect site-specific conditions or use other scientifically defensible methods to develop criteria before adopting these into standards. After adoption, states and authorized tribes are to submit new and revised water quality standards (WQS) to EPA for review and approval or disapproval. When approved by 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 §303(d) and derivation of water quality-based effluent limitations in permits issued under the CWA §402 National Pollutant Discharge Elimination System (NPDES) permit program.

As required by the CWA, EPA periodically reviews and revises §304(a) AWQC to ensure they are consistent with the latest scientific information. EPA previously published ambient water quality criteria recommendations for aluminum in 1988 (EPA-440/5-86-008¹), and is updating these criteria through its authority under §304(a) of the CWA. The goal of the CWA is to protect and restore the biological, chemical and physical integrity of waters of the United States. Section 304(a)(1) of the CWA requires EPA to develop criteria for water quality that accurately reflect the latest scientific knowledge. Criteria are developed following the guidance outlined in the Agency'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 scientifically defensible water quality criteria values for aluminum pursuant to CWA §304(a), derived utilizing best available

¹ <http://water.epa.gov/scitech/swguidance/standards/criteria/current/index.cfm>

data in a manner consistent with the 1985 Guidelines and reflecting best professional scientific judgments of toxicological effects of aluminum on aquatic organisms.

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 is consistent with EPA's *Guidance for Ecological Risk Assessment* (U.S. EPA 1998). This ecological effects assessment describes scientifically defensible water quality criteria values for aluminum under §304(a)(1) of the CWA.

2.1 Overview of Aluminum Sources and Occurrence

Aluminum is the third most abundant element and the most common metal in the earth's crust, comprising about 8 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 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. 2006). The mechanism of this conversion is not well understood.

Aluminum is still actively mined in the U.S. from bauxite, the primary aluminum ore (primarily 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, resistant to corrosion, electrical conductivity, and durability), it has many diverse uses including in: 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 are defined below. "Dissolved" refers to constituents that exist in chemical solution in a water sample. The designation "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 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 will be assumed to be total aluminum.

Aluminum data for freshwater systems were obtained from the Water Quality Data Portal (<https://www.waterqualitydata.us/>, 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 NAWQA database collected during 1992-2003 are presented in **Figure 1**, with a 90th percentile concentration of dissolved aluminum concentrations of 11 µg/L.

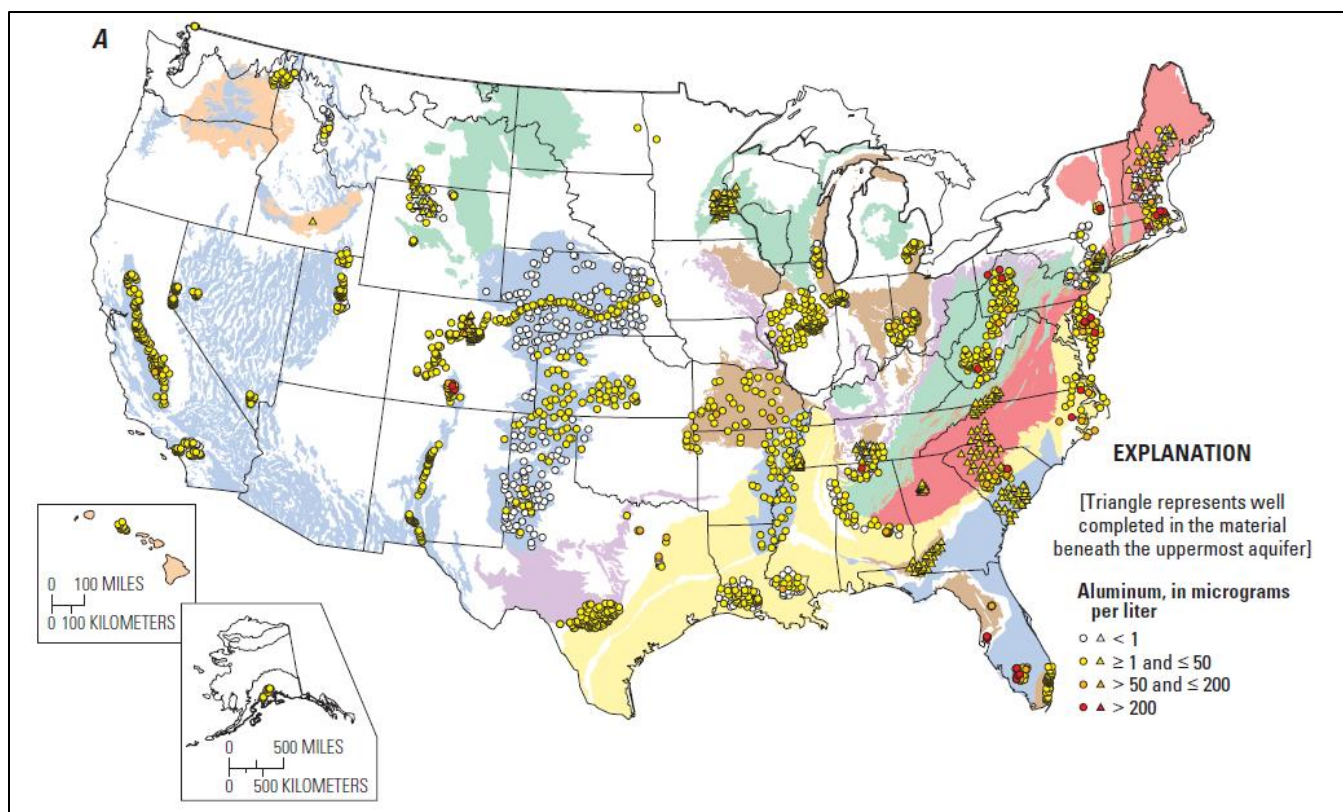


Figure 1. Geographic Distribution of Dissolved Aluminum Concentrations in Groundwater Collected from Wells as Part of the National Water-Quality Assessment Program, 1992–2003.

(Ayotte et al. 2011).

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). Dissolved aluminum data compiled from the scientific literature by Angel et al. (2016) indicate that concentrations range from 0.5 to 2 $\mu\text{g/L}$ in coastal waters, and from 0.008 to 0.68 $\mu\text{g/L}$ in the open ocean. Other researchers have also reported that values are generally ≤ 1 $\mu\text{g/L}$ 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 coordinates with the hydroxide ion, primarily as $\text{Al}(\text{OH})_4$.

Average total aluminum concentrations in the atmosphere were observed to range from 0.005 to 0.18 $\mu\text{g/m}^3$ (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). 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. Each aerosol filter was collected for 3 to 5 hours during head wind conditions in the direction of atmospheric phenomenon. Most reported atmospheric total aluminum concentrations were less than $1 \mu\text{g}/\text{m}^3$. 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 areas, 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 $8.0 \mu\text{g}/\text{m}^3$ (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 $827 \mu\text{g}/\text{L}$ (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 (Garcia et al. 2009). Average total aluminum precipitation concentrations reported in the rural area ($107.2 \mu\text{g}/\text{L}$, range of 28.8 - $222.7 \mu\text{g}/\text{L}$) were higher than observed in the urban area ($83.9 \mu\text{g}/\text{L}$, range 35.8 - $125.4 \mu\text{g}/\text{L}$). Samples of wet deposition collected in semi-rural Dexter, Michigan had an average mean total aluminum concentration of $57 \mu\text{g}/\text{L}$ (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 $6.06 \mu\text{g}/\text{L}$ (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 $1,200 \mu\text{g}/\text{L}$ 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 $700 \text{ mg}/\text{kg}$ to over $100,000 \text{ mg}/\text{kg}$ (Shacklette and Boerngen 1984; Sorenson et al. 1974), averaging $71,000 \text{ mg}/\text{kg}$ (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 $\mu\text{g/g}$ dry 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 salt marsh ecosystem had aluminum concentrations ranging from 17-820 $\mu\text{g/g}$ dry weight (Kumar et al. 2008).

Aluminum floc coprecipitates nutrients, suspended material, and microorganisms. Floc forms when aluminum-rich water meets less acidic water thereby co-precipitating with other ions and material. 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 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. 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 $\text{g/m}^2\text{-year}$ on Massachusetts Bay (Golomb et al. 1997).

Aqueous aluminum chemistry is multifaceted and several comprehensive reviews have been published on its chemistry and biological effects in the aquatic environment (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 can react with other ions and organic matter to form soluble complexes. However, 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+} , $\text{Al}(\text{OH})^{2+}$, $\text{Al}(\text{OH})_2^+$, $\text{Al}(\text{OH})_3$, and $\text{Al}(\text{OH})_4^-$), as amorphous $\text{Al}(\text{OH})_3$ leading to gibbsite formation and precipitation, and as polynuclear species such as the tridecameric Al_{13} polynuclear species (Gensemer and Playle 1999).

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 as monomeric, dimeric, and polymeric hydroxides and as complexes with fulvic and humic acids, chloride, phosphate, sulfate, and less common anions. Aluminum solubility increases in 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 (Schofield 1977; Wilson 2012).

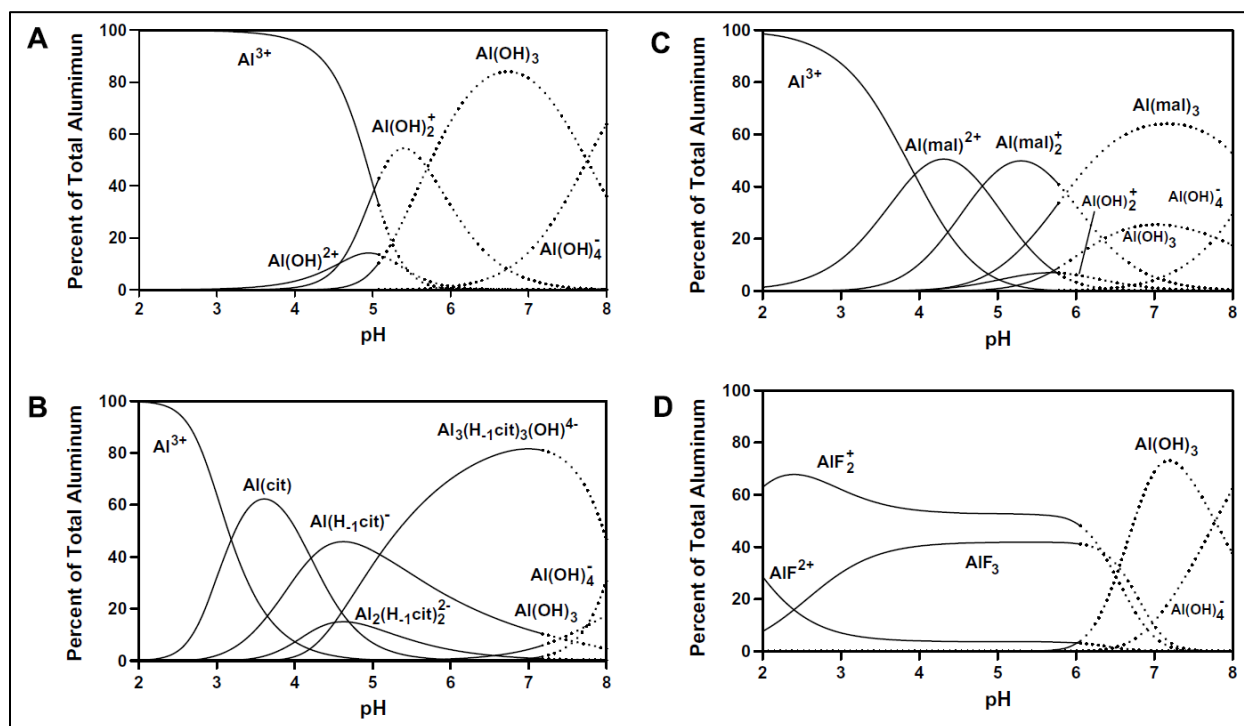


Figure 2. Results of Al Speciation Calculations at a Total of 65 μM Al in the Absence of Ligands (panel A) and in the Presence of Citrate (65 μM) (panel B), Maltolate (195 μM) (panel C), and Fluoride (260 μM) (panel D) in the pH Range 2 to 8.

The dotted lines indicate solutions that would be supersaturated with respect to freshly prepared $\text{Al}(\text{OH})_3$. (Zhou et al. 2008, Figure 1).

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 also been shown to increase respiration, and thereby energy demands, among mayfly species (Herrmann and Anderson 1986).

For fish, the gill is the primary site of aluminum toxic action, resulting in ionoregulatory, osmoregulatory, and respiratory dysfunction. 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). 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.

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 as the aluminum from the stock solution equilibrates with the test water and the pH increases, the monomeric species of aluminum transform to the insoluble polymeric hydroxide species, which are more toxic (Cardwell et al. 2017). Thus, soon after test initiation, there is a transformation

period of rapid speciation changes from short-lived transient amorphous and colloidal forms of aluminum to more stable crystalline forms (Gensemer et al. 2017). Aged stock solutions (aluminum solutions that have been given time 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).

Several investigators have found different trends in the toxicity of aluminum under different pH conditions, and toxicity of aluminum appears to be lowest at normal (approximately 7) pH, with toxicity tending to increase with either increasing or decreasing pH (above and below normal pH). Freeman and Everhart (1971) found that the chronic toxicity of nominal (unmeasured) aluminum increased as pH increased from 6.8 to 8.99 in rainbow trout in flow-through tests, and 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 pH's 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 and Hunter et al. were static renewal or flow-through and showed the lowest acute values, whereas the Call tests were static. The flow-through and renewal tests are considered to be the more reliable contaminant assessments 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.

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 a study of the toxicity of available aluminum to a green alga, *Chlorella pyrenoidosa*, Helliwell et al. (1983) found that maximum toxicity 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 $\text{Al}(\text{OH})_2^+$. 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 ($\text{Al}(\text{OH})^{+2}$ and $\text{Al}(\text{OH})_2^+$) are regarded as the most dangerous forms, while organically bound Al and polymeric forms are less toxic or essentially harmless.”

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 <1 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 aggregates 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.

For fish, the gill is the primary site of aluminum toxicity under either acidic or alkaline conditions (Wilson 2012). 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 specific mechanisms of aluminum toxicity at alkaline pH are not well understood.

Overall, aquatic plants are generally insensitive to aluminum. Algae productivity and biomass are seldom affected if the pH is above 3.0. Aluminum and acid toxicity tend to be additive to some algae when the pH is less than 4.5. Because the metal binds with inorganic phosphorus, it may reduce the availability of this nutrient thereby reducing productivity (Sparling and Lowe 1996a).

2.3.1 Water Quality Parameters Affecting Toxicity

Bioavailability of aluminum is affected by water chemistry parameters such as pH, hardness, and DOC. The pH of waters affects aluminum speciation and solubility. Aluminum can sorb to DOC, such as humic and fulvic acids, and form organic aluminum complexes. An increase in dissolved organic carbon (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 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 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 hardness-toxicity relationship was observed for rainbow trout exposed to three different hardness levels at a controlled pH of 8.3 (Gundersen et al. 1994).

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 alkalinity, pH and dissolved organic carbon (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, hardness and DOC. While MLR models are less complex than BLM models, they also estimate the bioavailability of aluminum to aquatic species. EPA evaluated the use of empirical, non-mechanistic MLR models for aluminum (DeForest et al. 2017) as a bioavailability-based approach for deriving water quality criteria as well as a BLM model for aluminum (Santore et al. 2017). EPA decided to use an empirical MLR approach in this draft 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 hardness equation-based criteria, an MLR approach, and a BLM approach for aluminum criteria development was conducted in 2015 and peer-reviewer comments were considered in the selection of the MLR-based criteria approach. EPA independently examined and verified the quality and fit of the DeForest et al. (2017) MLR models before applying them in this draft criteria document.

2.4 Conceptual Model

Conceptual models consist of a written description and diagram (U.S. EPA 1998) 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, ground water recharge, spray drift, 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 assume exposure occurs 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.

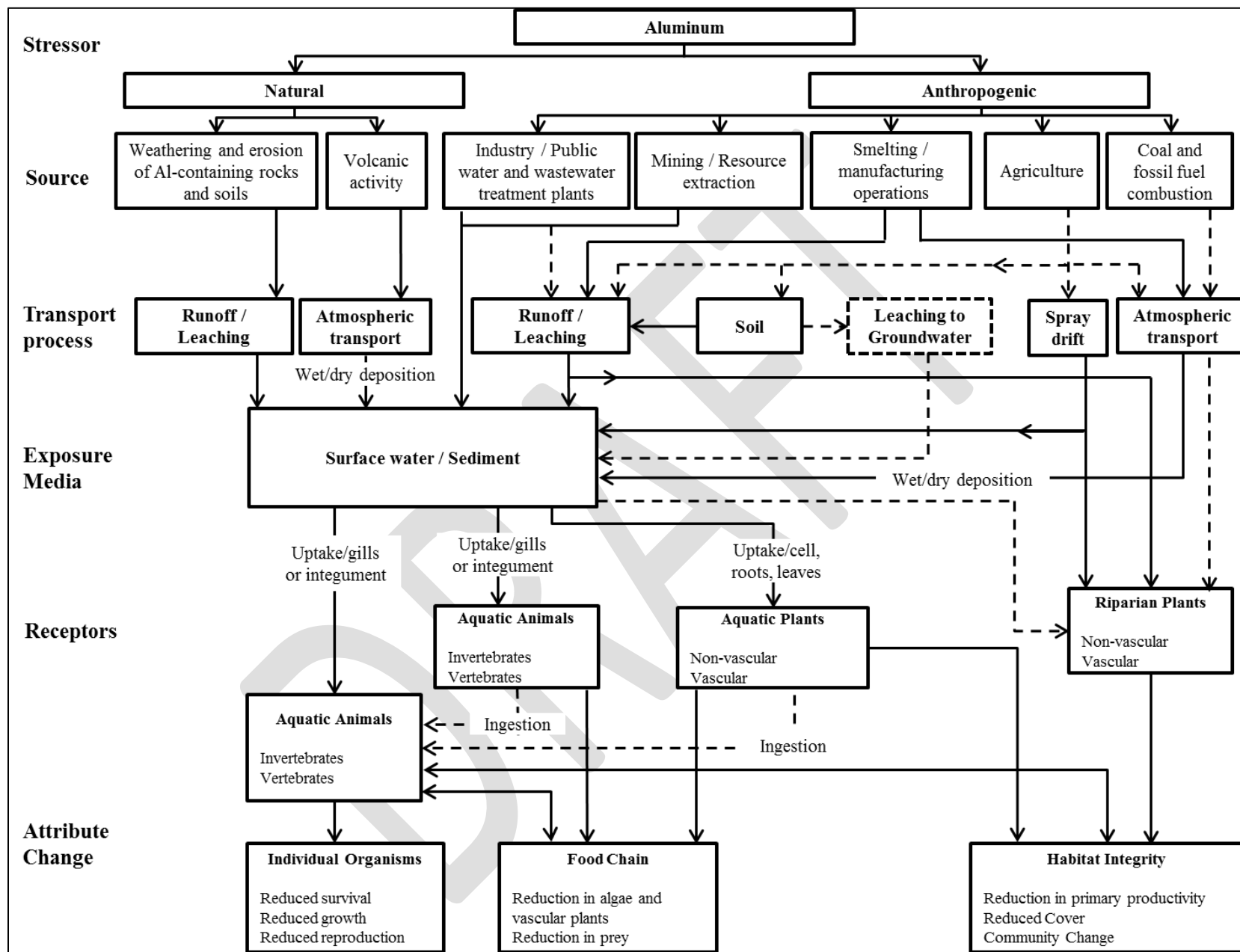


Figure 3. Conceptual Model for Aluminum Effects on Aquatic Organisms.

(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 1998). Assessment endpoints may be identified at any level of organization (e.g., individual, population, community). In 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). 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 and their uses is based on the theory that effects occurring to a species in appropriate, 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 (SD) 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 are 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). Thus, if properly derived and used, the combination of a freshwater or estuarine/marine acute CMC and chronic CCC 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)	For effects: 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

LC₅₀ = Lethal concentration to 50% of the test population

EC₅₀/EC₂₀/EC₁₀ = Effect concentration to 50%/20%/10% of the test population

IC₅₀ = Concentration of aluminum at which growth is inhibited 50% compared to control organism growth

2.6 Measurement Endpoints

Assessment endpoints require one or more measures of ecological effect, which are termed “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 1998). Toxicity data are used as measures of direct and indirect effects on representative biological receptors. The selected measures of effect 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 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

EPA has specific data requirements to assess the potential effects of a stressor on an aquatic ecosystem and develop 304(a) aquatic life criteria under the CWA. 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 8 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 8 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)
 - 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. However, 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 EC₂₀s (DeForest et al. 2017), except at unrealistically high pH and very high 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. The measures of effect are provided by the acute and chronic toxicity data. These toxicity endpoints (expressed as genus means) 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**.

Measure of Aluminum Exposure Concentration

As with EPA's previous ambient water quality criteria (AWQC) document for aluminum from 1988, only data from toxicity tests conducted using chloride, nitrate and sulfate salts (either anhydrous or hydrated) are used in effects assessment. The 1988 AWQC criteria for aluminum were based on acid-soluble concentrations, and were subsequently expressed in terms of total

recoverable aluminum. The current EPA approved CWA Test Methods for aluminum in water and wastes by inductively coupled plasma-atomic emission spectrometry and inductively-coupled plasma-mass spectrometry measure total recoverable aluminum (U.S. EPA 1994a,b).

The 1988 criteria considered use of dissolved aluminum, but instead recommended acid-soluble aluminum for several reasons. EPA noted that organisms in available toxicity tests were exposed to both dissolved and undissolved aluminum, but that not enough data were available to allow derivation of a criterion based on dissolved aluminum. They also indicated that resulting criteria based on dissolved aluminum concentrations would be lower than criteria developed using acid-soluble or total recoverable aluminum concentrations. Applying the aluminum criteria to total recoverable aluminum may be 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). Research on analytical methods is ongoing to address concerns with aluminum bound to particulate matter (i.e., clay) from natural waters being included in the total recoverable aluminum concentrations.

Data are now available to compare toxicity of aluminum using total recoverable aluminum and dissolved aluminum. In tests with the brook trout at low pH and hardness, toxic effects increased with increasing concentrations of total recoverable aluminum even though the 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, 2012e), 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 observed no toxicity when the test water was filtered prior to exposure (Gensemer et al. 2017). Toxicity was only observed when the test solutions were unfiltered; furthermore, dose-response was only observed using total aluminum as opposed to measurements of dissolved or monomeric forms (Gensemer et al. 2017). 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. 2017).

Thus, if aluminum criteria are based on dissolved concentrations, toxicity would likely be underestimated, as colloidal forms and hydroxide precipitates of the metal that can dissolve under natural conditions and become biologically available would not be measured (GEI Consultants, Inc. 2010; U.S. EPA 1988). Therefore, this AWQC update will also be based on measurements of total recoverable aluminum. All concentrations for toxicity tests are expressed as total recoverable aluminum in this document (unless otherwise specified), and not as the form of the chemical tested.

This document addresses the toxicity of total aluminum to freshwater organisms in the pH range of 5.0-9.0. The previous document only addressed waters with a pH between 6.5 and 9.0 (U.S. EPA 1988). The pH range for fresh water 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 on the test organisms of a low pH and aluminum, and the inability to definitively attribute a particular effect level to one or the other of these stressors below this pH level. Studies that had control survival issues were not used (i.e., studies where acute and chronic control mortality was >10% and >20%, respectively), regardless of test conditions.

Aluminum chemistry in surface waters is highly 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 ability to distinguish between aqueous and particulate aluminum, and between inorganic and organic forms of aluminum (Driscoll and Postek 1996; Gensemer and Playle 1999). 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 recoverable 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).

Acute Measures of Effect

The acute measures of effect on aquatic organisms are the LC₅₀, EC₅₀, and IC₅₀. LC stands for “Lethal Concentration” and an LC₅₀ is the concentration of a chemical that is estimated to kill 50 percent of the test organisms. EC stands for “Effect Concentration” and the EC₅₀ 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 IC₅₀ 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 EC₂₀, 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 EC₅, 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 the population from long-term effects. EPA selected an EC₂₀ 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 EC₂₀ 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., EC₂₀s) 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. Chronic toxicity data that met the test acceptability and quality assurance/control 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 §304(a) criteria development, 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 minimum dataset requirements (MDR) 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 three phyla, 12 families, 18 genera and 20 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, no acute estuarine/marine criterion value can be developed 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, 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 no chronic estuarine/marine criterion was derived. Aluminum toxicity data on estuarine/marine species remain a data gap; additional acute and chronic toxicity testing on estuarine/marine taxa would be useful 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 / Perlidae / Acroneuria	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	Arthropoda/ Chironomidae/ Chironomus	Annelida / Aeolosomatidae / Aeolosoma
Family Minimum Data Requirement (Estuarine/Marine)	Acute (Phylum / Family / Genus)	Chronic (Phylum / Family / Genus)
Family in the phylum Chordata	-	-
Family in the phylum Chordata	-	-
Either the Mysidae or Penaeidae family	-	-
Family in a phylum other than Arthropoda or Chordata	Mollusca / Ostreidae / Crassostrea	-
Family in a phylum other than Chordata	Annelida / Nereididae / Neanthes	-
Family in a phylum other than Chordata	Annelida / Capitellidae / Capitella	-
Family in a phylum other than Chordata	Annelida / Ctenodrilidae / Ctenodrilus	-
Any other family	Arthropoda / Ameiridae / Nitokra	-

Dash (-) indicates requirement not met (*i.e.*, no acceptable data).

* Data used qualitatively, see Section 3.2.1.

Phylum	Freshwater Acute			Freshwater Chronic			Estuarine/Marine Acute			Estuarine/Marine Chronic		
	Families	GMAVs	SMAVs	Families	GMCVs	SMCVs	Families	GMAVs	SMAVs	Families	GMCVs	SMCVs
Annelida	-	-	-	1	1	1	3	3	3	-	-	-
Arthropoda	6	8	9	3	3	3	1	1	1	-	-	-
Chordata	4	8	9	2	4	4	-	-	-	-	-	-
Mollusca	2	2	2	2	2	2	1	1	1	-	-	-
Rotifera	-	-	-	1	1	1	-	-	-	-	-	-
Total	12	18	20	9	11	11	5	5	5	0	0	0

2.7.1 pH, 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 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**.

Recent publications by Cardwell et al. (2017) and Gensemer et al. (2017) summarized short-term aluminum chronic toxicity data across a range of DOC, pH and hardness values. Seventy-two hour 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, 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, 22-120 mg/L hardness and 0.3-1.9 mg/L DOC (DeForest et al. 2017). 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 hardness and 0.1-4 mg/L DOC (DeForest et al. 2017). 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 hardness and 0.08-5.0 mg/L DOC (DeForest et al. 2017). DeForest et al. (2017) used these data to evaluate the ability of MLR models to predict chronic toxicity of aluminum as a function of multiple combinations of pH, hardness, and DOC conditions. These three parameters are thought to be the most influential for aluminum bioavailability and can be used to explain the magnitude of differences in the observed toxicity values (Cardwell et al. 2017).

The approach described by DeForest et al. (2017) incorporated pH, DOC and hardness 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 EPA methodologies (Stephan et al. 1985). Only the MLR model development for the fathead minnow and *C. dubia* using EC₂₀ effects concentrations is described below. Note that while a 7-d 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. 2017, 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. (2017) 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, hardness and DOC; all independent variables) were non-linear. Effect concentrations (EC₂₀s) for each species were plotted against each independent variable using data where the other two parameters were held constant. Overall, EC₂₀s increased with each independent variable. However, there was some evidence of a unimodal relationship with pH, with increased EC₂₀s around pH 7 and decreasing EC₂₀s at low and high pH, as well as potential differences regarding the effects of hardness at low and high pH (DeForest et al. 2017). 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. 2017).

Beginning with a seven-parameter model consisting of the three main effect terms (pH, 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. 2017). 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.

For *C. dubia*, the final model, based on AIC, included both the pH:hardness interaction and the squared pH term. The negative pH^2 term accounts for the fact that Al 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. 2017). The negative pH:hardness term is reflective of the decreasing effects of hardness mitigating toxicity as pH increases (DeForest et al. 2017). The adjusted R^2 for the final model was 0.73, compared to an R^2 of 0.67 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 91% of the tests. 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 (DeForest et al. 2017). The final MLR model for *C. dubia* is:

$$C. dubia EC_{20}$$

$$= e^{[-41.026 + [0.525 \times \ln(DOC)] + [2.201 \times \ln(hard)] + (11.282 \times pH) - (0.633 \times pH^2) - [0.264 \times pH : \ln(hard)]]}$$

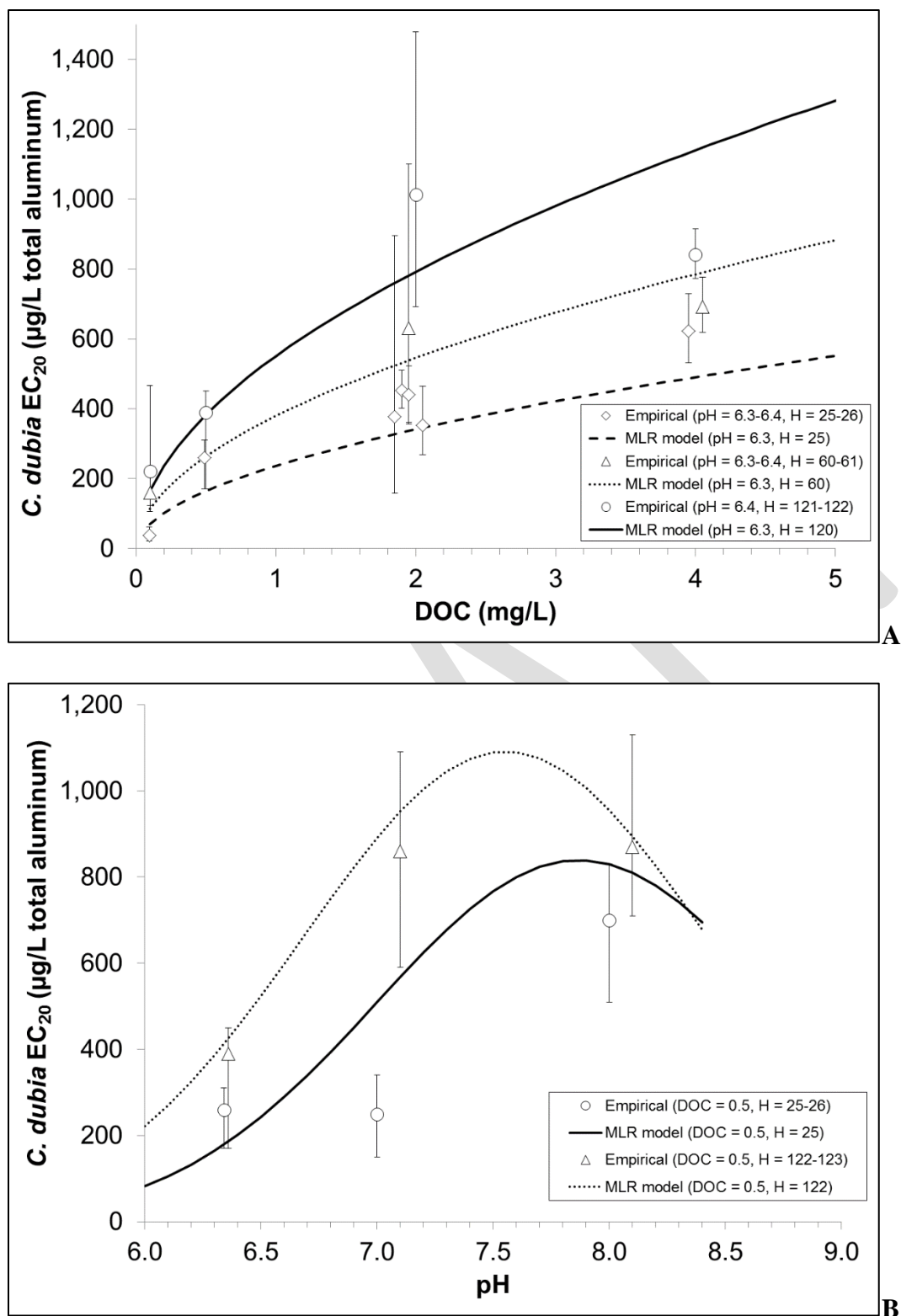


Figure 4. Observed and MLR-Predicted Aluminum EC₂₀s ($\pm 95\%$ CLs) for *C. dubia* where DOC or pH was Varied.

(Panel A: DOC is varied; Panel B: pH is varied; Adapted from Figure S6, from DeForest et al. 2017, used with permission).

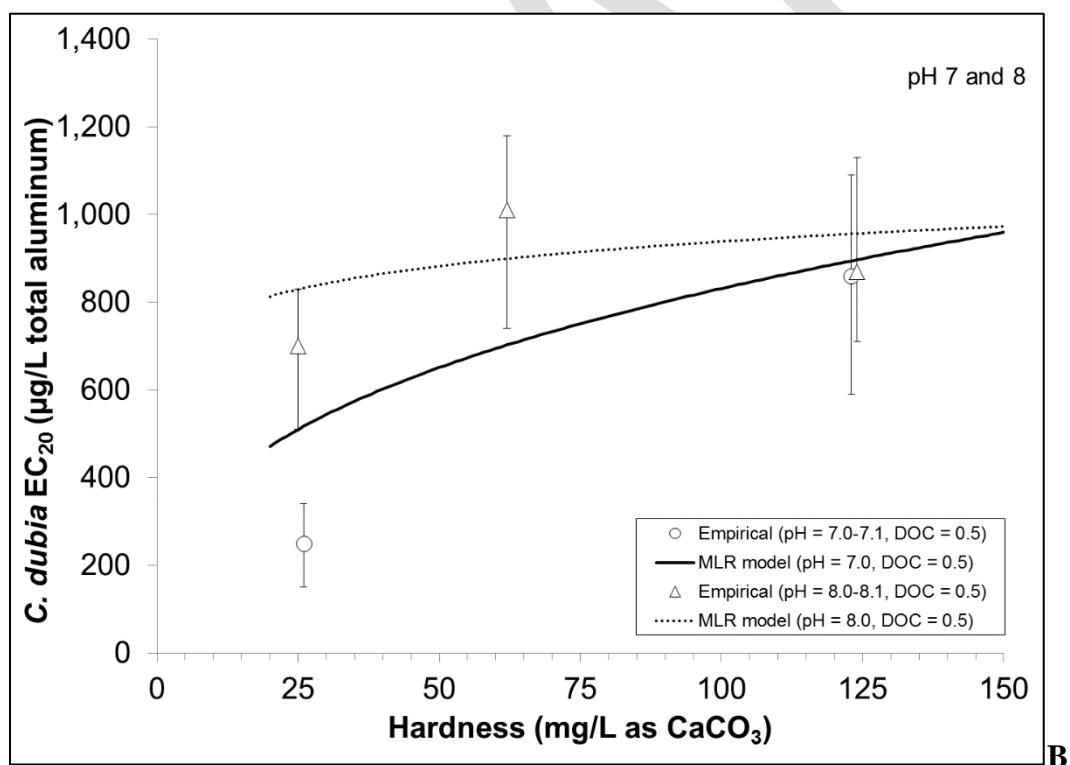
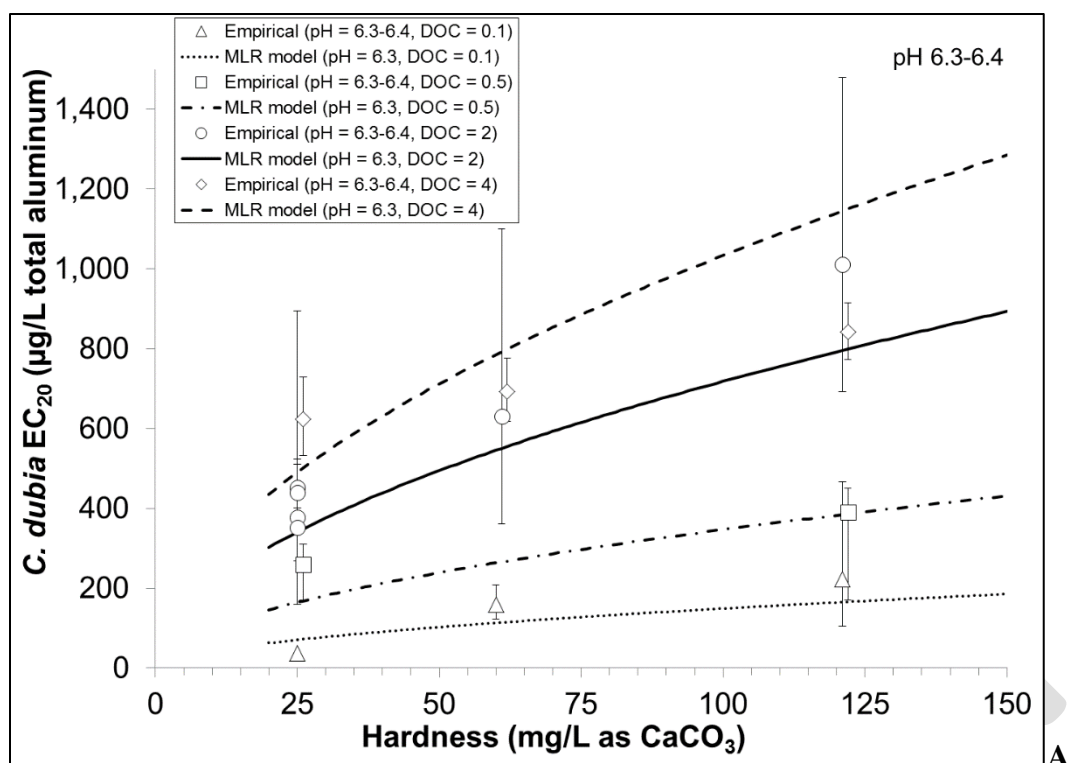


Figure 5. Observed and MLR-Predicted Aluminum EC₂₀s (±95% CLs) for *C. dubia* where Hardness was Varied.

(Panel A: pH 6.3-6.4, Panel B: pH 7 and 8; Adapted from Figure S6, from DeForest et al. 2017, used with permission).

For *P. promelas*, the final model, based on AIC and BIC, included the pH:hardness interaction term. Again, this interaction term was retained because of the unique chemistry of aluminum where hardness has less of a mitigating effect on bioavailability at higher pH levels (DeForest et al. 2017; Gensemer et al. 2017). The adjusted R^2 for the final model was 0.87, compared to an R^2 of 0.85 for the model consisting of the three main independent variables [$\ln(\text{DOC})$, pH, and $\ln(\text{hardness})$]. In the final MLR model, predicted EC_{20} s were within a factor of two of observed values used to create the model for 95% of the tests. The comparison of MLR predicted versus observed *P. promelas* values where one water chemistry parameter was varied is seen 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 (DeForest et al. 2017). The final MLR model for *P. promelas* is:

$$P. promelas \text{ EC}_{20} = e^{[-14.029 + [0.503 \times \ln(\text{DOC})] + [3.443 \times \ln(\text{hard})] + (3.131 \times \text{pH}) - [0.494 \times \text{pH} : \ln(\text{hard})]}$$

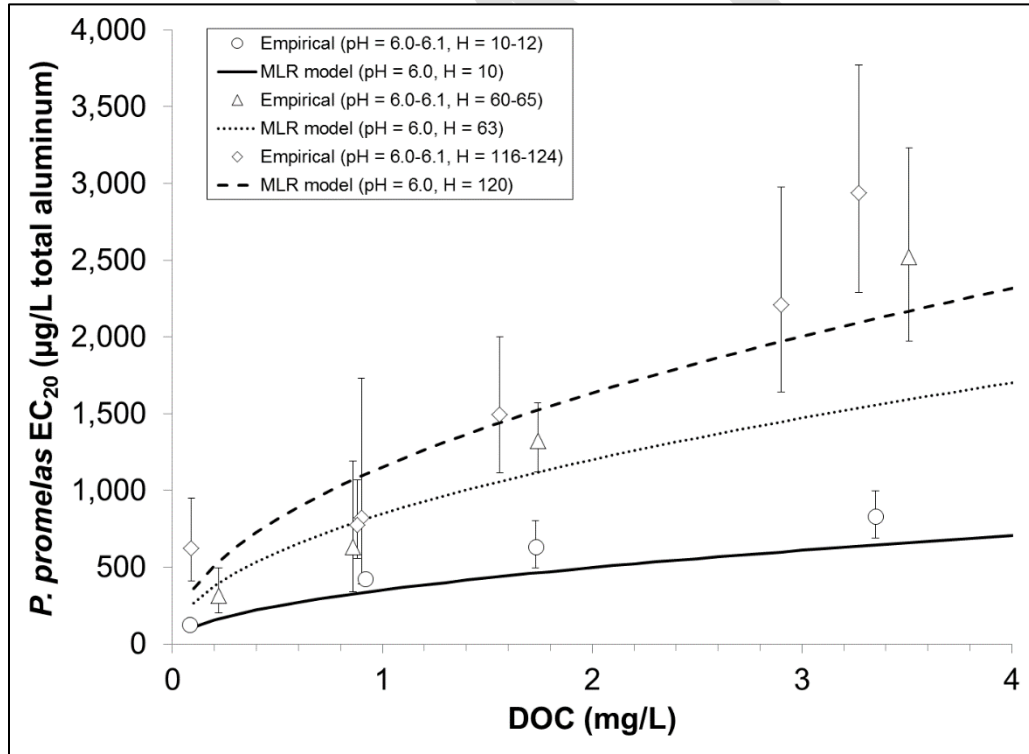


Figure 6. Observed and MLR-Predicted Aluminum EC_{20} s ($\pm 95\%$ CLs) for *P. promelas* where DOC was Varied.

(Adapted from Figure S7, from DeForest et al. 2017, used with permission).

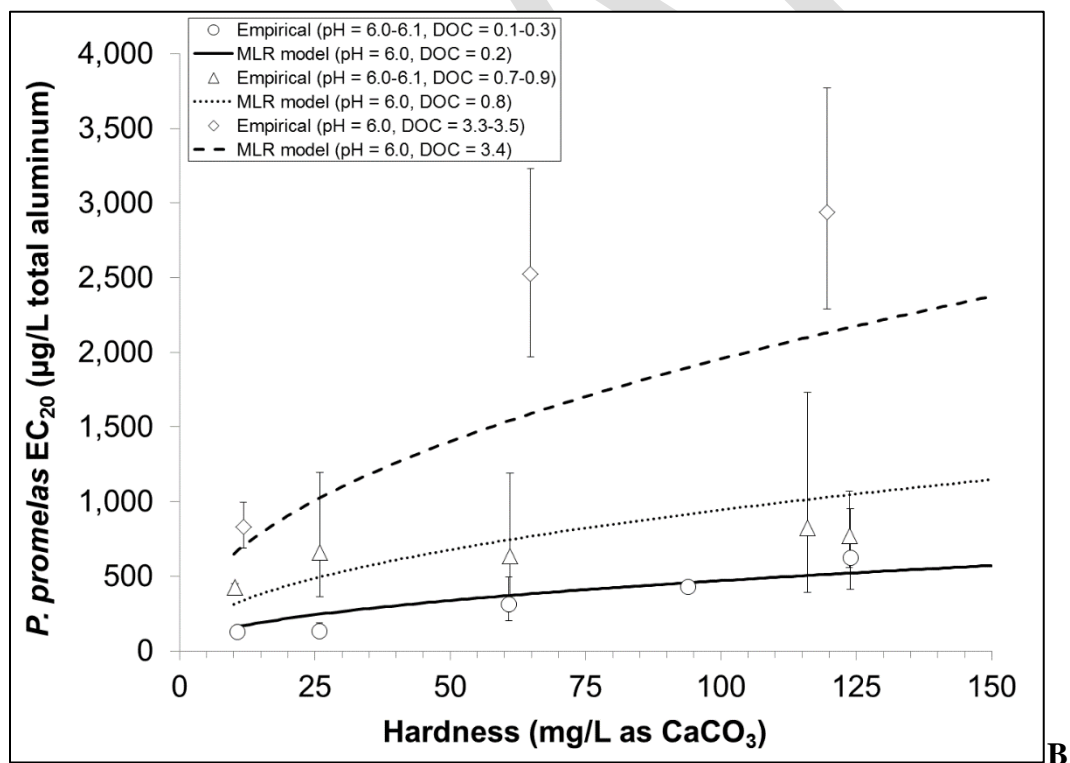
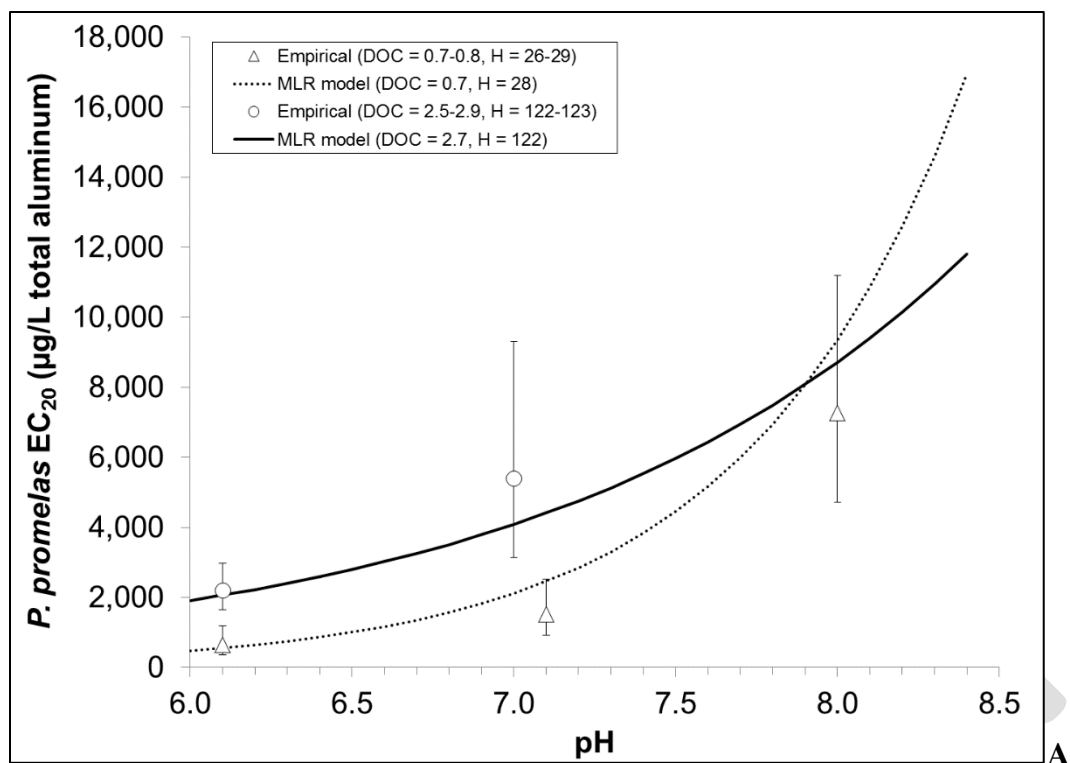


Figure 7. Observed and MLR-Predicted Aluminum EC_{20} s ($\pm 95\%$ CLs) for *P. promelas* where pH or Hardness was Varied.

(Panel A: pH, Panel B: Hardness; Adapted from Figure S7, from DeForest et al. 2017, used with permission).

The models developed followed the trends seen in the empirical data, 1) at pH 6 predicted effects concentrations increased with both hardness and DOC concentrations, 2) at pH 7 predicted effect concentrations increased with DOC concentrations, but not hardness, and 3) at pH 8 predicted effect concentrations increased with DOC concentrations, but predicted effect concentrations decreased with increased hardness concentrations (DeForest et al. 2017). The models developed by DeForest et al. (2017) were used to normalize the freshwater acute and chronic data in **Appendix A** and **Appendix C**. Invertebrate data were normalized using the MLR model for *C. dubia* and vertebrate data were normalized using the MLR model for *P. promelas*. Invertebrate and vertebrate data were normalized with the following equations:

Invertebrate Normalized EC₂₀/LC₅₀

$$= e^{\left[(\ln EC_{20,test}/LC_{50,test}) - [0.525 \times (\ln DOC_{test} - \ln DOC_{target})] - [11.282 \times (pH_{test} - pH_{target})] - [2.201 \times (\ln hard_{test} - \ln hard_{target})] + [0.663 \times (pH_{test}^2 - pH_{target}^2)] + [0.264 \times (pH_{test} \times \ln hard_{test}) - (pH_{target} \times \ln hard_{target})] \right]}$$

Vertebrate Normalized EC₂₀/LC₅₀

$$= e^{\left[(\ln EC_{20,test}/LC_{50,test}) - [0.503 \times (\ln DOC_{test} - \ln DOC_{target})] - [3.131 \times (pH_{test} - pH_{target})] - [3.443 \times (\ln hard_{test} - \ln hard_{target})] + [0.494 \times (pH_{test} \times \ln hard_{test}) - (pH_{target} \times \ln hard_{target})] \right]}$$

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, hardness of 100 mg/L and DOC of 1 mg/L. These specific values were chosen to represent pH, hardness and DOC levels found in the environment.

2.7.2 Acute Criterion

Acute criteria are derived from the sensitivity distribution (SD) comprised of genus mean acute values (GMAVs), calculated from species mean acute values (SMAVs) for acceptable available 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 freshwater and estuarine/marine 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 LC₅₀-based FAV by two decreases potential acute effects to a level comparable to control mortality levels. Therefore, the CMC 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., EC₂₀) 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). Details of this process are described in **Appendix L**, since the freshwater aluminum chronic criterion is derived using the same method used for the acute criterion.

The criteria presented herein are the agency's best 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 and the number of places beyond the decimal point does not reflect the precision of the value. The CMC and CCC 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 U.S. 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 2015 and supplemented by additional data made available by researchers.

A further evaluation of the quality of the available data was performed by 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 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.

3.1.1 Freshwater

Twenty freshwater species encompassing 18 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 CaCO₃ for hardness, and <0.5-4.0 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 ambient water quality criteria 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 SD. Normalizing the toxicity data to the

same pH, 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, hardness of 100 mg/L CaCO₃, 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 LC₅₀ (i.e., the LC₅₀ is a “greater than” or “less than” value). The decision rule for using these non-definitive LC₅₀s to calculate SMAVs is consistent with methods used previously in criteria development. The freshwater ammonia ambient aquatic life criteria document explains how chronic values (CVs, EC₂₀s) 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 CVs and “less than” (<) high CVs were not used in the calculation of the SMCV; but “less than” (<) low CVs and a “greater than” (>) high CVs 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 true ranking of sensitivities. Again, in this section and below, the relative rankings only apply when the set of chemistry conditions are pH 7, hardness of 100 mg/L and DOC of 1.0 mg/L. SMAVs ranged from 3,332 µg/L for the cladoceran, *Daphnia magna*, to >62,318 µg/L for the midge, *Paratanytarsus dissimilis*. There is no apparent trend between freshwater taxon and acute sensitivity to aluminum (**Table 3**). For this set of water chemistry conditions, a salmonid (*Oncorhynchus*) represents the second most sensitive genus; cladocerans represent the first and fifth most sensitive genera; fish genera rank second, third, fourth and sixth in the sensitivity distribution; and an ostracod (*Stenocypris*) ranks seventh.

Other fish species were less sensitive with SMAVs of 23,097 µg/L for the brook trout, *Salvelinus fontinalis*, >24,028 µg/L for the green sunfish, *Lepomis cyanellus*, and >39,414 µg/L for the Rio Grande silvery minnow, *Hybognathus amarus*. The aquatic-phase stonefly nymph (*Acroneuria sp.*, SMAV = >20,498 µg/L), the aquatic air-breathing snail (*Physa sp.*, SMAV = 35,462 µg/L), and the freshwater juvenile mussel (*Lampsilis siliquoidea*, SMAV = >29,834) were comparatively insensitive to aluminum. The SMAV for Chinook salmon, *O. tshawytscha*, could not be calculated because the unreported DOC of the unknown dilution water could not be estimated, and therefore was not used in the calculation of the GMAV for *Oncorhynchus*. Thus, the GMAV for *Oncorhynchus* is based only on the SMAV for rainbow trout (3,661 µg/L).

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** (*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. Please note that the normalized values mentioned below are for pH of 7, total hardness of 100 mg/L as CaCO₃ and DOC of 1.0 mg/L.

Invertebrates

Daphnia magna

The pH/total hardness/DOC-normalized SMAV/GMAV of 3,332 µg/L aluminum for *D. magna* is based on the geometric mean of five 48-hr LC₅₀s (ranged from 920.4 to 20,303 µg/L aluminum) as reported by Biesinger and Christensen (1972), European AI 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.

Ceriodaphnia

Two species of *Ceriodaphnia*, *C. dubia* and *C. reticulata*, are used to derive the pH/total hardness/DOC-normalized GMAV of 7,328 µg/L aluminum. The *C. dubia* SMAV of 5,094 µg/L aluminum is calculated from 52 normalized LC₅₀ values that ranged from 243.7 to 48,800 µg/L aluminum (ENSR 1992d; European AI Association 2009, 2010; Fort and Stover 1995; 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

10,542 µg/L aluminum is based on the two flow-through measured test results reported by Shephard (1983).

Stenocypris major

Shuhaimi-Othman et al. (2011a) reported a 96-hr LC₅₀ of 3,102 µg/L aluminum for the ostracod, *S. major*, which equates to a pH/total hardness/DOC-normalized LC₅₀/SMAV/GMAV of 10,216 µg/L aluminum. The adult organisms were exposed to static-renewal conditions and the test solutions were measured.

Crangonyx pseudogracilis

Martin and Holdich (1986) conducted a static-renewal test with the amphipod *C. pseudogracilis* and reported a 96-hr LC₅₀ of 9,190 µg/L aluminum, which equates to a pH/total hardness/DOC-normalized LC₅₀/SMAV/GMAV of 12,174 µg/L aluminum. The adult organisms were exposed to eight concentrations and the exposure solutions were not measured.

Vertebrates

Oncorhynchus

Acute data are available for two *Oncorhynchus* species, rainbow trout (*O. mykiss*) and Chinook salmon (*O. tshawytscha*). The pH/total hardness/DOC-normalized SMAV of 3,661 µg/L aluminum for rainbow trout is based on the geometric mean of eight 96-hr LC₅₀s as reported by Gundersen et al. (1994). The eight flow-through measured normalized LC₅₀s ranged from 1,190 to 7,662 µg/L aluminum. Only one study is available for Chinook salmon (Peterson et al. 1974), but the authors did not report the DOC of the unnamed dilution water, so no estimate could be used. The data, therefore, could not be normalized and thus a SMAV is not available for this species.

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 CaCO₃) and two different pH levels. The 96-hr LC₅₀ 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 21,042 and 2,430 and the resulting normalized SMAV/GMAV for the species is 7,151 µg/L total aluminum.

Micropterus dolomieu

Three acceptable acute values from one study (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 12.45 mg/L (as CaCO₃) and three different pH levels. The LC₅₀ values were 130, >978.4 and >217 µg/L total aluminum conducted at pH levels of 5.05, 6.75 and 7.45, respectively. The corresponding pH/total hardness/DOC-normalized values are 3,929, >1,199 and >71.08. The SMAV/GMAV for the species/genus is based only on the determinate normalized LC₅₀ of 3,929 µg/L total aluminum since the other values are unbounded (i.e., greater than values).

GMAVs for 18 freshwater genera are provided in **Table 3**, and the four most sensitive genera were within a factor of 2.1 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, a hardness of 100 mg/L and DOC of 1.0 mg/L is 2,741 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, hardness of 100 mg/L and DOC of 1.0 mg/L is 1,400 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 multiple linear regression (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, hardness, and DOC concentrations at the site (see **Appendix K 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, Hardness of 100 mg/L, and DOC of 1 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)
18	>62,318	Paratanytarsus	Midge, <i>Paratanytarsus dissimilis</i>	>62,318
17	>39,414	Hybognathus	Rio Grande silvery minnow, <i>Hybognathus amarus</i>	>39,414
16	35,462	Physa	Snail, <i>Physa sp.</i>	35,462
15	>29,834	Lampsilis	Fatmucket, <i>Lampsilis siliquoidea</i>	>29,834
14	>28,002	Hyalella	Amphipod, <i>Hyalella azteca</i>	>28,002
13	25,361	Chironomus	Midge, <i>Chironomus plumosus</i>	25,361
12	>24,028	Lepomis	Green sunfish, <i>Lepomis cyanellus</i>	>24,028
11	23,097	Salvelinus	Brook trout, <i>Salvelinus fontinalis</i>	23,097
10	>20,498	Acroneuria	Stonefly, <i>Acroneuria sp.</i>	>20,498
9	>20,016	Hyla	Green tree frog, <i>Hyla cinerea</i>	>20,016
8	12,174	Crangonyx	Amphipod, <i>Crangonyx pseudogracilis</i>	12,174
7	10,216	Stenocypris	Ostracod, <i>Stenocypris major</i>	10,216
6	10,168	Pimephales	Fathead minnow, <i>Pimephales promelas</i>	10,168
5	7,328	Ceriodaphnia	Cladoceran, <i>Ceriodaphnia dubia</i>	5,094
-	-	Ceriodaphnia	Cladoceran, <i>Ceriodaphnia reticulata</i>	10,542
4	7,151	Salmo	Atlantic salmon, <i>Salmo salar</i>	7,151
3	3,929	Micropterus	Smallmouth bass, <i>Micropterus dolomieu</i>	3,929
2	3,661	Oncorhynchus	Rainbow trout, <i>Oncorhynchus mykiss</i>	3,661
-	-	Oncorhynchus	Chinook salmon, <i>Oncorhynchus tshawytscha</i>	NA ^c
1	3,332	Daphnia	Cladoceran, <i>Daphnia magna</i>	3,332

^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, hardness of 100 mg/L as CaCO₃, and DOC of 1 mg/L.).

^c Missing water quality parameters and the dilution water source, so value could not be normalized.

Table 4. Freshwater Final Draft Acute Value and Criterion Maximum Concentration (normalized to pH 7, hardness of 100 mg/L and DOC of 1 mg/L).

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

Calculated Freshwater FAV based on 4 lowest values: Total Number of GMAVs in Data Set = 18						
Rank	Genus	GMAV (µg/L)	lnGMAV	(lnGMAV)²	P=R/(n+1)	SQRT(P)
4	Salmo	7,151	8.88	78.77	0.211	0.459
3	Micropterus	3,929	8.28	68.49	0.158	0.397
2	Oncorhynchus	3,661	8.21	67.33	0.105	0.324
1	Daphnia	3,332	8.11	65.79	0.053	0.229
		Σ (Sum):	33.47	280.4	0.526	1.41
$S^2 = 12.23$ $L = 7.134$ $A = 7.916$						
$S = \text{slope}$ $P = \text{cumulative probability}$ $A = \ln \text{FAV}$						
FAV = 2,741 µg/L total aluminum CMC = 1,400 µg/L total aluminum (rounded to two significant figures)						

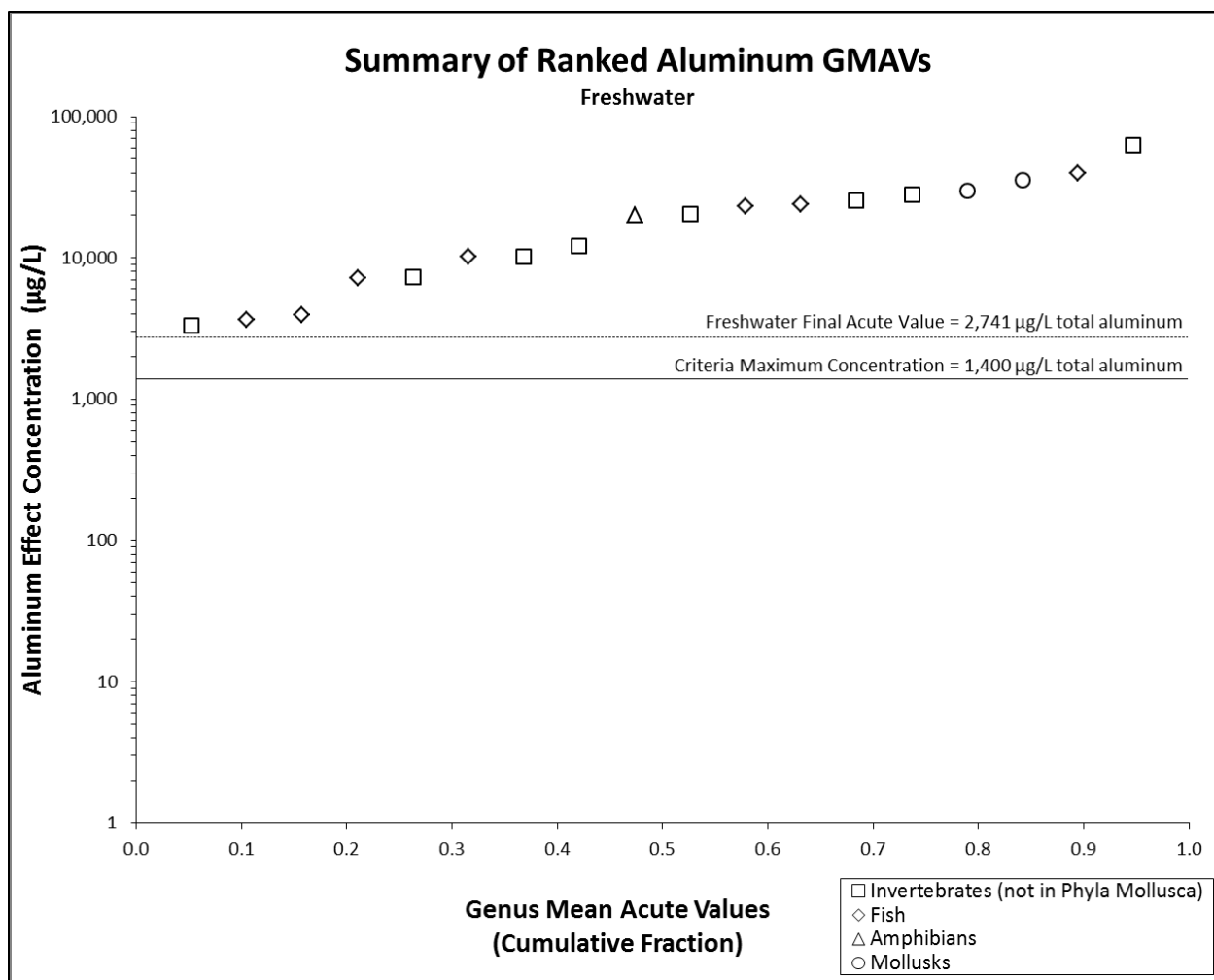


Figure 8. Ranked Summary of Total Aluminum Genus Mean Acute Values (GMAVs) - Freshwater at pH 7, Hardness of 100 mg/L, and DOC of 1 mg/L.

3.1.2 Estuarine/Marine

SMAVs for five genera representing five species of estuarine/marine organisms were calculated for aluminum (**Table 5**). 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 >404.8 µg/L, respectively. The most tolerant genus was a copepod, (*Nitokra spinipes*) with a SMAV of 10,000 µg/L (**Figure 9**).

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. Since data are available for only five families (**Table 5**), an estuarine/marine FAV (and consequently an estuarine/marine CMC) cannot be calculated. It may be noted, however, that the freshwater CMC (1,400 µg/L total aluminum) is much higher than the most sensitive acute estuarine/marine species LC₅₀ (97.15 µg/L total aluminum). Thus, at least some invertebrate estuarine/marine species would not be protected if the freshwater acute aluminum draft criteria were applied in those systems.

Table 5. 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, <i>Nitokra spinipes</i>	10,000
4	>1,518	American oyster, <i>Crassostrea virginica</i>	>1,518
3	>404.8	Polychaete worm, <i>Neanthes arenaceodentata</i>	>404.8
2	404.8	Polychaete worm, <i>Capitella capitata</i>	404.8
1	97.15	Polychaete worm, <i>Ctenodrilus serratus</i>	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.

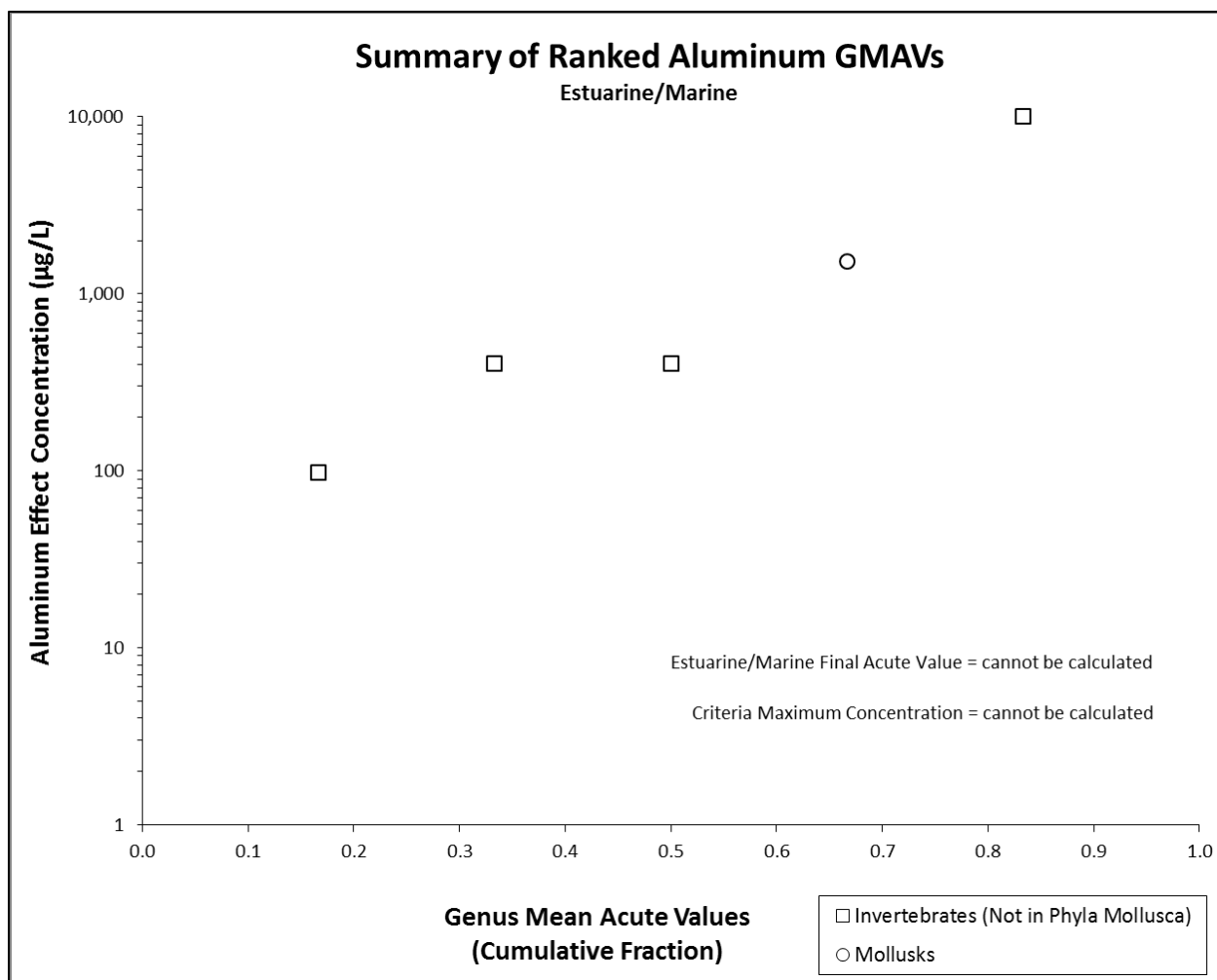


Figure 9. Ranked Summary of Total Aluminum Genus Mean Acute Values (GMAVs) - Estuarine/Marine.

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 EC₂₀s for all but one test where an EC₂₀ 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, 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 CaCO₃), and all four studies reported using the same dilution water preparation from Cleveland et al. (1986).

Aluminum chronic toxicity data are available for eleven species of freshwater organisms: two mollusks (a freshwater mussel and a snail), five other invertebrate species (a rotifer, a cladoceran, 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 29 toxicity tests ranged from 5.1-8.1 for pH, 11.8-220 mg/L as CaCO₃ for hardness, and <0.5-1.9 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. Biomass was selected over growth endpoints when it was the most sensitive, consistent with methods used previously in criteria development (e.g., U.S. EPA 2013).

In this section and below, the relative rankings only apply when the set of chemistry conditions are pH 7, hardness of 100 mg/L and DOC of 1.0 mg/L. Ranked GMCVs are provided in **Table 6**. 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, 2017). 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 hardness of 100 mg/L as CaCO₃. The calculated biomass EC₂₀ of 169 µg/L was reported in the study, with a corresponding normalized EC₂₀ of 1,042 µg/L (normalized to pH 7, hardness = 100 mg/L as CaCO₃ and DOC = 1.0 mg/L).

Three chronic aluminum studies were conducted in separate laboratories with the cladoceran, *Ceriodaphnia dubia* (CECM 2014; ENSR 1992b; McCauley et al. 1986). 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 aluminum/L in each respective dilution water. The EC_{20} and MATC were estimated to 1,780 and $<1,100$ $\mu\text{g}/\text{L}$, respectively, or 1,898 and <946.2 $\mu\text{g}/\text{L}$ 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 7.3, 7.5, 7.9 and 8.1, respectively. The mean number of young produced per female was the most sensitive endpoint with normalized (to pH 7, hardness = 100 mg/L as CaCO_3 and $\text{DOC} = 1.0$ mg/L) EC_{20} s of 2,719, 1,102, 796.1 and 888.4 $\mu\text{g}/\text{L}$, respectively (**Appendix C**).

The Center for the Ecotoxicology and Chemistry of Metals (CECM 2014) also evaluated the effect of aluminum on the survival and reproduction of *C. dubia* at different pH and hardness levels. Less than 24-hr old neonates were exposed to aluminum nitrate for seven days using low DOC (0.5 mg/L) reconstituted laboratory water established at different nominal hardness (25, 60 or 120 mg/L as CaCO_3) and pH (6.3, 7.0 or 8.0) levels. Test solutions were renewed daily and the pH was maintained with synthetic buffers. Reproduction (young/female) was the most sensitive endpoint, with EC_{20} s ranging from 250 to 1,010 $\mu\text{g}/\text{L}$ aluminum, and corresponding normalized (to pH 7, hardness = 100 mg/L as CaCO_3 and $\text{DOC} = 1.0$ mg/L) EC_{20} s ranging from 563.4 to 1,758 $\mu\text{g}/\text{L}$ (**Appendix C**).

Two acceptable *Hyaella 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 (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 EC₂₀ of 199.3 µg/L and a normalized EC₂₀ of 1,014 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, 2017) 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 hardness of 100 mg/L as CaCO₃. Silica sand was provided as a substrate. The calculated biomass EC₂₀ was 425 µg/L, with a corresponding normalized EC₂₀ of 2,895 µg/L (normalized to pH 7, hardness = 100 mg/L as CaCO₃ 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 6.5-6.7). The authors reported an EC₂₀ for the number of eggs per case to be 3,387 µg/L, or 7,664 µg aluminum/L when normalized to pH 7, hardness of 100 mg/L as CaCO₃ 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, at pH 5.6 and 5.0, with calculated EC₂₀s of 29.55 and 84.42 µg/L and normalized EC₂₀s of 1,192 and 22,578 µg/L, respectively. The resultant normalized SMCV of 5,908 µg/L is calculated from all three test results.

Oregon State University also conducted several chronic studies for three invertebrate species: an oligochaete, *Aeolosoma sp.*; a rotifer, *Brachionus calyciflorus*; the great pond snail, *Lymnaea stagnalis*; and one fish species, an early life cycle test with the zebrafish (OSU 2012b,c,e, 2013). All tests were conducted with aluminum nitrate, and at a nominal pH of 6.0. The normalized EC₂₀s from the aforementioned studies are 17,098 (oligochaete 17-day population count), 2,555 (48-hr rotifer population count), 4,877 (pond snail 30-day biomass) and 1,102 (33-day zebrafish biomass) µg/L, respectively (**Appendix C**).

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 than percent hatchability, growth and survival to the aluminum exposures, with a resulting EC₂₀ of 6,194 µg/L, or 3,569 µg/L when normalized.

The chronic toxicity of aluminum to fathead minnows was also evaluated by OSU (2012g). Very similar exposure methodology and the same dilution water were used as described above for the amphipod and midge tests (OSU 2012f, h), except that <24-hr old fertilized eggs were used at initiation of the 33-day test. Fry survival was the most sensitive endpoint with an estimated EC₂₀ of 428.6 µg/L, and normalized EC₂₀ of 1,734 µg/L.

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 (hardness = 12.5 mg/L as CaCO₃). 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 (personal communication, Russ Hockett/ORD to Diana Eignor/OW, 5/25/17) 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 it in the criteria document. The biomass EC₂₀ for the test conducted at pH 5.7 was 143.5 µg/L, and at pH 6.5 the biomass EC₂₀ was 164.4 µg/L. The normalized EC₂₀s at pH 5.7 and 6.5 were 1,295 µg/L and 270.1 µg/L, respectively.

Atlantic salmon eyed eggs were exposed to flow-through conditions for 60 days at pH 5.7 and a hardness of 12.7 mg/L as CaCO₃ 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 EC₂₀ 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 (hardness of 12.7 mg/L as CaCO₃) 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 EC₂₀ of 154.2 µg/L (normalized EC₂₀ = 1,274 µg/L).

When calculating the Atlantic salmon EC_{20s} for the two studies (Buckler et al. 1995 and McKee et al. 1989), we 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 EC₂₀ was used in the calculation of the SMCV. The most sensitive EC₂₀ of 61.56 µg/L (or 508.5 µg/L when normalized to pH 7, hardness of 100 mg/L as CaCO₃ 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 family Chordata missing. Because derivation of a chronic freshwater criterion is important for environmental protection, 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, hardness of 100 mg/L and DOC of 1.0 mg/L was 9,746 µg/L (the highest concentration tested), with a chronic value of >9,746 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; thus its use to fulfill the MDR is considered justified (U.S. EPA 2008). After adding this additional study, the chronic dataset consists of 12 freshwater species representing 12 freshwater genera (**Table 6**).

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 CCC is 390 µg/L total aluminum at pH 7, hardness of 100 mg/L (as CaCO₃) and DOC of 1.0 mg/L (**Table 7**). The chronic toxicity data are normalized using the MLR equations described in the Analysis Plan that account for the effects of pH, 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, hardness, and DOC concentrations at the site (see **Appendix K Criteria for Various Water Chemistry Conditions** for additional criteria values and four most sensitive genera for each set of conditions). The criteria values generated using the MLR models should be protective of approximately 95% of freshwater genera in an ecosystem that are potentially exposed to aluminum under long-term conditions (**Figure 10**).

Table 6. Ranked Genus Mean Chronic Values at pH 7, Hardness of 100 mg/L, and DOC of 1 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)
12	17,098	Aeolosoma	Oligochaete, <i>Aeolosoma sp.</i>	17,098
11	>9,746	Rana	Wood frog, ^c <i>Rana sylvatica</i>	>9,746
10	5,908	Chironomus	Midge, <i>Chironomus riparius</i>	5,908
9	4,877	Lymnaea	Great pond snail, <i>Lymnaea stagnalis</i>	4,877
8	2,555	Brachionus	Rotifer, <i>Brachionus calyciflorus</i>	2,555
7	2,488	Pimephales	Fathead minnow, <i>Pimephales promelas</i>	2,488
6	1,713	Hyaella	Amphipod, <i>Hyaella azteca</i>	1,713
5	1,182	Ceriodaphnia	Cladoceran, <i>Ceriodaphnia dubia</i>	1,182
4	1,102	Danio	Zebrafish, <i>Danio rerio</i>	1,102
3	1,042	Lampsilis	Fatmucket, <i>Lampsilis siliquoidea</i>	1,042
2	591.4	Salvelinus	Brook trout, <i>Salvelinus fontinalis</i>	591.4
1	508.5	Salmo	Atlantic salmon, <i>Salmo salar</i>	508.5

^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, hardness of 100 mg/L as CaCO₃, and DOC of 1 mg/L).

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

Table 7. Freshwater Final Draft Chronic Value and Criterion Maximum Concentration (normalized to pH 7, hardness of 100 mg/L and DOC of 1 mg/L).

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

Calculated Freshwater FCV based on 4 lowest values: Total Number of GMCVs in Data Set = 12						
Rank	Genus	GMCV (µg/L)	lnGMCV	(lnGMCV)²	P=R/(n+1)	SQRT(P)
4	Danio	1,102	7.00	49.07	0.308	0.555
3	Lampsilis	1,042	6.95	48.29	0.231	0.480
2	Salvelinus	591.4	6.38	40.74	0.154	0.392
1	Salmo	508.5	6.23	38.83	0.077	0.277
		Σ (Sum):	26.57	176.9	0.769	1.70
$S^2 = 10.799$ S = slope $L = 5.241$ P = cumulative probability $A = 5.976$ A = lnFCV						
FCV = 394.0 µg/L total aluminum CCC = 390 µg/L total aluminum (rounded to two significant figures)						

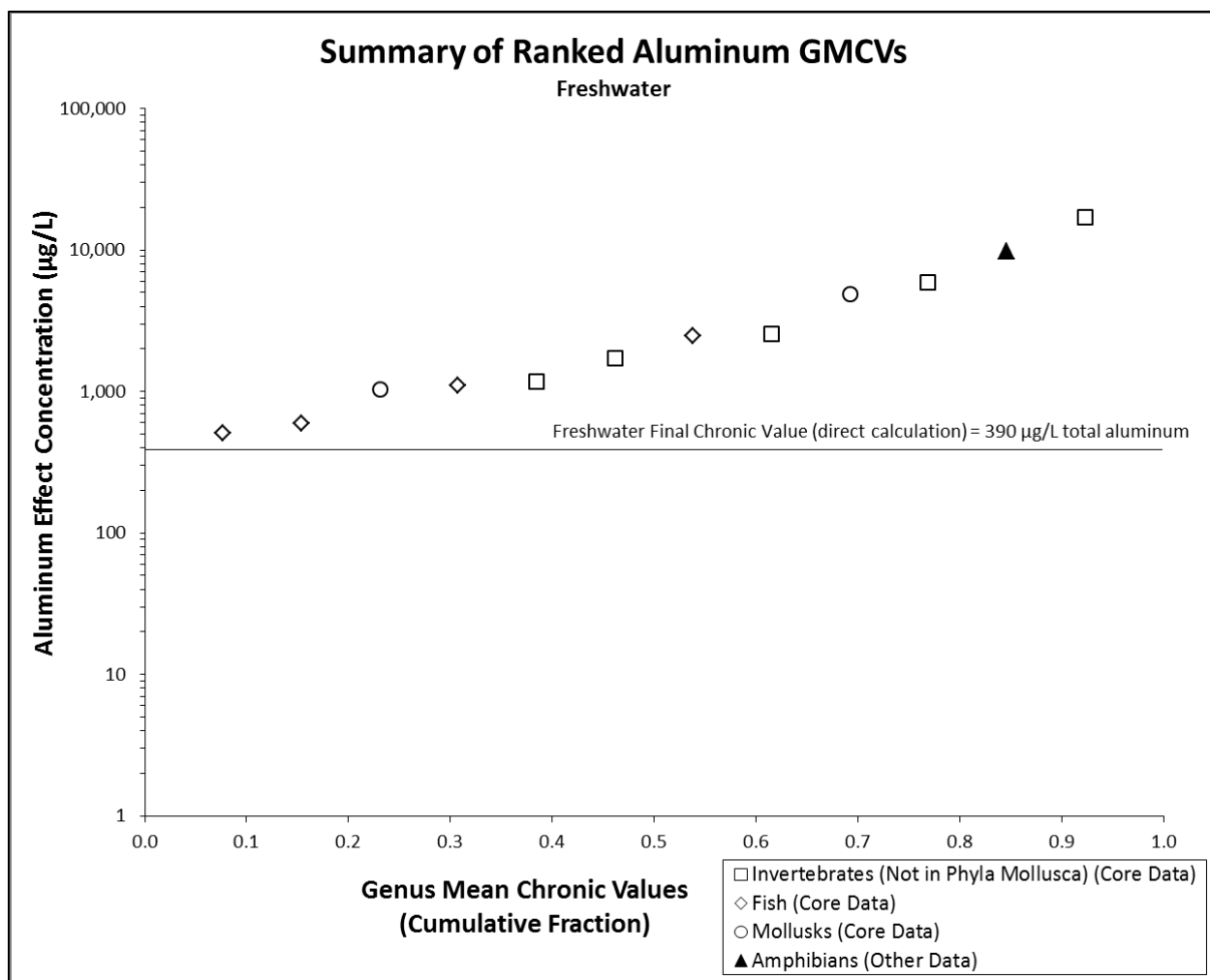


Figure 10. Ranked Summary of Total Aluminum Genus Mean Chronic Values (GMCVs) – Freshwater Supplemented with Other Data to Fulfill Missing MDRs at pH 7, Hardness of 100 mg/L, and DOC of 1 mg/L.

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 bioavailability 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). A more detailed discussion of bioaccumulative 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, a Final Plant Value cannot be determined. Effects on aquatic plants are discussed qualitatively in the Effects Characterization section (**Section 5.2**).

4 SUMMARY OF NATIONAL CRITERIA

4.1 Freshwater

The 2017 draft aluminum criteria are derived using multiple linear regression (MLR) models that incorporate pH, DOC, and hardness 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, DOC and hardness on the bioavailability, and hence toxicity of aluminum. The numeric magnitude of the criteria (CMC or CCC) for a given set of conditions, therefore, will depend on the specific pH, 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 CMC and CCC for a given set of input conditions (pH, hardness and DOC) are numeric magnitude values that would be protective for that set of input conditions. The recommended criteria for aluminum can be calculated in two different ways: 1) use the look-up tables provided (see **Appendix K Criteria for Various Water Chemistry Conditions**) to find the numeric

aluminum CMC and CCC corresponding to the pH, DOC, and hardness conditions of interest, or 2) use the Aluminum Criteria Calculator V.1.0 (*Aluminum Criteria Calculator V.1.0.xlsx*) to enter the pH, DOC, and hardness conditions of interest.

For the purposes of illustration, the following criteria values are provided at pH 7, 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):

Criterion Maximum Concentration (CMC) =

1,400 µg/L total aluminum at a pH 7, hardness of 100 mg/L as CaCO₃ and DOC of 1.0 mg/L;

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

Criterion Continuous Concentration (CCC) =

390 µg/L total aluminum at pH 7, hardness of 100 mg/L as CaCO₃ 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 that affect the expression of aluminum toxicity (see **Appendix K** *Criteria for Various Water Chemistry Conditions*). **Table 8** provides a detailed break-down of the freshwater CMC and CCC across different pH and hardness levels when the DOC = 1 mg/L. **Appendix K** provides additional criteria values across pH and total hardness levels when DOC = 0.5, 2.5 and 5 mg/L, and provides the four most sensitive genera for both the CMC and CCC.

As displayed in **Table 8** and **Appendix K**, the total hardness and DOC are bounded at a maximum of 150 mg/L as CaCO₃ and 5.0 mg/L, respectively. This approach is conservative in that the maximum inputs for these parameters are closely aligned to the model input ranges, thereby avoiding the use of extrapolation beyond the upper model input range for each parameter. In contrast, the pH covers a broad range of 5.0 to 9.0, extrapolating outside the model

input range of 6.0 to 8.1. The criteria values outside of the model input data range are more stringent than those within the model input range under the same hardness and DOC conditions and have greater uncertainty. Additional information regarding the uncertainty associated with the MLR models is provided in **Section 5.3.6**.

The EPA created an Aluminum Criteria Calculator V.1.0 (*Aluminum Criteria Calculator V.1.0.xlsx*) that allows users to enter the pH, hardness and DOC of their choosing and automatically calculates the freshwater criteria for site-specific parameters. The calculator also indicates when any of the water quality parameters selected is “outside MLR model inputs,” to alert end users.

Table 8. Freshwater CMC and CCC at DOC of 1 mg/L and Various Water Hardness Levels and pHs.

Hardness	CMC (µg/L total aluminum)									CCC (µg/L total aluminum)								
	pH									pH								
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
25	7.6	43	180	510	1,100	1,700	1,800	1,400	760	3.3	21	99	220	490	900	780	590	330
50	14	72	280	680	1,300	1,900	1,900	1,300	670	6.1	35	150	250	440	890	960	580	290
75	20	98	350	780	1,300	2,000	2,000	1,300	620	8.8	47	180	260	410	740	1,100	570	270
100	26	120	420	860	1,400	2,000	2,000	1,300	590	11	59	210	270	390	650	1,100	560	260
150	37	160	530	970	1,500	1,900	2,100	1,300	550	16	80	250	280	380	540	910	620	240
200	37	160	530	970	1,500	1,900	2,100	1,300	550	16	80	250	280	380	540	910	620	240
250	37	160	530	970	1,500	1,900	2,100	1,300	550	16	80	250	280	380	540	910	620	240
300	37	160	530	970	1,500	1,900	2,100	1,300	550	16	80	250	280	380	540	910	620	240
350	37	160	530	970	1,500	1,900	2,100	1,300	550	16	80	250	280	380	540	910	620	240
400	37	160	530	970	1,500	1,900	2,100	1,300	550	16	80	250	280	380	540	910	620	240

4.2 Estuarine/Marine

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

5 EFFECTS CHARACTERIZATION

The purpose of this section is to characterize the potential effects of aluminum on aquatic life based on available test data and to describe additional lines of evidence not used directly in the criteria calculations, but which support the 2017 criteria values. This section also provides a

summary of the uncertainties and assumptions associated with the criteria derivation and explanations for decisions regarding data acceptability and usage in the effects assessment. Finally, this section describes substantive differences between the 1988 aluminum AWQC and the 2017 update resulting from incorporation of the latest scientific knowledge.

5.1 Effects on Aquatic Animals

5.1.1 Freshwater Acute Toxicity

Several acute studies were identified as not meeting 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 ≥ 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 $\mu\text{g/L}$ 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 $\mu\text{g/L}$ (76,102 $\mu\text{g/L}$ when normalized to conditions in **Appendix A**) for the zebra mussel *Dreissena polymorpha* (Mackie and Kilgour 1995) was similarly insensitive like the mollusk *Physa sp.* (**Appendix A**). In a series of 96-hr tests conducted at low pH and 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 $\mu\text{g/L}$ when pH was 3.5, and 400 $\mu\text{g/L}$ 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 $>937,313 \mu\text{g/L}$.

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/hardness/DOC-normalized 48-hr LC_{50} values of 2,179 $\mu\text{g/L}$ and 3,185 $\mu\text{g/L}$. 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/hardness/DOC normalized concentration of 3,551 $\mu\text{g/L}$; Khangarot and Ray (1989) observed a normalized 48-hr LC_{50} of 31,146 $\mu\text{g/L}$ 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 1,102 $\mu\text{g/L}$ in *Daphnia magna* using lake water as dilution water.

Although no data from benthic crustaceans were used to calculate the freshwater CMC, evidence suggests they are somewhat acutely sensitive to aluminum. The isopod *Asellus aquaticus* was found to be somewhat sensitive to aluminum, with a pH/hardness/DOC-normalized 72-hr LC₅₀ of 10,661 µg/L that was not included because of the test duration (Martin and Holdich 1986). The isopod values would fall 8th out of 18 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 LC₅₀s from the two Borgmann et al. (2005) studies comparing soft reconstituted water and dechlorinated tap water were 179.9 and >3,431 µg/L, respectively (values normalized to **Appendix A** conditions), but these data were not included because of both insufficient test length and unacceptable control mortality. Three pH/hardness/DOC adjusted unbounded *H. azteca* LC₅₀ values reported by Mackie (1989) ranged from >4,231 to >278,004 µg/L, the highest concentrations tested. The lowest of these values would rank this taxa 4th in the acute genus sensitivity. These data were included in **Appendix H** because of uncertainty regarding whether bromide (Br) and chloride (Cl) 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 Br and Cl 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**, LC₅₀s for the damselfly would be >937,313 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 CMC, 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 3,043 µg/L aluminum (pH/hardness/DOC normalized). Cutthroat trout (*O. clarkii*) alevin and swim-up larvae also exposed at pH 5 for seven days exhibited reduced survival at 635.6 µg/L (60% reduction) and 449.5 µg/L (~50% reduction) (pH/hardness/DOC normalized), respectively (Woodward et al. 1989). Both studies were excluded from CMC calculations because of the atypical acute test duration.

In two studies examining the effects of aluminum on rainbow trout survival, pH/hardness/DOC-normalized *O. mykiss* LC_{50s} after 6 and 7-12 days, respectively, were 4,373 and 563.5 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 1,902 and 533.2 µg/L aluminum, respectively, when normalized. While these studies demonstrated the sensitivity of rainbow trout survival to aluminum, they were excluded from CMC calculations because of atypical acute test durations. In contrast, Hunter et al. (1980) observed 40% mortality at pH/hardness/DOC-adjusted concentration of 8,281 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/number of fish per replicate, and the fish were fed during the study, precluding it from consideration as a reliable toxicity prediction and from use in CMC calculations.

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/hardness/DOC-normalized LC_{50s} ranging from 2,230-61,731 µg/L. Similarly, Wilkinson et al. (1990) observed a 7-day LC₅₀ at pH 4.5 of 88 µg/L (or 16,771 µg/L when normalized to **Appendix A** conditions) for juvenile Atlantic salmon. These studies were not included in the CMC 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/ hardness/DOC-normalized LC₅₀ of 332.1 µg/L (Birge et al. 2000). While this value is below the CMC at the same normalized conditions (1,400 µg/L), the study provided little exposure details and exceeded the duration for an acceptable acute exposure toxicity test, where 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/hardness/DOC-normalized 96-hr and 8-day LC₅₀s were 23,858 and 15,557 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/hardness/DOC-normalized 96-hour LC₅₀ was >579.2 µg/L (Palmer et al. 1989). In contrast, Buhl (2002) observed a pH/hardness/DOC-normalized 96-hr EC₅₀ for death and immobility of >39,414 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/hardness/DOC-normalized LC₅₀s of 156.6 and 191.2 µg/L, respectively. In contrast, Sanborn (1945) observed no mortality in juvenile *M. salmoides* after a 7-day exposure to a pH/hardness/DOC-normalized concentration of 39,279 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) hardness, Freda and McDonald (1990) observed pH/hardness/DOC-normalized 4- to 5-day LC₅₀s ranging from 175,456 to >2,320,084 µg/L. In two separate studies conducted at pH 4.5 and low hardness, the pH/hardness/DOC-normalized 96-hr LC₅₀ for American toad (*Bufo americanus*) tadpoles was 893,036 µg/L (Freda et al. 1990); and the pH/hardness/DOC-normalized 96-hr LC₅₀ for the green tree frog (*Hyla cinerea*) was 560,411 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 LC₅₀ of 90.56 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 LC₅₀ of 90.56 and 281.8 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/hardness/DOC-normalized 96-hr LC₅₀ for *R. pipiens* embryos at pH 4.8 was 205,062 µg/L (Freda et al. 1990), similar to the LC₅₀s 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, reproductive LC₂₅s for *Ceriodaphnia dubia* were 566 and 641 µg/L (pH not reported so values could not be normalized), within the range of observed acceptable chronic values for this species (Zuiderveen and Birge 1997). Similarly, several unmeasured chronic tests conducted for the same species by the European AI Association (2009, 2010) demonstrated similar sensitivity across a range of hardness and DOC concentrations, with both increasing hardness and DOC reducing the toxicity of aluminum. In three unmeasured 21-day *Daphnia magna* tests, LC₅₀ and reproductive EC₁₆ and EC₅₀ pH/hardness/DOC-normalized endpoints were 1,214, 277.5 and 589.7 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/hardness/DOC-normalized 28-day EC₅₀ (death and deformity) for *O. mykiss* of 568.2 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 LC₅₀s for rainbow trout at two different test hardness levels (20.3 and 103 mg/L as CaCO₃) observed by Gundersen et al. (1994) were 176.5 and 1,034 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/hardness/DOC-normalized MATC for survival was 855.3 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 hardness and DOC concentrations revealed that both an increase in hardness and DOC reduced the toxicity of aluminum (non-normalized EC₂₀s ranged from 127.2 to 2,938 µg/L or 1,249 to 4,296 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 Orthoclaadiinae 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 ≥ 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

Acceptable saltwater acute data are available for three polychaete species (*Capitella capitata*, *Ctenodrilus serratus*, *Neanthes arenaceodentata*), a copepod (*Nitokra spinipes*) and the American oyster (*Crassostrea virginica*). Although data are limited, they suggest that saltwater species are acutely sensitive to aluminum, with SMAVs ranging from 97.15 to 10,000 µg/L (**Appendix B**), levels lower than the acute freshwater criterion of 1,400 µg/L (at pH 7, hardness 100 mg/L, DOC 1 mg/L). 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, LC₅₀s 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 >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, several chronic studies were identified 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 LC₅₀ 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, but was not a full life cycle test.

5.1.6 Bioaccumulation

Two 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 3 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.

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 hardness and DOC concentrations revealed that both an increase in pH, hardness and DOC reduced the toxicity of aluminum (European AI Association 2009). In contrast to other freshwater plants, duckweed is highly tolerant to aluminum, with an effect concentration based on reduced growth of >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*, still 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**).

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 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 SMAV and subsequently the 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. The GMAV is still valid, however, in spite of absence of these additional data. Additionally, many of the acute studies did not report a definitive LC₅₀ (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 LC₅₀ is unknown.

The CMC 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 11 species and subsequently 11 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 is being 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.

Likewise, the FCV could be calculated using the Final Acute-Chronic Ratio (FACR) (see **Appendix L**). While there are four freshwater ACRs, there are no ACRs available for estuarine/marine species. If the requirement for an estuarine/marine species ACR is ignored, the FACR, calculated as the geometric mean of the four species ACRs, is 8.068 (**Table L-1**). Using the FACR to calculate an alternate FCV, results in a value of 340 µg/L (division of the FAV of

2,741 µg/L by the FACR of 8.068) (**Figure L-1**). This result demonstrates that the chronic criterion of 390 µg/L total aluminum at pH 7, hardness of 100 mg/L as CaCO₃ and DOC of 1.0 mg/L, derived via the use of a more robust sensitivity distribution of empirical chronic data is supported via calculations by this other, more indirect ACR-based chronic criterion calculation.

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. 2017; Gensemer et al. 2017). 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 particulate form (Santore et al. 2017). 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. 2017; Wilson 2012). This creates uncertainty because the total aluminum concentrations measured in natural waters may overestimate the potential risks of toxicity to aquatic organisms.

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, estuarine/marine acute and chronic criteria could not be derived. This data gap prevents the recommendations of aluminum estuarine/marine criteria at this time and is a major data gap for aluminum. This is especially a concern because the available data indicate freshwater aluminum acute and chronic criteria are not protective of downstream estuarine/marine species. 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, EPA considered using an empirical 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 hardness. Also, a mechanistic BLM model for aluminum was recently developed (Santore et al. 2017). Finally, recently, an approach described in DeForest et al. (2017) incorporated pH, DOC and hardness 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 are based on the same toxicity test database. The MLR approach empirically curve-fits log-log hardness, pH 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 a comparison of 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, hardness, dissolved organic carbon, temperature), and MLR models to facilitate evaluation of the most appropriate approaches to consider across aluminum modeling approaches. Based on external peer review comments, ease of use, and transparency, EPA applied the DeForest et al. (2017)

MLR models 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. EPA independently examined and verified the quality and fit of the DeForest et al. (2017) MLR models before applying them in this draft criteria document.

5.3.6 pH, DOC and Hardness 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. (2017). 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, 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 uncertainty in the application of the *C. dubia* model across other invertebrate taxa. However, among fish (and amphibians), the MLR approach is believed to have an advantage in using a model optimized solely for those taxa, when compared to a BLM which uses one model to normalize the data for multiple taxa for criteria calculations. Thus, this 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 rather than 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 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 are uncertainties associated with the model are future research areas that need to be investigated.

The models were developed using data that encompass a pH range of 6-8.1, DOC range of 0.08-5 mg/L and hardness range of 9.8-127 mg/L (as CaCO₃). The authors (DeForest et al. 2017) noted that the empirical data evaluated support a reduced 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. When any of the water quality parameters selected is “outside model inputs”, the Aluminum Criteria Calculator V.1.0 (*Aluminum Criteria Calculator V.1.0.xlsx*) provides the user a warning to use discretion in applying criteria under those conditions.

5.4 Protection of Endangered Species

Although the dataset for aluminum is not extensive, it does include some data representing species that are Federally-listed as threatened or endangered by the U.S. Fish and Wildlife Service and/or NOAA Fisheries. Summaries are provided here describing the available aluminum toxicity data for listed species indicating that the 2017 aluminum criteria update is 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 3,661 µg/L (Call et al. 1984; Gundersen et al. 1994; Holtze 1983); Rio Grande silvery minnow, *Hybognathus amarus* with a normalized SMAV of >39,414 µg/L (Buhl 2002); and Atlantic salmon, *Salmo salar* with a SMAV of 7,151 µg/L (Hamilton and Haines 1995). [Note: all SMAVs are normalized to a pH 7, a hardness of 100 mg/L as CaCO₃ and a DOC of 1.0 mg/L]. All of the normalized SMAVs are above the recommended CMC of 1,400 µg/L at the same pH, 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 5.5, yielded a pH/hardness/DOC normalized species mean chronic value (SMCV) of 508.5 µg/L (McKee et al. 1989). This value is greater than the recommended CCC of 390 µg/L at the same 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 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*). While the 96-hr LC₅₀ juvenile test failed to elicit an acute 50% response at the highest concentration tested (6,302 µg/L total aluminum, or 29,834 µg/L when normalized), the 28-day biomass normalized SMCV ranked as the third most sensitive genus in the dataset. However, the SMCV was more than 2-fold greater than that of the most sensitive species, Atlantic salmon, and 2.7 times higher than the freshwater criterion. Thus, the chronic criterion is expected to be protective of this and related species. The fatmucket 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. 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 2017 Criteria Values

The 1988 aluminum freshwater acute criterion was based on data from 8 species of invertebrates and 7 species of fish grouped into 14 genera. This 2017 update now includes 11 species of invertebrates, 8 species of fish, and one frog species for a total of 20 species grouped

into 18 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 hardness and DOC ranges, based on a dataset that included 2 species of invertebrates and one fish species. This 2017 draft criteria update includes new data for an additional 8 species, and consists of 7 invertebrates and 4 fish species grouped into 11 genera and is a function of pH, hardness and DOC.

Like the previous AWQC for aluminum, there are still insufficient data to fulfill the estuarine/marine MDR as per the 1985 Guidelines, so that no estuarine/marine criteria can be recommended 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. Summary Overview of 2017 Draft Aluminum Aquatic Life Criteria Compared to Current 1988 Criteria.

Version	Freshwater Acute^a (1 day, total aluminum)	Freshwater Chronic^a (4-day, total aluminum)
2017 Draft AWQC Criteria (MLR normalized to pH = 7, hardness = 100 mg/L, DOC = 1 mg/L)	1,400 µg/L	390 µg/L
1988 AWQC Criteria (pH 6.5 – 9.0, across all 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: 2017 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.1.0 (*Aluminum Criteria Calculator V.1.0.xlsx*) or found in the tables in Appendix K). See Appendix K for specific comparisons of 1988 and 2017 draft criteria values across water chemistry parameter ranges.

6 UNUSED DATA

For this 2017 criteria update document, 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 Quality Assurance/Quality Control (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.

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**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	Hardness (mg/L as CaCO ₃)	pH	DOC (mg/L)	LC50/ EC50 (µg/L)	Normalized Acute Value ^b (µg/L)	Species Mean Acute Value (µg/L)	Reference
Snail (adult), <i>Physa sp.</i>	S, M, T	Aluminum chloride	47.4	6.59	1.1 ^d	>23,400	> 48,425	-	Call 1984; Call et al. 1984
Snail (adult), <i>Physa sp.</i>	S, M, T	Aluminum chloride	47.4	7.55	1.1 ^d	30,600	26,986	-	Call 1984; Call et al. 1984
Snail (adult), <i>Physa sp.</i>	S, M, T	Aluminum chloride	47.4	8.17	1.1 ^d	>24,700	> 24,040	-	Call 1984; Call et al. 1984
Snail (adult), <i>Physa sp.</i>	S, M, T	Aluminum chloride	47.4	7.46	1.1 ^d (aged solution)	55,500	50,338	35,462	Call 1984; Call et al. 1984
Fatmucket (juvenile, 6 d), <i>Lampsilis siliquoidea</i>	R, M, T	Aluminum chloride	107.0	8.19	0.5	>54,300	>78,369 ^f	-	Ivey et al. 2014
Fatmucket (juvenile, 7-8 d, 0.38 mm), <i>Lampsilis siliquoidea</i>	F, M, T	Aluminum nitrate	106 (104-108)	6.12 (6.10-6.13)	0.48	>6,302	> 29,834	>29,834	Wang et al. 2016, 2017
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, M, A	Aluminum chloride	50.0	7.42	1.1 ^d	1,900	1,728	-	McCauley et al. 1986
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, M, A	Aluminum chloride	50.5	7.86	1.1 ^d	1,500	1,294	-	McCauley et al. 1986
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, M, A	Aluminum chloride	50.0	8.13	1.1 ^d	2,560	2,431	-	McCauley et al. 1986
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	R, M, T	Aluminum chloride	26	7.5	0.5 ^d	720	1,113	-	ENSR 1992d
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	R, M, T	Aluminum chloride	46	7.6	0.5 ^d	1,880	2,495	-	ENSR 1992d
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	R, M, T	Aluminum chloride	96	7.8	0.5 ^d	2,450	2,894	-	ENSR 1992d

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	DOC (mg/L)	LC50/ EC50 (µg/L)	Normalized Acute Value ^b (µg/L)	Species Mean Acute Value (µg/L)	Reference
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	R, M, T	Aluminum chloride	194	8.1	0.5 ^d	>99,600	>129,431 ^c	-	ENSR 1992d
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, NR	Aluminum sulfate	90 (80-100)	7.15 (7.0-7.3)	0.5 ^d	3,727	5,002	-	Fort and Stover 1995
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, NR	Aluminum sulfate	90 (80-100)	7.15 (7.0-7.3)	0.5 ^d	5,673	7,613	-	Fort and Stover 1995
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, NR	Aluminum sulfate	89	7.6	0.5 ^d	2,880	3,362	-	Soucek et al. 2001
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	6.01 (5.99-6.03)	0.5 ^d	71.12	1,691	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	6.05 (6.02-6.07)	2	686.5	7,088	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	6.09 (6.03-6.15)	4	1,558.1	10,072	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	6.01 (5.95-6.06)	0.5 ^d (solution aged 3 hrs)	68.1	1,620	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	6.03 (5.95-6.10)	0.5 ^d (solution aged 27 hrs)	163.0	3,674	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	5.97 (5.92-6.01)	0.5 ^d (solution aged 51 hrs)	178.5	4,732	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	5.92 (5.87-5.96)	0.5 ^d (solution aged 99 hrs)	141.0	4,295	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	6.99 (6.96-7.01)	0.5 ^d	>1,300	>4,189	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	7.85 (7.77-7.93)	0.5 ^d	>5,000	>7,960	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	6.80 (6.55-7.04)	2	>10,000	>20,755	-	European AI Association 2009

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	DOC (mg/L)	LC50/ EC50 (µg/L)	Normalized Acute Value ^b (µg/L)	Species Mean Acute Value (µg/L)	Reference
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	7.82 (7.49-8.14)	2	>15,000	>11,626	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	6.77 (6.51-7.03)	4	>10,000	>15,161	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	7.66 (7.39-7.93)	4	>15,000	>8,608	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	7.91 (7.82-7.99)	0.5 ^d (solution aged 3 hrs)	>2,000	>3,150	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	10.6	7.89 (7.83-7.95)	0.5 ^d (solution aged 27 hrs)	>2,000	>3,156	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	60	6.04 (6.02-6.05)	0.5 ^d	110.8	850.1	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	60	5.98 (5.90-6.05)	2	1,137.1	4,817	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	60	5.73 (5.39-6.06)	4	8,046.7	43,570	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	60	6.71 (6.44-6.98)	0.5 ^d	>10,000	>23,786	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	60	7.83 (7.74-7.92)	0.5 ^d	>5,000	>6,344	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	60	6.79 (6.55-7.03)	2	>10,000	>10,394	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	60	7.67 (7.41-7.92)	2	>15,000	>9,082	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	60	6.68 (6.35-7.01)	4	>15,000	>12,461	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	60	7.62 (7.35-7.89)	4	>15,000	>6,332	-	European AI Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	120	6.06 (5.97-6.14)	2	3,386.8	7,920	-	European AI Association 2009

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	DOC (mg/L)	LC50/ EC50 (µg/L)	Normalized Acute Value ^b (µg/L)	Species Mean Acute Value (µg/L)	Reference
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	120	5.60 (5.22-5.97)	4	10,484.2	48,800	-	European Al Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	120	6.93 (6.84-7.02)	0.5 ^d	>5,000	>7,126	-	European Al Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	120	7.88 (7.80-7.95)	0.5 ^d	>5,000	>5,898	-	European Al Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	120	6.76 (6.43-7.09)	2	>15,000	>12,117	-	European Al Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	120	7.71 (7.46-7.95)	2	>15,000	>8,096	-	European Al Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	120	6.60 (6.21-6.98)	4	>15,000	>10,139	-	European Al Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, U, T	Aluminum nitrate	120	7.60 (7.32-7.87)	4	>15,000	>5,545	-	European Al Association 2009
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, M, T	Aluminum nitrate	10.6	6.03 (6.02-6.03)	0.5 ^d (stock solution not buffered)	119.71	2,699	-	European Al Association 2010
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, M, T	Aluminum nitrate	10.6	6.03 (6.02-6.03)	0.5 ^d (stock solution buffered)	274.78	6,194	-	European Al Association 2010
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, M, T	Aluminum nitrate	10.6	6.03 (6.02-6.03)	0.5 ^d (test solution MES buffered)	119.98	2,705	-	European Al Association 2010
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	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	1,876	-	European Al Association 2010

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	DOC (mg/L)	LC50/ EC50 (µg/L)	Normalized Acute Value ^b (µg/L)	Species Mean Acute Value (µg/L)	Reference
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	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	6,035	-	European Al Association 2010
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	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	6,238	-	European Al Association 2010
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, M, T	Aluminum nitrate	10.6	7.08 (7.06-7.09)	0.5 ^d (test solution HCl buffered)	>886.4	>2,534	-	European Al Association 2010
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, M, T	Aluminum nitrate	10.6	7.79 (7.70-7.88)	0.5 ^d (test solution HEPES buffered)	>4,278.3	>6,930	-	European Al Association 2010
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, M, T	Aluminum nitrate	10.6	7.53 (7.45-7.61)	0.5 ^d (test solution NaOH adjusted)	132.04	243.7	-	European Al Association 2010
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, M, T	Aluminum nitrate	60.0	6.01 (5.99-6.03)	0.5 ^d (stock solution not buffered)	463.26	3,798	-	European Al Association 2010
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	S, M, T	Aluminum nitrate	60.0	5.99 (5.98-5.99)	0.5 ^d (stock solution buffered)	>859.0	>7,366	5,094	European Al Association 2010
Cladoceran (0-24 hr), <i>Ceriodaphnia reticulata</i>	S, U, T	Aluminum chloride	45.1	7.25 (6.8-7.7)	1.1 ^d	2,800	2,868 ^f	-	Shephard 1983
Cladoceran (0-24 hr), <i>Ceriodaphnia reticulata</i>	F, M, T	Aluminum chloride	45.1	6.0	1.1 ^d	304	2,009	-	Shephard 1983
Cladoceran (0-24 hr), <i>Ceriodaphnia reticulata</i>	F, M, T	Aluminum chloride	4.0	5.5	1.1 ^d	362	55,307	10,542	Shephard 1983

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	DOC (mg/L)	LC50/ EC50 (µg/L)	Normalized Acute Value ^b (µg/L)	Species Mean Acute Value (µg/L)	Reference
Cladoceran (0-24 hr), <i>Daphnia magna</i>	S, U, NR	Aluminum chloride	45.3	7.74	1.1 ^d	3,900	3,382	-	Biesinger and Christensen 1972
Cladoceran (0-24 hr), <i>Daphnia magna</i>	S, M, T	Aluminum sulfate	220	7.60 (7.05-8.15)	1.6 ^d	38,200	20,303	-	Kimball 1978
Cladoceran (0-24 hr), <i>Daphnia magna</i>	S, U, T	Aluminum chloride	45.1	7.25 (6.8-7.7)	1.1 ^d	2,800	2,868	-	Shephard 1983
Cladoceran (<24 hr), <i>Daphnia magna</i>	S, U, T	Aluminum nitrate	168	5.99 (5.98-5.99)	0.5 ^d	>500	>2,265	-	European AI Association 2009
Cladoceran (<24 hr), <i>Daphnia magna</i>	S, U, T	Aluminum nitrate	168	6.98 (6.97-6.98)	0.5 ^d	>500	>607.0 ^c	-	European AI Association 2009
Cladoceran (<24 hr), <i>Daphnia magna</i>	S, U, T	Aluminum nitrate	168	7.93 (7.92-7.94)	0.5 ^d	>500	>582.2 ^c	-	European AI Association 2009
Cladoceran (<24 hr), <i>Daphnia magna</i>	S, U, T	Aluminum nitrate	168	7.92 (7.90-7.93)	0.5 ^d	795.0	920.4	-	European AI Association 2009
Cladoceran (<24 hr), <i>Daphnia magna</i>	S, U, T	Aluminum nitrate	168	7.95 (7.92-7.97)	2	>1,200	>683.0 ^c	-	European AI Association 2009
Cladoceran (<24 hr), <i>Daphnia magna</i>	S, U, T	Aluminum nitrate	168	7.93 (7.92-7.94)	3	>1,200	>545.5 ^c	3,332	European AI Association 2009
Ostracod (adult, 1.5 mm, 0.3 mg), <i>Stenocypris major</i>	R, M, T	Aluminum sulfate	15.63	6.51	1.6 ^d	3,102	10,216	10,216	Shuhaimi-Othman et al. 2011a
Amphipod (4 mm), <i>Crangonyx pseudogracilis</i>	R, U, T	Aluminum sulfate	50	6.75	1.6 ^d	9,190	12,174	12,174	Martin and Holdich 1986
Amphipod (juvenile, 7 d, 1.32 mm), <i>Hyalella azteca</i>	F, M, T	Aluminum nitrate	105 (103-108)	6.13 (6.09-6.16)	0.48	>5,997	>28,002	>28,002	Wang et al. 2016, 2017

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	DOC (mg/L)	LC50/ EC50 (µg/L)	Normalized Acute Value ^b (µg/L)	Species Mean Acute Value (µg/L)	Reference
Stonefly (nymph), <i>Acroneuria sp.</i>	S, M, T	Aluminum chloride	47.4	7.46	1.1 ^d	>22,600	> 20,498	>20,498	Call et al. 1984
Midge (3rd-4th instar larvae), <i>Chironomus plumosus</i>	S, U, T	Aluminum chloride	80	7.0	1.6 ^d	30,000	25,361	25,361	Fargasova 2001
Midge (2nd-3rd instar larvae), <i>Paratanytarsus dissimilis</i>	S, U, T	Aluminum sulfate	17.43	7.28 (6.85-7.71)	2.8 ^d	>77,700	> 62,318	>62,318	Lamb and Bailey 1981, 1983
Rainbow trout (alevin), <i>Oncorhynchus mykiss</i>	S, U, T	Aluminum sulfate	14.3	5.5	1.6 ^d	160	4,644 ^f	-	Holtze 1983
Rainbow trout (alevin), <i>Oncorhynchus mykiss</i>	S, U, T	Aluminum sulfate	14.3	5.5	1.6 ^d	310	3,627 ^f	-	Holtze 1983
Rainbow trout (fingerling), <i>Oncorhynchus mykiss</i>	S, M, T	Aluminum chloride	47.4	6.59	1.1 ^d	7,400	11,525 ^f	-	Call et al. 1984
Rainbow trout (fingerling), <i>Oncorhynchus mykiss</i>	S, M, T	Aluminum chloride	47.4	7.31	1.1 ^d	14,600	9,414 ^f	-	Call et al. 1984
Rainbow trout (fingerling), <i>Oncorhynchus mykiss</i>	S, M, T	Aluminum chloride	47.4	8.17	1.1 ^d	>24,700	>5,554 ^f	-	Call et al. 1984
Rainbow trout (fingerling), <i>Oncorhynchus mykiss</i>	S, M, T	Aluminum chloride	47.4	7.46	1.1 ^d (aged solution)	8,600	4,614 ^f	-	Call et al. 1984
Rainbow trout (juvenile, 1-3 g), <i>Oncorhynchus mykiss</i>	F, M, T	Aluminum chloride	27.4	7.58	0.5 ^d	>9,840	> 5,745	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), <i>Oncorhynchus mykiss</i>	F, M, T	Aluminum chloride	45.2	7.62	0.5 ^d	>8,070	> 5,212	-	Gundersen et al. 1994

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	DOC (mg/L)	LC50/ EC50 (µg/L)	Normalized Acute Value ^b (µg/L)	Species Mean Acute Value (µg/L)	Reference
Rainbow trout (juvenile, 1-3 g), <i>Oncorhynchus mykiss</i>	F, M, T	Aluminum chloride	89.5	7.58	0.5 ^d	>8,160	> 6,807	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), <i>Oncorhynchus mykiss</i>	F, M, T	Aluminum chloride	130.4	7.58	0.5 ^d	>8,200	> 7,662	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), <i>Oncorhynchus mykiss</i>	F, M, T	Aluminum chloride	23.2	8.25	0.5 ^d	6,170	1,190	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), <i>Oncorhynchus mykiss</i>	F, M, T	Aluminum chloride	35.0	8.26	0.5 ^d	6,170	1,523	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), <i>Oncorhynchus mykiss</i>	F, M, T	Aluminum chloride	83.6	8.29	0.5 ^d	7,670	3,205	-	Gundersen et al. 1994
Rainbow trout (juvenile, 1-3 g), <i>Oncorhynchus mykiss</i>	F, M, T	Aluminum chloride	115.8	8.30	0.5 ^d	6,930	3,554	3,661	Gundersen et al. 1994
Chinook salmon (juvenile), <i>Oncorhynchus tshawytscha</i>	S, M, NR	Sodium aluminate	28.0	7.00	-	>40,000	NA^e	NA ^e	Peterson et al. 1974
Atlantic salmon (sac fry, ≈0.2 g), <i>Salmo salar</i>	S, U, T	Aluminum chloride	6.8 (6.6-7.0)	5.5	0.5 ^d	584	21,042	-	Hamilton and Haines 1995
Atlantic salmon (sac fry, ≈0.2 g), <i>Salmo salar</i>	S, U, T	Aluminum chloride	6.8 (6.6-7.0)	6.5	0.5 ^d	599	2,430	7,151	Hamilton and Haines 1995
Brook trout (14 mo., 210 mm, 130 g), <i>Salvelinus fontinalis</i>	F, M, T	Aluminum sulfate	-	6.5	-	3,600	NA ^e	-	Decker and Menendez 1974

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	DOC (mg/L)	LC50/ EC50 (µg/L)	Normalized Acute Value ^b (µg/L)	Species Mean Acute Value (µg/L)	Reference
Brook trout (14 mo., 210 mm, 130 g), <i>Salvelinus fontinalis</i>	F, M, T	Aluminum sulfate	-	6.0	-	4,400	NA ^e	-	Decker and Menendez 1974
Brook trout (14 mo., 210 mm, 130 g), <i>Salvelinus fontinalis</i>	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), <i>Salvelinus fontinalis</i>	S, U, T	Aluminum sulfate	40	5.6	1.6 ^d	6,530	31,767	-	Tandjung 1982
Brook trout (0.6 g, 4.4-7.5 cm), <i>Salvelinus fontinalis</i>	S, U, T	Aluminum sulfate	18	5.6	1.6 ^d	3,400	28,391	-	Tandjung 1982
Brook trout (0.6 g, 4.4-7.5 cm), <i>Salvelinus fontinalis</i>	S, U, T	Aluminum sulfate	2	5.6	1.6 ^d	370	13,663	23,097	Tandjung 1982
Green sunfish (juvenile, 3 mo.), <i>Lepomis cyanellus</i>	S, M, T	Aluminum chloride	47.4	7.55	1.1 ^d	>50,000	>24,028	>24,028	Call et al. 1984
Rio Grande silvery minnow (larva, 3-5 dph), <i>Hybognathus amarus</i>	R, M, T	Aluminum chloride	140	8.1	0.5 ^d	>59,100	>39,414	>39,414	Buhl 2002
Fathead minnow (adult), <i>Pimephales promelas</i>	S, U, NR	Aluminum sulfate	-	7.6	-	>18,900	NA ^e	-	Boyd 1979
Fathead minnow (juvenile, 32-33 d), <i>Pimephales promelas</i>	S, M, T	Aluminum chloride	47.4	7.61	1.1 ^d	>48,200	>21,522	-	Call et al. 1984
Fathead minnow (juvenile, 32-33 d), <i>Pimephales promelas</i>	S, M, T	Aluminum chloride	47.4	8.05	1.1 ^d	>49,800	>12,972	-	Call et al. 1984

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	DOC (mg/L)	LC50/ EC50 (µg/L)	Normalized Acute Value ^b (µg/L)	Species Mean Acute Value (µg/L)	Reference
Fathead minnow (juvenile, 11 mm, 3 mg dw), <i>Pimephales promelas</i>	F, U, T	Aluminum chloride	21.6	6.5	1.6 ^d	>400	>691.3 ^c	-	Palmer et al. 1989
Fathead minnow (juvenile, 11 mm, 3 mg dw), <i>Pimephales promelas</i>	F, U, T	Aluminum chloride	21.6	7.5	0.9	>400	>184.0 ^c	-	Palmer et al. 1989
Fathead minnow (yolk-sac larva, 1 dph), <i>Pimephales promelas</i>	F, U, T	Aluminum chloride	21.6	6.5	0.9	>400	>923.4 ^c	-	Palmer et al. 1989
Fathead minnow (yolk-sac larva, 1 dph), <i>Pimephales promelas</i>	F, U, T	Aluminum chloride	21.6	7.5	0.9	>400	>184.0 ^c	-	Palmer et al. 1989
Fathead minnow (≤7 d), <i>Pimephales promelas</i>	R, M, T	Aluminum chloride	26	7.8	0.5 ^d	1,160	477.0	-	ENSR 1992c
Fathead minnow (≤7 d), <i>Pimephales promelas</i>	R, M, T	Aluminum chloride	46	7.6	0.5 ^d	8,180	5,446	-	ENSR 1992c
Fathead minnow (≤7 d), <i>Pimephales promelas</i>	R, M, T	Aluminum chloride	96	8.1	0.5 ^d	20,300	10,966	-	ENSR 1992c
Fathead minnow (≤7 d), <i>Pimephales promelas</i>	R, M, T	Aluminum chloride	194	8.1	0.5 ^d	44,800	35,847	-	ENSR 1992c
Fathead minnow (larva, 4-6 dph), <i>Pimephales promelas</i>	R, M, T	Aluminum chloride	140	8.1	0.5 ^d	>59,100	>39,414	10,168	Buhl 2002
Smallmouth bass (larva, 48 hr post hatch), <i>Micropterus dolomieu</i>	S, M, T	Aluminum sulfate	12.45 (12.1-12.8)	5.05 (4.7-5.4)	1.6 ^d	130	3,929	-	Kane and Rabeni 1987
Smallmouth bass (larva, 48 hr post hatch), <i>Micropterus dolomieu</i>	S, M, T	Aluminum sulfate	12.45 (12.1-12.8)	6.75 (6.0-7.5)	1.6 ^d	>978.4	>1,199 ^c	-	Kane and Rabeni 1987

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	DOC (mg/L)	LC50/ EC50 (µg/L)	Normalized Acute Value ^b (µg/L)	Species Mean Acute Value (µg/L)	Reference
Smallmouth bass (larva, 48 hr post hatch), <i>Micropterus dolomieu</i>	S, M, T	Aluminum sulfate	12.45 (12.1-12.8)	7.45 (7.2-7.7)	1.6 ^d	>217	>71.08 ^c	3,929	Kane and Rabeni 1987
Green tree frog (tadpole, <1 dph), <i>Hyla cinerea</i>	R, M, T	Aluminum chloride	4.55	5.49 (5.48-5.50)	0.5 ^d	>405.2	>20,016	>20,016	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, hardness of 100 mg/L as CaCO₃ and DOC of 1 mg/L (see **Section 2.7.1**). Values in bold are used in SMAV calculation.

^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.

**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	LC50/ EC50 (µg/L)	Species Mean Acute Value (µg/L)	Reference
Polychaete worm, <i>Capitella capitata</i>	S, U	Aluminum chloride	-	-	404.8	404.8	Petrich and Reish 1979
Polychaete worm, <i>Ctenodrilus serratus</i>	S, U	Aluminum chloride	-	-	97.15	97.15	Petrich and Reish 1979
Polychaete worm, <i>Neanthes arenaceodentata</i>	S, U	Aluminum chloride	-	-	>404.8	>404.8	Petrich and Reish 1979
Copepod (adult), <i>Nitokra spinipes</i>	S, U	Aluminum chloride	7	8	10,000	10,000	Bengtsson 1978
American oyster (fertilized eggs, ≤1 hr), <i>Crassostrea virginica</i>	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 SMAV calculation).

(Species are organized phylogenetically).

Species	Test ^a	Chemical	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), <i>Aelosoma sp.</i>	17 d	Aluminum nitrate	48	6.0 (5.9-6.1)	<0.5 ^c	Reproduction (population size)	1,235	17,098	17,098	OSU 2012e; Cardwell et al. 2017 (Manuscript)
Rotifer (newly hatched, <2 hr), <i>Brachionus calyciflorus</i>	48 hr	Aluminum nitrate	100	6.2 (5.9-6.5)	<0.5 ^c	Reproduction (population size)	431.0	2,555	2,555	OSU 2012c; Cardwell et al. 2017 (Manuscript)
Great pond snail (newly- hatched, <24 hr), <i>Lymnaea stagnalis</i>	30 d	Aluminum nitrate	117	6.1 (6.0-6.2)	<0.5 ^c	Biomass	745.7	4,877	4,877	OSU 2012b; Cardwell et al. 2017 (Manuscript)
Fatmucket (6 wk, 1.97 mm), <i>Lampsilis siliquoidea</i>	28 d	Aluminum nitrate	105.5 (105-106)	6.04 (5.95-6.12)	0.40 (0.34- 0.45)	Biomass	169	1,042	1,042	Wang et al. 2016, 2017
Cladoceran (≤16 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum chloride	50	7.15	1.1 ^c	Reproduction (young/adult)	1,780	1,898	-	McCauley et al. 1986
Cladoceran (≤16 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum chloride	50.5	7.61	1.1 ^c	Reproduction (young/adult)	<1,100 (MATC)	<946.2 ^f	-	McCauley et al. 1986
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum chloride	26	7.3	0.5 ^c	Reproduction (young/female)	1,557	2,719	-	ENSR 1992b
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum chloride	46	7.5	0.5 ^c	Reproduction (young/female)	808.7	1,102	-	ENSR 1992b
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum chloride	96	7.9	0.5 ^c	Reproduction (young/female)	651.9	796.1	-	ENSR 1992b
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum chloride	194	8.1	0.5 ^c	Reproduction (young/female)	683.6	888.4	-	ENSR 1992b

Species	Test ^a	Chemical	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), <i>Ceriodaphnia dubia</i>	LC	Aluminum nitrate	25.5	7.03 (7.01-7.05)	0.5	Reproduction (young/female)	250	563.4	-	CECM 2014; Gensemer et al. 2017 (Manuscript)
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum nitrate	122	7.13 (7.10-7.16)	0.5	Reproduction (young/female)	860	1,061	-	CECM 2014; Gensemer et al. 2017 (Manuscript)
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum nitrate	25	7.98 (7.97-7.99)	0.5	Reproduction (young/female)	700	1,006	-	CECM 2014; Gensemer et al. 2017 (Manuscript)
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum nitrate	61	8.03 (8.01-8.04)	0.5	Reproduction (young/female)	1,010	1,363	-	CECM 2014; Gensemer et al. 2017 (Manuscript)
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum nitrate	122	8.10 (8.09-8.11)	0.5	Reproduction (young/female)	870	1,164	-	CECM 2014; Gensemer et al. 2017 (Manuscript)
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum nitrate	25.5	6.33 (6.31-6.35)	0.5	Reproduction (young/female)	260	1,758	-	CECM 2014; Gensemer et al. 2017 (Manuscript)
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	LC	Aluminum nitrate	121	6.36 (6.34-6.37)	0.5	Reproduction (young/female)	390	1,101	1,182	CECM 2014; Gensemer et al. 2017 (Manuscript)
Amphipod (juvenile, 7-9 d), <i>Hyalella azteca</i>	28 d	Aluminum nitrate	95	6.1 (5.9-6.3)	0.51	Biomass	199.3	1,014	-	OSU 2012h; Cardwell et al. 2017 (Manuscript)
Amphipod (juvenile, 7 d, 1.31 mm), <i>Hyalella azteca</i>	28 d	Aluminum nitrate	106 (105-107)	6.04 (5.92-6.16)	0.33 (0.26- 0.39)	Biomass	425	2,895	1,713	Wang et al. 2016, 2017

Species	Test ^a	Chemical	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), <i>Chironomus riparius</i>	30 d	Aluminum sulfate	11.8	5.58 (5.51-5.64)	1.8 ^e	Adult midge emergence	29.55	1,192	-	Palawski et al. 1989
Midge (1st instar larva, <24 hr), <i>Chironomus riparius</i>	30 d	Aluminum sulfate	11.9	5.05 (4.99-5.1)	1.8 ^e	Adult midge emergence	84.42	22,578	-	Palawski et al. 1989
Midge (1st instar larva, 3d), <i>Chironomus riparius</i>	28 d	Aluminum nitrate	91	6.6 (6.5-6.7)	0.51	Reproduction (# of eggs/case)	3,387	7,664	5,908	OSU 2012f; Cardwell et al. 2017 (Manuscript)
Atlantic salmon (embryo), <i>Salmo salar</i>	ELS	Aluminum sulfate	12.7	5.7 (5.6-5.8)	1.8 ^e	Biomass	61.56	508.5	-	McKee et al. 1989
Atlantic salmon (fertilized eggs), <i>Salmo salar</i>	ELS	Aluminum sulfate	12.7	5.7 (5.6-5.8)	1.8 ^e	Survival	154.2	1,274 ^d	508.5	Buckler et al. 1995
Brook trout (eyed eggs), <i>Salvelinus fontinalis</i>	ELS	Aluminum sulfate	12.3	6.55 (6.5-6.6)	1.9	Biomass	164.4	270.1	-	Cleveland et al. 1989
Brook trout (eyed eggs), <i>Salvelinus fontinalis</i>	ELS	Aluminum sulfate	12.8	5.65 (5.6-5.7)	1.8	Biomass	143.5	1,295	591.4	Cleveland et al. 1989
Fathead minnow, <i>Pimephales promelas</i>	ELS	Aluminum sulfate	220	7.70 (7.27-8.15)	1.6 ^c	Biomass	6,194	3,569	-	Kimball 1978
Fathead minnow (embryo, <24 hr), <i>Pimephales promelas</i>	ELS	Aluminum nitrate	96	6.20 (5.9-6.5)	<0.5 ^c	Survival	428.6	1,734	2,488	OSU 2012g; Cardwell et al. 2017 (Manuscript)
Zebrafish (embryo, <36hpf), <i>Danio rerio</i>	ELS	Aluminum nitrate	83	6.10 (5.9-6.3)	<0.5 ^c	Biomass	234.4	1,102	1,102	OSU 2013; Cardwell et al. 2017 (Manuscript)

^a LC=Life cycle, ELS=Early life-stage.

^b Normalized to pH 7, hardness of 100 mg/L as CaCO₃ and DOC of 1 mg/L (see **Section 2.7.1**). Values in bold are used in SMCV calculation.

^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 EC₂₀ 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	Hardness (mg/L as CaCO ₃)	pH	Duration	Effect	Chronic Limits (µg/L)	Concentration (µg/L)	Reference
Freshwater Species									
Green alga, <i>Arthrodesmus octocornus</i>	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50	Pillsbury and Kingston 1990
Green alga, <i>Arthrodesmus indentatus</i>	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50	Pillsbury and Kingston 1990
Green alga, <i>Arthrodesmus quiriferus</i>	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50	Pillsbury and Kingston 1990
Green alga, <i>Dinobryon bavaricum</i>	S, M	-	-	5.7	21 d	NOEC (number of cells)	-	>200	Pillsbury and Kingston 1990
Green alga, <i>Elaktothrix sp.</i>	S, M	-	-	5.7	21 d	Number of cells	100-200	141.4	Pillsbury and Kingston 1990
Green alga, <i>Oedogonium sp.</i>	S, M	-	-	5.7	21 d	NOEC (number of cells)	-	>200	Pillsbury and Kingston 1990
Green alga, <i>Peridinium limbatum</i>	S, M	-	-	5.7	21 d	NOEC (number of cells)	-	>200	Pillsbury and Kingston 1990
Green alga, <i>Staurostrum arachne v. curvatum</i>	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50	Pillsbury and Kingston 1990

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	Duration	Effect	Chronic Limits (µg/L)	Concentration (µg/L)	Reference
Green alga, <i>Staurastrum longipes</i> v. <i>contractum</i>	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50	Pillsbury and Kingston 1990
Green alga, <i>Staurastrum pentacerum</i>	S, M	-	-	5.7	21 d	LOEC (number of semicells)	-	50.0	Pillsbury and Kingston 1990
Green alga, <i>Mougeotia</i> sp.	S, U	Aluminum sulfate	-	4.1	14 d	NOEC (chlorophyll a)	-	3,600	Graham et al. 1996
Green alga, <i>Monoraphidium</i> <i>dybowskii</i>	S, U	Aluminum chloride	-	5.0	12 d	EC50 (growth)	-	1,000	Claesson and Tornqvist 1988
Green alga, <i>Monoraphidium</i> <i>dybowskii</i>	S, U	Aluminum chloride	-	5.5	12 d	EC50 (growth)	-	1,000	Claesson and Tornqvist 1988
Green alga, <i>Monoraphidium</i> <i>dybowskii</i>	S, U	Aluminum chloride	-	6.0	12 d	EC50 (growth)	-	550	Claesson and Tornqvist 1988
Green alga, <i>Monoraphidium</i> <i>dybowskii</i>	S, U	Aluminum chloride	14.9	4.8	4 d	Growth	600-1,000	774.6	Hornstrom et al. 1995
Green alga, <i>Monoraphidium</i> <i>dybowskii</i>	S, U	Aluminum chloride	14.9	6.8	4 d	LOEC (growth)	-	200	Hornstrom et al. 1995
Green alga, <i>Monoraphidium griffithii</i>	S, U	Aluminum chloride	14.9	4.8	4 d	LOEC (growth)	-	100	Hornstrom et al. 1995
Green alga, <i>Monoraphidium griffithii</i>	S, U	Aluminum chloride	14.9	6.8	4 d	LOEC (growth)	-	100	Hornstrom et al. 1995

Species	Method ^a	Chemical	Hardness (mg/L as CaCO ₃)	pH	Duration	Effect	Chronic Limits (µg/L)	Concentration (µg/L)	Reference
Green alga, <i>Scenedesmus quadricauda</i>	S, U	Aluminum chloride	12	7.5	4 d	LOEC (growth inhibition)	-	1,500	Bringmann and Kuhn 1959b
Green alga, <i>Pseudokirchneriella subcapitata</i>	-	Sodium aluminate	15	7.0	14 d	Reduce cell counts and dry weight	990-1,320	1,143	Peterson et al. 1974
Green alga, <i>Pseudokirchneriella subcapitata</i>	S, U	Aluminum chloride	14.9	7.6	4 d	EC50 (biomass)	-	570	Call et al. 1984
Green alga, <i>Pseudokirchneriella subcapitata</i>	S, U	Aluminum chloride	14.9	8.2	4 d	EC50 (biomass)	-	460	Call et al. 1984
Green alga, <i>Pseudokirchneriella subcapitata</i>	S, U	Aluminum sulfate	-	5.5	4 d	LOEC (growth inhibition)	-	160	Kong and Chen 1995
Green alga, <i>Stichococcus sp.</i>	S, U	Aluminum chloride	-	5.0	9 d	IC50 (growth rate)	-	560	Tornqvist and Claesson 1987
Green alga, <i>Stichococcus sp.</i>	S, U	Aluminum chloride	-	5.0	9 d	EC50 (growth)	-	500	Claesson and Tornqvist 1988
Green alga, <i>Stichococcus sp.</i>	S, U	Aluminum chloride	-	5.5	9 d	EC50 (growth)	-	220	Claesson and Tornqvist 1988
Diatom, <i>Asterionella ralfsii var. americana</i>	S, M	Aluminum chloride	-	5.0	7-9 d	Growth	404.7-620.5	501.1	Gensemer 1989
Diatom, <i>Asterionella ralfsii var. americana</i>	S, M	Aluminum chloride	-	6.0	7-9 d	Growth	404.7-647.5	511.9	Gensemer 1989
Diatom, <i>Asterionella ralfsii var. americana</i>	S, M	-	-	5.7	21 d	LOEC (number of live cells)	-	50	Pillsbury and Kingston 1990

Species	Method ^a	Chemical	Hardness (mg/L as CaCO3)	pH	Duration	Effect	Chronic Limits (µg/L)	Concentration (µg/L)	Reference
Diatom, <i>Cyclotella meneghiniana</i>	S, U	Aluminum chloride	-	7.9	16 d	Partially inhibit growth	-	809.6	Rao and Subramanian 1982
Diatom, <i>Cyclotella meneghiniana</i>	S, U	Aluminum chloride	-	7.9	16 d	Algistatic	-	3,238	Rao and Subramanian 1982
Diatom, <i>Cyclotella meneghiniana</i>	S, U	Aluminum chloride	-	7.9	16 d	Algicidal	-	6,477	Rao and Subramanian 1982
Eurasian watermilfoil, <i>Myriophyllum spicatum</i>	S, U	-	95.93	-	32 d	IC50 (root dry weight)	-	2,500	Stanley 1974
Duckweed, <i>Lemna minor</i>	S, M	Aluminum chloride	14.9	7.6	4 d	NOEC (reduce frond production)	-	>45,700	Call et al. 1984
Duckweed, <i>Lemna minor</i>	S, M	Aluminum chloride	14.9	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, <i>Halophila stipulacea</i>	R, U	-	35.0	6.5-7.0	12 d	Observed protoplast necrosis	0.02698-0.2698	0.08532	Malea and Haritonidis 1996
Seagrass, <i>Halophila stipulacea</i>	R, U	-	35.0	6.5-7.0	12 d	Greater than 50% mortality of teeth cells	-	269.8	Malea and Haritonidis 1996
Seagrass, <i>Halophila stipulacea</i>	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)	Hardness (mg/L as CaCO ₃)	pH	Tissue	Duration	BCF or BAF	Reference
Freshwater Species									
Brook trout, <i>Salvelinus fontinalis</i>	30 d	Aluminum sulfate	214.0	~12.5	5.3	Whole body	14 d	142	Cleveland et al. 1991a
Brook trout, <i>Salvelinus fontinalis</i>	30 d	Aluminum sulfate	223.5	~12.5	6.1	Whole body	14 d	104	Cleveland et al. 1991a
Brook trout, <i>Salvelinus fontinalis</i>	30 d	Aluminum sulfate	267.6	~12.5	7.2	Whole body	56 d	14.2	Cleveland et al. 1991a
Atlantic salmon, <i>Salmo salar</i>	larva	Aluminum sulfate	33	12.8	5.5	Whole body	60 d (embryo to post-hatch)	76	Buckler et al. 1995
Atlantic salmon, <i>Salmo salar</i>	larva	Aluminum sulfate	71	12.8	5.5	Whole body	60 d (embryo to post-hatch)	154	Buckler et al. 1995
Atlantic salmon, <i>Salmo salar</i>	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	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, <i>Aphanizomenon flos-aquae</i>	Aluminum sulfate	22 hr	-	8	IC50 (nitrogen fixation)	>3,942	Peterson et al. 1995	Duration
Green alga, <i>Dunaliella acidophila</i>	Aluminum chloride	4-5 d	-	1.0	IC50 (photosynthesis)	>269,800	Gimmler et al. 1991	Lack of exposure details
Green alga, <i>Dunaliella acidophila</i>	Aluminum chloride	4-5 d	-	7.0	IC50 (photosynthesis)	134,900	Gimmler et al. 1991	Lack of exposure details
Green alga, <i>Dunaliella acidophila</i>	Aluminum chloride	4-5 d	-	1.0	IC50 (growth)	>269,800	Gimmler et al. 1991	Lack of exposure details
Green alga, <i>Dunaliella parva</i>	Aluminum chloride	4-5 d	-	7.0	IC50 (photosynthesis)	26,980	Gimmler et al. 1991	Lack of exposure details
Green alga, <i>Dunaliella parva</i>	Aluminum chloride	4-5 d	-	5.5	IC50 (growth)	1,619	Gimmler et al. 1991	Lack of exposure details
Green alga, <i>Chlorella sp.</i>	Aluminum sulfate	72 hr	1.0 (DOC = 1 mg/L)	5.0	IC50 (growth)	275	Trenfield et al. 2012	Duration
Green alga, <i>Chlorella sp.</i>	Aluminum sulfate	72 hr	1.0 (DOC = 2 mg/L)	5.0	IC50 (growth)	613	Trenfield et al. 2012	Duration
Green alga, <i>Chlorella sp.</i>	Aluminum sulfate	72 hr	4.1 (DOC = 1 mg/L)	5.0	IC50 (growth)	437	Trenfield et al. 2012	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Chlorella sp.</i>	Aluminum sulfate	72 hr	4.1 (DOC = 2 mg/L)	5.0	IC50 (growth)	801	Trenfield et al. 2012	Duration
Green alga, <i>Chlorella pyrenoidosa</i>	Aluminum sulfate	26 d	-	4.6	Reduced growth	6,000-12,000 (NOEC-LOEC)	Foy and Gerloff 1972	pH too low
Green alga, <i>Chlorella pyrenoidosa</i>	Aluminum chloride	5 d	-	5.0	Growth	50-100 (NOEC-LOEC)	Parent and Campbell 1994	pH too low
Green alga, <i>Chlorella vulgaris</i>	Aluminum chloride	3-4 mo.	-	<7.0	Inhibited growth	4,000	De Jong 1965	Lack of exposure details
Green alga, <i>Chlorella vulgaris</i>	Aluminum chloride	15 d	-	6.8	LC50	107,952	Rai et al. 1998	Lack of exposure details
Green alga, <i>Chlorella vulgaris</i>	Aluminum chloride	15 d	-	6.0	LC50	5,937	Rai et al. 1998	Lack of exposure details
Green alga, <i>Chlorella vulgaris</i>	Aluminum chloride	3 d	-	4.5	LC50	4,048	Rai et al. 1998	Lack of exposure details
Green alga, <i>Monoraphidium dybowskii</i>	Aluminum chloride	9 d	-	5.0	IC56 (growth rate)	1,800	Tornqvist and Claesson 1987	Atypical endpoint
Green alga, <i>Monoraphidium dybowskii</i>	Aluminum chloride	9 d	-	5.0	IC42 (growth rate)	560	Tornqvist and Claesson 1987	Atypical endpoint
Green alga, <i>Desmodesmus subspicatus</i>	Aluminum chloride	72 hr	-	-	EC50 (growth) - flask	2,206	Eisentraeger et al. 2003	Duration
Green alga, <i>Desmodesmus subspicatus</i>	Aluminum chloride	72 hr	-	-	EC50 (growth) - flask	2,894	Eisentraeger et al. 2003	Duration
Green alga, <i>Desmodesmus subspicatus</i>	Aluminum chloride	72 hr	-	-	EC50 (growth) - 24 well microplate	2,834	Eisentraeger et al. 2003	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Desmodesmus subspicatus</i>	Aluminum chloride	72 hr	-	-	EC50 (growth) - 24 well microplate	3,340	Eisentraeger et al. 2003	Duration
Green alga, <i>Desmodesmus subspicatus</i>	Aluminum chloride	72 hr	-	-	EC50 (growth) - 96 well microplate	2,773	Eisentraeger et al. 2003	Duration
Green alga, <i>Desmodesmus subspicatus</i>	Aluminum chloride	72 hr	-	-	EC50 (growth) - 96 well microplate	2,915	Eisentraeger et al. 2003	Duration
Green alga, <i>Desmodesmus subspicatus</i>	Aluminum chloride	72 hr	-	-	EC50 (biomass) - flask	2,028	Eisentraeger et al. 2003	Duration
Green alga, <i>Desmodesmus subspicatus</i>	Aluminum chloride	72 hr	-	-	EC50 (biomass) - flask	2,423	Eisentraeger et al. 2003	Duration
Green alga, <i>Desmodesmus subspicatus</i>	Aluminum chloride	72 hr	-	-	EC50 (unidentified) - flask	2,605	Eisentraeger et al. 2003	Duration
Green alga, <i>Desmodesmus subspicatus</i>	Aluminum chloride	72 hr	-	-	EC50 (unidentified) - flask	2,467	Eisentraeger et al. 2003	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	6.25	EC50 (biomass)	28.3	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	7.23- 7.26	EC50 (biomass)	155.5	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	8.05- 8.12	EC50 (biomass)	851.4	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	6.29- 6.30	EC50 (biomass)	76.4	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	7.12- 7.13	EC50 (biomass)	232.9	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	7.90- 8.12	EC50 (biomass)	516.2	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	6.22- 6.24	EC50 (biomass)	74.2	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	7.10- 7.13	EC50 (biomass)	226.3	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	7.94- 8.11	EC50 (biomass)	366.9	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	6.25	EC50 (growth rate)	72.1	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	7.23- 7.26	EC50 (growth rate)	345.6	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 0 mg/L)	8.05- 8.12	EC50 (growth rate)	1,351.8	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	6.29- 6.30	EC50 (growth rate)	206.2	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	7.12- 7.13	EC50 (growth rate)	584.0	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 0 mg/L)	7.90- 8.12	EC50 (growth rate)	1,607.2	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	6.22- 6.24	EC50 (growth rate)	323.4	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	7.10- 7.13	EC50 (growth rate)	550.1	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 0 mg/L)	7.94- 8.11	EC50 (growth rate)	889.1	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	6.19- 6.23	EC50 (biomass)	669.9	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	6.96- 7.05	EC50 (biomass)	1,815.8	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	7.74- 7.96	EC50 (biomass)	2,157.0	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	6.13- 6.19	EC50 (biomass)	1,030.1	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	6.97- 7.04	EC50 (biomass)	2,266.7	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	7.82- 8.04	EC50 (biomass)	927.1	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	6.09- 6.18	EC50 (biomass)	1,451.5	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	6.94- 7.12	EC50 (biomass)	2,591.7	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	7.87- 8.05	EC50 (biomass)	774.2	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	6.19- 6.23	EC50 (growth rate)	1,181.1	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	6.96- 7.05	EC50 (growth rate)	2,896.0	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 2 mg/L)	7.74- 7.96	EC50 (growth rate)	4,980.9	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	6.13- 6.19	EC50 (growth rate)	1,473.5	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	6.97- 7.04	EC50 (growth rate)	4,332.3	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 2 mg/L)	7.82- 8.04	EC50 (growth rate)	2,000.0	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	6.09- 6.18	EC50 (growth rate)	2,100.1	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	6.94- 7.12	EC50 (growth rate)	3,645.8	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 2 mg/L)	7.87- 8.05	EC50 (growth rate)	1,639.9	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	6.09- 6.19	EC50 (biomass)	778.2	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	6.98- 7.10	EC50 (biomass)	2,630.2	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	7.82- 7.98	EC50 (biomass)	2,229.7	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	6.10- 6.19	EC50 (biomass)	1,273.7	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	7.0- 7.05	EC50 (biomass)	2,736.4	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	7.78- 7.87	EC50 (biomass)	1,660.2	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	6.09- 6.24	EC50 (biomass)	1,572.8	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	7.0- 7.09	EC50 (biomass)	3,546.2	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	7.77- 7.81	EC50 (biomass)	1,521.2	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	6.09- 6.19	EC50 (growth rate)	1,443.9	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	6.98- 7.10	EC50 (growth rate)	3,845.9	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	24.3 (DOC = 4 mg/L)	7.82- 7.98	EC50 (growth rate)	4,716.1	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	6.10- 6.19	EC50 (growth rate)	1,890.7	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	7.0- 7.05	EC50 (growth rate)	4,260.0	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	60 (DOC = 4 mg/L)	7.78- 7.87	EC50 (growth rate)	2,905.0	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	6.09- 6.24	EC50 (growth rate)	2,429.3	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	7.0- 7.09	EC50 (growth rate)	4,930.0	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	120 (DOC = 4 mg/L)	7.77- 7.81	EC50 (growth rate)	2,556.3	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Solution aged 3 hr (DOC = 0 mg/L)	6.23- 6.24	EC50 (growth)	196.2	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Solution aged 27 hr (DOC = 0 mg/L)	6.12- 6.23	EC50 (growth)	182.7	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Solution aged 3 hr (DOC = 0 mg/L)	7.93- 8.06	EC50 (growth)	1,762.4	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Solution aged 27 hr (DOC = 0 mg/L)	7.93- 8.23	EC50 (growth)	1,328.0	European AI Association 2009; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Medium not buffered (DOC = 0 mg/L)	7.80- 8.21	EC50 (growth rate)	1,282.1	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	8.05- 8.12	EC50 (growth rate)	1,351.8	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	7.99- 8.08	EC50 (growth rate)	1,476.6	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	7.65- 7.70	EC50 (growth rate)	1,417.9	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Medium not buffered (DOC = 0 mg/L)	7.80-8.21	EC50 (biomass)	626.6	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	8.05-8.12	EC50 (biomass)	851.4	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	7.99-8.08	EC50 (biomass)	717.9	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Duration
Green alga, <i>Pseudokirchneriella subcapitata</i>	Aluminum nitrate	72 hr	Medium HEPES buffered (DOC = 0 mg/L)	7.65-7.70	EC50 (biomass)	563.3	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Duration
Red alga, <i>Cyanidium caldarium</i>	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, <i>Euglena gracilis</i>	Aluminum chloride	10 min	-	6.0-7.0	Some survival	111,800	Ruthven and Cairns 1973	Single-cell organism
Protozoa (1 wk), <i>Euglena gracilis</i>	Aluminum chloride	7 d	-	-	Growth	10,000-15,000 (NOEC-LOEC)	Danilov and Ekelund 2002	Single-cell organism
Protozoa, <i>Chilomonas paramecium</i>	Aluminum chloride	10 min	-	5.5-7.4	Some survival	110	Ruthven and Cairns 1973	Single-cell organism
Protozoa, <i>Microregma heterostoma</i>	Aluminum chloride	28 hr	-	7.5-7.8	Incipient inhibition	12,000	Bringmann and Kuhn 1959a	Single-cell organism

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Protozoa, <i>Peranema trichoporum</i>	Aluminum chloride	10 min	-	5.5- 6.5	Some survival	62,600	Ruthven and Cairns 1973	Single-cell organism
Protozoa, <i>Tetrahymena pyriformis</i>	Aluminum chloride	10 min	-	5.5- 6.5	Some survival	100	Ruthven and Cairns 1973	Single-cell organism
Protozoa, <i>Tetrahymena pyriformis</i>	Aluminum chloride	96 hr	-	6.5	IC50 (growth)	15,000	Sauvant et al. 2000	Single-cell organism
Protozoa, <i>Tetrahymena pyriformis</i>	Aluminum sulfate	96 hr	-	6.5	IC50 (growth)	10,000	Sauvant et al. 2000	Single-cell organism
Protozoa, <i>Tetrahymena pyriformis</i>	Aluminum nitrate	96 hr	-	6.5	IC50 (growth)	14,000	Sauvant et al. 2000	Single-cell organism
Rotifer (0-2 hr), <i>Brachionus calyciflorus</i>	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), <i>Caenorhabditis elegans</i>	Aluminum nitrate	-	-	-	LC50	1,800	Williams and Dusenbery 1990	Test species fed
Nematode, <i>Caenorhabditis elegans</i>	Aluminum nitrate	24 hr	-	4.5- 6.5	LC50	49,000	Dhawan et al. 2000	Duration; test species fed
Nematode, <i>Caenorhabditis elegans</i>	Aluminum nitrate	24 hr	-	4.5- 6.5-	EC50 (movement)	3,000	Dhawan et al. 2000	Duration; test species fed
Nematode, <i>Caenorhabditis elegans</i>	Aluminum chloride	48 hr	-	-	LC50	18,150	Chu and Chow 2002	Duration
Nematode (adult), <i>Caenorhabditis elegans</i>	Aluminum chloride	4 hr	-	-	EC50 (rate of movement)	1,241	Anderson et al. 2004	Duration
Tubificid worm, <i>Tubifex tubifex</i>	Aluminum ammonium sulfate	96 hr	245	7.6	EC50 (death and immobility)	50,230	Khargarot 1991	Inappropriate form of toxicant
Planarian (adult), <i>Dugesia tigrina</i>	Aluminum chloride	48 hr	47.4	7.48	Mortality	>16,600 (NOEC)	Brooke 1985	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Planarian, <i>Dugesia tigrina</i>	-	48 hr	~47.42	7.48	LC50	>23,200	Lange 1985	Duration
Brown hydra, <i>Hydra oligactis</i>	Aluminum sulfate	72 hr	-	-	86% mortality	475,000	Kovacevic et al. 2007	Duration
Brown hydra, <i>Hydra oligactis</i>	Aluminum sulfate	72 hr	-	-	Tail growth	250,000 (LOEC)	Kovacevic et al. 2007	Duration; atypical endpoint
Green hydra, <i>Hydra viridissima</i>	Aluminum sulfate	72 hr	-	-	LC50	475,000- 480,000	Kovacevic et al. 2007	Duration
Green hydra, <i>Hydra viridissima</i>	Aluminum sulfate	72 hr	-	-	Tail growth	250,000- 475,000 (NOEC-LOEC)	Kovacevic et al. 2007	Duration; atypical endpoint
Green hydra, <i>Hydra viridissima</i>	Aluminum nitrate	7 d	1.0 (DOC = 1 mg/L)	5.0	IC50 (population growth rate)	56	Trenfield et al. 2012	Duration
Green hydra, <i>Hydra viridissima</i>	Aluminum nitrate	7 d	1.0 (DOC = 2 mg/L)	5.0	IC50 (population growth rate)	90	Trenfield et al. 2012	Duration
Green hydra, <i>Hydra viridissima</i>	Aluminum nitrate	7 d	4.1 (DOC = 1 mg/L)	5.0	IC50 (population growth rate)	152	Trenfield et al. 2012	Duration
Green hydra, <i>Hydra viridissima</i>	Aluminum nitrate	7 d	4.1 (DOC = 2 mg/L)	5.0	IC50 (population growth rate)	166	Trenfield et al. 2012	Duration
Snail, <i>Amnicola limosa</i>	Aluminum	96 hr	15.3	3.5	LC50	>1,000	Mackie 1989	pH too low
Snail, <i>Amnicola limosa</i>	Aluminum	96 hr	15.3	4.0	LC50	>400	Mackie 1989	pH too low
Snail, <i>Amnicola limosa</i>	Aluminum	96 hr	15.3	4.5	LC50	>400	Mackie 1989	pH too low

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Snail (adult, 3.5-5.6 g), <i>Lymnaea stagnalis</i>	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), <i>Lymnaea stagnalis</i>	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), <i>Lymnaea stagnalis</i>	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), <i>Lymnaea stagnalis</i>	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), <i>Dreissena polymorpha</i>	Aluminum sulfate	24 hr	137.1	7.42- 7.48	LC50	130,500	Mackie and Kilgour 1995	Duration
Pea cockle, <i>Pisidium casertanum</i>	-	96 hr	15.3	3.5	LC50	>1,000	Mackie 1989	pH too low
Pea cockle, <i>Pisidium casertanum</i>	-	96 hr	15.3	4.0	LC50	>400	Mackie 1989	pH too low
Pea cockle, <i>Pisidium casertanum</i>	-	96 hr	15.3	4.5	LC50	>400	Mackie 1989	pH too low
Ridged-beak peaclam, <i>Pisidium compressum</i>	-	96 hr	15.3	3.5	LC50	>1,000	Mackie 1989	pH too low
Ridged-beak peaclam, <i>Pisidium compressum</i>	-	96 hr	15.3	4.0	LC50	>400	Mackie 1989	pH too low
Ridged-beak peaclam, <i>Pisidium compressum</i>	-	96 hr	15.3	4.5	LC50	>400	Mackie 1989	pH too low
Cladoceran (<24 hr), <i>Ceriodaphnia sp.</i>	Aluminum chloride	8 d	47.4	7.68	LC50	8,600	Call et al. 1984	Duration
Cladoceran (<24 hr), <i>Ceriodaphnia sp.</i>	Aluminum chloride	48 hr	47.4	7.68	LC50	3,690	Call et al. 1984	Species not defined; other data available for the genus

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Cladoceran (<24 hr), <i>Ceriodaphnia sp.</i>	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), <i>Ceriodaphnia sp.</i>	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, <i>Ceriodaphnia dubia</i>	Aluminum chloride	LC (3 broods)	90 (80-100)	-	IC25 (reproduction)	566	Zuiderveen and Birge 1997	Unmeasured chronic exposure
Cladoceran, <i>Ceriodaphnia dubia</i>	Aluminum chloride	LC (3 broods)	90 (80-100)	-	IC25 (reproduction)	641	Zuiderveen and Birge 1997	Unmeasured chronic exposure
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	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 AI Association 2009	Unmeasured chronic exposure
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	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 AI Association 2009	Unmeasured chronic exposure
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	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 AI Association 2009	Unmeasured chronic exposure
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	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 AI Association 2009	Unmeasured chronic exposure
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	Aluminum nitrate	LC (3 broods)	25 (DOC = 0 mg/L)	6.33- 6.35	Reproduction - # of juveniles	62.5-125 (NOEC-LOEC)	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Unmeasured chronic exposure

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	Aluminum nitrate	LC (3 broods)	25 (DOC = 2 mg/L)	6.33- 6.35	Reproduction - # of juveniles	500-1,000 (NOEC-LOEC)	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Unmeasured chronic exposure
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	Aluminum nitrate	LC (3 broods)	25 (DOC = 4 mg/L)	6.32- 6.34	Reproduction - # of juveniles	500-1,000 (NOEC-LOEC)	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Unmeasured chronic exposure
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	Aluminum nitrate	LC (3 broods)	60 (DOC = 0 mg/L)	6.39- 6.40	Reproduction - # of juveniles	125-250 (NOEC-LOEC)	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Unmeasured chronic exposure
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	Aluminum nitrate	LC (3 broods)	60 (DOC = 2 mg/L)	6.36- 6.38	Reproduction - # of juveniles	500-1,000 (NOEC-LOEC)	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Unmeasured chronic exposure
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	Aluminum nitrate	LC (3 broods)	60 (DOC = 4 mg/L)	6.12- 6.37	Reproduction - # of juveniles	500-1,000 (NOEC-LOEC)	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Unmeasured chronic exposure
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	Aluminum nitrate	LC (3 broods)	120 (DOC = 0 mg/L)	6.37- 6.38	Reproduction - # of juveniles	100-200 (NOEC-LOEC)	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Unmeasured chronic exposure

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	Aluminum nitrate	LC (3 broods)	120 (DOC = 2 mg/L)	6.36- 6.38	Reproduction - # of juveniles	500-1,000 (NOEC-LOEC)	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Unmeasured chronic exposure
Cladoceran (<24 hr), <i>Ceriodaphnia dubia</i>	Aluminum nitrate	LC (3 broods)	120 (DOC = 4 mg/L)	6.37- 6.39	Reproduction - # of juveniles	1,000-2,000 (NOEC-LOEC)	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Unmeasured chronic exposure
Cladoceran (mature), <i>Daphnia catawba</i>	Aluminum chloride	72 hr	8.07	6.5	Reduced survival	1,020	Havas and Likens 1985b	Duration
Cladoceran (<8 hr), <i>Daphnia magna</i>	Aluminum sulfate	16 hr	-	-	Incipient immobilization	10,717	Anderson 1944	Duration
Cladoceran (<8 hr), <i>Daphnia magna</i>	Potassium aluminum sulfate	16 hr	-	-	Incipient immobilization	15,677	Anderson 1944	Duration, inappropriate form of toxicant
Cladoceran, <i>Daphnia magna</i>	Aluminum chloride	48 hr	-	7.5	Toxic effect	1,000,000	Bringmann and Kuhn 1959a	Endpoint not clearly defined
Cladoceran (≥12 hr), <i>Daphnia magna</i>	Aluminum chloride	21 d	45.3	7.74	EC16 (reduced reproduction)	320	Biesinger and Christensen 1972	Unmeasured chronic exposure
Cladoceran (≥12 hr), <i>Daphnia magna</i>	Aluminum chloride	21 d	45.3	7.74	EC50 (reduced reproduction)	680	Biesinger and Christensen 1972	Unmeasured chronic exposure
Cladoceran (≥12 hr), <i>Daphnia magna</i>	Aluminum chloride	21 d	45.3	7.74	LC50	1,400	Biesinger and Christensen 1972	Unmeasured chronic exposure
Cladoceran, <i>Daphnia magna</i>	Sodium aluminate	96 hr	27	7	Mortality	>40,000	Peterson et al. 1974	LC50 or EC50 endpoint not defined
Cladoceran (≥12 hr), <i>Daphnia magna</i>	Aluminum sulfate	28 d	220	8.3	Reproduction	4,260 (NOEC)	Kimball 1978	Control survival (70%)

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Cladoceran (≥12 hr), <i>Daphnia magna</i>	Aluminum sulfate	28 d	220	8.3	Survival	540-1,020 (NOEC-LOEC)	Kimball 1978	Control survival (70%)
Cladoceran (0-24 hr), <i>Daphnia magna</i>	-	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]
Cladoceran (14 d), <i>Daphnia magna</i>	-	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, <i>Daphnia magna</i>	-	28 d	-	-	LC50	38,000	Stephan 1978	Author reported that the results are considered questionable for one reason or another [not provided]
Cladoceran, <i>Daphnia magna</i>	Aluminum chloride	48 hr	45.4	7.61	EC50	>25,300	Brooke 1985	No dose response observed
Cladoceran, <i>Daphnia magna</i>	Aluminum chloride	48 hr	8.26	6.5	Mortality	320	Havas 1985	Dilution water is lake water, atypical endpoint
Cladoceran, <i>Daphnia magna</i>	Aluminum chloride	24 hr	8.26	6.5	BCF = 18,000	20	Havas 1985	Duration, lack of exposure details; dilution water is lake water

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Cladoceran, <i>Daphnia magna</i>	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, <i>Daphnia magna</i>	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
Cladoceran, <i>Daphnia magna</i>	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, <i>Daphnia magna</i>	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, <i>Daphnia magna</i>	Aluminum chloride	48 hr	-	6.5	Loss of sodium	1,020	Havas and Likens 1985a	Dilution water is lake water, atypical endpoint
Cladoceran, <i>Daphnia magna</i>	Aluminum ammonium sulfate	48 hr	240	7.6	LC50	59,600	Khangarot and Ray 1989	Inappropriate form of toxicant
Cladoceran (<24 hr), <i>Daphnia magna</i>	Aluminum nitrate	LC (3 broods)	140 (DOC = 2 mg/L)	6.27- 6.32	Reproduction - # of juveniles	600-1,200 (NOEC-LOEC)	European AI Association 2010; Gensemer et al. 2017 (Manuscript)	Unmeasured chronic exposure
Isopod (7 mm), <i>Asellus aquaticus</i>	Aluminum sulfate	72 hr	50	6.75	LC50	4,370	Martin and Holdich 1986	Duration
Amphipod, <i>Gammarus pseudolimnaeus</i>	Aluminum chloride	96 hr	47.4	7.53	LC50	22,000	Call et al. 1984	Test species fed

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Amphipod, <i>Hyalella azteca</i>	-	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, <i>Hyalella azteca</i>	-	96 hr	15.3	5.5	LC50	>400	Mackie 1989	Not enough information in the paper to determine is acceptable test conditions are met
Amphipod, <i>Hyalella azteca</i>	-	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), <i>Hyalella azteca</i>	-	7 d	18	7.39- 8.27	LC50	89	Borgmann et al. 2005	Duration, control mortality (≥80 %)
Amphipod (1-11 d), <i>Hyalella azteca</i>	-	7 d	-	8.21- 8.46	LC50	>3,150	Borgmann et al. 2005	Duration, control mortality (≥80 %)
Crayfish (80-160 cm), <i>Pacifastacus leniusculus</i>	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), <i>Pacifastacus leniusculus</i>	Aluminum nitrate	20 d	-	-	BCF = 527.5 (gill content)	436	Alexopoulos et al. 2003	Gill content not whole body
Crayfish (larvae), <i>Procambarus clarkii</i>	-	30 min	-	-	Oxygen consumption	>100,000 (NOEC)	Becker and Keller 1983	Duration
Caddisfly (larva, 5th instar), <i>Arctopsyche ladogensis</i>	Aluminum sulfate	4 d	-	5.0	EC50 (frequency of abnormalities)	938-1,089	Vuori 1996	Atypical endpoint, effect range reported

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Damselfly, <i>Enallagma sp.</i>	-	96 hr	15.3	3.5	LC50	>1,000	Mackie 1989	pH too low
Damselfly, <i>Enallagma sp.</i>	-	96 hr	15.3	4.0	LC50	>400	Mackie 1989	pH too low
Damselfly, <i>Enallagma sp.</i>	-	96 hr	15.3	4.5	LC50	>400	Mackie 1989	pH too low
Midge (1st instar larva, 3d), <i>Chironomus riparius</i>	Aluminum nitrate	10 d	91	6.5- 6.7	Survival	4,281.8- >4,281.9 (NOEC-LOEC)	OSU 2012f; Cardwell et al. 2017 (Manuscript)	Duration
Midge (1st instar larva, 3d), <i>Chironomus riparius</i>	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. 2017 (Manuscript)	Duration
Midge, <i>Paratanytarsus dissimilis</i>	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), <i>Libellula julia</i>	Aluminum chloride	96 hr	-	4	Oxygen uptake inhibition	3,000-30,000 (NOEC-LOEC)	Rockwood et al. 1990	Atypical endpoint
Golden trout (egg), <i>Oncorhynchus aguabonita aguabonita</i>	Aluminum sulfate	7 d	42.5	5.0	Survival	>300 (NOEC)	DeLonay et al. 1993	Duration
Golden trout (alevin), <i>Oncorhynchus aguabonita aguabonita</i>	Aluminum sulfate	7 d	42.5	5.0	Survival	97-293 (NOEC-LOEC)	DeLonay et al. 1993	Duration
Golden trout (swim-up larvae), <i>Oncorhynchus aguabonita aguabonita</i>	Aluminum sulfate	7 d	42.5	5.0	Survival	97-293 (NOEC-LOEC)	DeLonay et al. 1993	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Cutthroat trout (egg/embryo), <i>Oncorhynchus clarkii</i>	-	7 d	42.5	5	Survival	300->300 (NOEC-LOEC)	Woodward et al. 1989	Duration
Cutthroat trout (egg/embryo), <i>Oncorhynchus clarkii</i>	-	7 d	42.5	5	Growth	300->300 (NOEC-LOEC)	Woodward et al. 1989	Duration
Cutthroat trout (alevin, 2 d post hatch), <i>Oncorhynchus clarkii</i>	-	7 d	42.5	5	Survival	50-100 (NOEC-LOEC)	Woodward et al. 1989	Duration
Cutthroat trout (alevin/larvae), <i>Oncorhynchus clarkii</i>	-	7 d	42.5	5	Growth	50->50 (NOEC-LOEC)	Woodward et al. 1989	Duration
Cutthroat trout (swim-up larvae), <i>Oncorhynchus clarkii</i>	-	7 d	42.5	5	Survival	<50-50 (NOEC-LOEC)	Woodward et al. 1989	Duration
Rainbow trout (fingerling), <i>Oncorhynchus mykiss</i>	Aluminum chloride	-	28.3	8.48	LT50=7.46 d	5,140	Freeman and Everhart 1971	Atypical endpoint, test species fed
Rainbow trout (fingerling), <i>Oncorhynchus mykiss</i>	Aluminum chloride	-	28.3	8.99	LT50=2.96 d	5,200	Freeman and Everhart 1971	Atypical endpoint, test species fed
Rainbow trout (fingerling), <i>Oncorhynchus mykiss</i>	Aluminum chloride	-	46.8	8.02	LT50=31.96 d	5,230	Freeman and Everhart 1971	Atypical endpoint, test species fed
Rainbow trout (fingerling), <i>Oncorhynchus mykiss</i>	Aluminum chloride	-	56.6	6.8	LT50=38.90 d	5,140	Freeman and Everhart 1971	Atypical endpoint, test species fed
Rainbow trout (fingerling), <i>Oncorhynchus mykiss</i>	Aluminum chloride	-	56.6	6.52	LT50=43.90 d	513	Freeman and Everhart 1971	Atypical endpoint, test species fed
Rainbow trout (embryo), <i>Oncorhynchus mykiss</i>	Aluminum chloride	Fert. to hatch	-	7.0- 9.0	No reduced fertility	5,200	Freeman and Everhart 1971	Lack of exposure details

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Rainbow trout (embryo/larvae), <i>Oncorhynchus mykiss</i>	Aluminum chloride	28 d	104	7.4	EC50 (death and deformity)	560	Birge 1978; Birge et al. 1978	Duration
Rainbow trout (juvenile), <i>Oncorhynchus mykiss</i>	Aluminum sulfate	10 d	25	7	0% dead	200,000	Hunter et al. 1980	Duration, test species fed
Rainbow trout (juvenile), <i>Oncorhynchus mykiss</i>	Aluminum sulfate	96 hr	25	8	40% dead	50,000	Hunter et al. 1980	Lack of exposure details
Rainbow trout (juvenile), <i>Oncorhynchus mykiss</i>	Aluminum sulfate	42 hr	25	8.5	100% dead	50,000	Hunter et al. 1980	Duration; lack of exposure details
Rainbow trout (juvenile), <i>Oncorhynchus mykiss</i>	Aluminum sulfate	42 hr	25	9	100% dead	50,000	Hunter et al. 1980	Duration; lack of exposure details
Rainbow trout, <i>Oncorhynchus mykiss</i>	-		-	5.0	LC50	160	Holtze 1983	pH too low
Rainbow trout, <i>Oncorhynchus mykiss</i>	-		-	4.5	LC50	120	Holtze 1983	pH too low
Rainbow trout (embryo/larvae), <i>Oncorhynchus mykiss</i>	Aluminum sulfate	8 d	14.3	6.5	No effect	1,000	Holtze 1983	Duration, lack of exposure details
Rainbow trout (embryo/larvae), <i>Oncorhynchus mykiss</i>	Aluminum sulfate	8 d	14.3	7.2	No effect	1,000	Holtze 1983	Duration, lack of exposure details
Rainbow trout (eyed embryo), <i>Oncorhynchus mykiss</i>	Aluminum sulfate	8 d	14.3	6.5	14.2% dead	1,000	Holtze 1983	Duration, lack of exposure details
Rainbow trout (eyed embryo), <i>Oncorhynchus mykiss</i>	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), <i>Oncorhynchus mykiss</i>	Aluminum sulfate	24 hr	-	6	Opercula rate	200-500 (NOEC-LOEC)	Ogilvie and Stechey 1983	Duration, atypical endpoint
Rainbow trout (juvenile, 5-8 cm), <i>Oncorhynchus mykiss</i>	Aluminum sulfate	24 hr	-	6	Cough frequency	100-200 (NOEC-LOEC)	Ogilvie and Stechey 1983	Duration, atypical endpoint

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Rainbow trout (3.5 g), <i>Oncorhynchus mykiss</i>	Aluminum sulfate	6 d	11.2	5.09-5.31	LC50	175	Orr et al. 1986	Duration
Rainbow trout (92-220 g), <i>Oncorhynchus mykiss</i>	-	1 hr	-	5.4	Gill content (50 µg/g)	954	Handy and Eddy 1989	Duration
Rainbow trout (juvenile, 1-3 g), <i>Oncorhynchus mykiss</i>	Aluminum chloride	16 d	20.3	8.3	LC50	1,940	Gundersen et al. 1994	Duration
Rainbow trout (juvenile, 1-3 g), <i>Oncorhynchus mykiss</i>	Aluminum chloride	16 d	103.0	8.3	LC50	3,910	Gundersen et al. 1994	Duration
Rainbow trout (embryo), <i>Oncorhynchus mykiss</i>	Aluminum chloride	7-12 d	100	7.0-7.8	LC50	560	Birge et al. 2000	Duration
Atlantic salmon (eggs), <i>Salmo salar</i>	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), <i>Salmo salar</i>	-	7 d	10.4	4.5	LC50	88	Wilkinson et al. 1990	Duration
Atlantic salmon (eggs), <i>Salmo salar</i>	Aluminum sulfate	60 d	12.8	5.5	Time to hatch	>264 (NOEC)	Buckler et al. 1995	Atypical endpoint
Atlantic salmon (larva), <i>Salmo salar</i>	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), <i>Salmo salar</i>	Aluminum sulfate	5 d	10.6	4.47	LC50	259	Roy and Campbell 1995	Duration
Atlantic salmon (juvenile, 1.4 g), <i>Salmo salar</i>	Aluminum sulfate	5 d	10.6	4.42	LC50	283	Roy and Campbell 1995	Duration
Atlantic salmon (juvenile, 1.4 g), <i>Salmo salar</i>	Aluminum sulfate	5 d	10.6	4.83	LC50	121	Roy and Campbell 1995	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Atlantic salmon (juvenile, 1.4 g), <i>Salmo salar</i>	Aluminum sulfate	5 d	10.6	5.26	LC50	54	Roy and Campbell 1995	Duration
Atlantic salmon (juvenile, 1.4 g), <i>Salmo salar</i>	Aluminum sulfate	5 d	10.6	5.24	LC50	51	Roy and Campbell 1995	Duration
Atlantic salmon (juvenile, 6.8 g), <i>Salmo salar</i>	Aluminum sulfate	96 hr	10.6	4.86	LC50	75.54	Roy and Campbell 1995	pH too low
Atlantic salmon (juvenile, 1.8 g), <i>Salmo salar</i>	Aluminum sulfate	96 hr	10.6	4.99	LC50	79.60	Roy and Campbell 1997	pH too low
Atlantic salmon (juvenile, 1.8 g), <i>Salmo salar</i>	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), <i>Salvelinus fontinalis</i>	-	15 min	7.2	6.9	Avoidance	389	Gunn and Noakes 1986	Duration, atypical endpoint
Brook trout (juvenile), <i>Salvelinus fontinalis</i>	Aluminum hydroxide	24 d	8-10	4.4	Survival	<200-200 (NOEC-LOEC)	Siddens et al. 1986	Duration
Brook trout (juvenile), <i>Salvelinus fontinalis</i>	Aluminum hydroxide	24 d	8-10	4.9	Survival	<200-200 (NOEC-LOEC)	Siddens et al. 1986	Duration
Brook trout (1.5 yr), <i>Salvelinus fontinalis</i>	-	147 d	Ca = 8 mg/L	5.2	100% survival	54	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), <i>Salvelinus fontinalis</i>	-	147 d	Ca = 8 mg/L	5.2	93% survival	162	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), <i>Salvelinus fontinalis</i>	-	147 d	Ca = 8 mg/L	4.8	100% survival	162	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), <i>Salvelinus fontinalis</i>	-	147 d	Ca = 8 mg/L	4.8	50% survival	486	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), <i>Salvelinus fontinalis</i>	-	147 d	Ca = 0.5 mg/L	5.2	93% survival	54	Mount 1987	Unmeasured chronic exposure

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Brook trout (1.5 yr), <i>Salvelinus fontinalis</i>	-	147 d	Ca = 0.5 mg/L	5.2	86% survival	162	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), <i>Salvelinus fontinalis</i>	-	147 d	Ca = 0.5 mg/L	4.8	86% survival	162	Mount 1987	Unmeasured chronic exposure
Brook trout (1.5 yr), <i>Salvelinus fontinalis</i>	-	147 d	Ca = 0.5 mg/L	4.8	36% survival	486	Mount 1987	Unmeasured chronic exposure
Brook trout (eggs), <i>Salvelinus fontinalis</i>	Aluminum sulfate	60 d	12.5	5.5	Strike frequency	142-292 (NOEC-LOEC)	Cleveland et al. 1989	Atypical endpoint
Brook trout (eggs), <i>Salvelinus fontinalis</i>	Aluminum sulfate	60 d	12.5	6.5	Strike frequency	350->350 (NOEC-LOEC)	Cleveland et al. 1989	Atypical endpoint
Brook trout (1 yr), <i>Salvelinus fontinalis</i>	Aluminum chloride	28 d	250	4.4	Survival	131-332 (NOEC-LOEC)	Ingersoll et al. 1990a	Duration; pH too low
Goldfish (60-90 mm), <i>Carassius auratus</i>	Aluminum potassium sulfate	96 hr	-	6.8	Reduced survival time	5,700	Ellis 1937	Atypical endpoint; no LC50 reported
Goldfish (eggs), <i>Carassius auratus</i>	Aluminum chloride	7 d	195	7.4	EC50 (death and deformity)	150	Birge 1978	Duration
Goldfish (embryo), <i>Carassius auratus</i>	Aluminum chloride	7-12 d	100	7.0- 7.8	LC50	330	Birge et al. 2000	Duration
Common carp (95 g), <i>Cyprinus carpio</i>	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), <i>Hybognathus amarus</i>	Aluminum chloride	96 hr	140	8.1	EC50 (death and immobility)	>59,100	Buhl 2002	Atypical endpoint
Fathead minnow (juvenile), <i>Pimephales promelas</i>	Aluminum sulfate	8 d	220	7.3	LC50	22,400	Kimball 1978	Duration, test species fed

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Fathead minnow (juvenile), <i>Pimephales promelas</i>	Aluminum sulfate	96 hr	220	7.34	LC50	35,000	Kimball 1978	Test species fed
Fathead minnow (adult), <i>Pimephales promelas</i>	Aluminum chloride	-	-	-	50% reduction in AChE	18,000	Olson and Christensen 1980	Duration unknown, atypical endpoint
Fathead minnow (juvenile, 11 mm), <i>Pimephales promelas</i>	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), <i>Pimephales promelas</i>	Aluminum chloride	7 d	46	7.5	Growth (weight)	400-740 (NOEC-LOEC)	ENSR 1992a	Duration
Fathead minnow (larvae, <24 hr), <i>Pimephales promelas</i>	Aluminum chloride	7 d	194	8.2	Growth (weight)	630-700 (NOEC-LOEC)	ENSR 1992a	Duration
Fathead minnow (larva, 4-6 dph), <i>Pimephales promelas</i>	Aluminum chloride	96 hr	140	8.1	EC50 (death and immobility)	>59,100	Buhl 2002	Atypical endpoint
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	12 (DOC = <0.08 mg/L)	6.0	EC20 (mean dry biomass)	127.2	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	12 (DOC = 0.92 mg/L)	6.1	EC20 (mean dry biomass)	425.7	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	12 (DOC = 1.73 mg/L)	6.1	EC20 (mean dry biomass)	632.8	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	16 (DOC = 3.35 mg/L)	6.0	EC20 (mean dry biomass)	828.8	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	24 (DOC = 0.19 mg/L)	6.1	EC20 (mean dry biomass)	135.8	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	60 (DOC = 0.22 mg/L)	6.0	EC20 (mean dry biomass)	314.3	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	60 (DOC = 0.86 mg/L)	6.1	EC20 (mean dry biomass)	633.9	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	56 (DOC = 1.74 mg/L)	6.0	EC20 (mean dry biomass)	1,325.8	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	60 (DOC = 3.51 mg/L)	6.0	EC20 (mean dry biomass)	2,523	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	116 (DOC = 0.088 mg/L)	6.1	EC20 (mean dry biomass)	624.1	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	116 (DOC = 0.88 mg/L)	6.1	EC20 (mean dry biomass)	773.4	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	108 (DOC = 1.56 mg/L)	6.0	EC20 (mean dry biomass)	1,493.7	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Fathead minnow (larva, <24 hr), <i>Pimephales promelas</i>	Aluminum nitrate	7 d	112 (DOC = 3.27 mg/L)	6.0	EC20 (mean dry biomass)	2,938	OSU 2012a; Gensemer et al. 2017 (Manuscript)	Duration
Zebrafish (egg, 1 d), <i>Danio rerio</i>	Aluminum chloride	24 hr	40	5	Median day to hatch	16,400 (NOEC)	Dave 1985	Duration
Zebrafish (egg, 1 d), <i>Danio rerio</i>	Aluminum chloride	24 hr	40	6	Median day to hatch	16,400 (NOEC)	Dave 1985	Duration
Zebrafish (egg, 1 d), <i>Danio rerio</i>	Aluminum chloride	24 hr	40	7	Median day to hatch	16,400 (NOEC)	Dave 1985	Duration
Zebrafish (egg, 1 d), <i>Danio rerio</i>	Aluminum chloride	24 hr	40	8	Median day to hatch	16,400 (NOEC)	Dave 1985	Duration
Zebrafish (egg, 1 d), <i>Danio rerio</i>	Aluminum chloride	24 hr	40	9	Median survival time	<500-500 (NOEC-LOEC)	Dave 1985	Duration
Zebrafish (larva, 7-8 d), <i>Danio rerio</i>	Aluminum chloride	48 hr	40	7	LC50	106,000	Dave 1985	Duration
Zebrafish (larva, 7-8 d), <i>Danio rerio</i>	Aluminum chloride	48 hr	40	7.4- 7.9	LC50	80,000	Dave 1985	Duration
Zebrafish (3 cm, 5g), <i>Danio rerio</i>	Aluminum chloride	4 d	-	-	LC50	56,920	Anandhan and Hemalatha 2009	Lack of exposure details (assumed fed too)
Zebrafish (adult, female), <i>Danio rerio</i>	Aluminum chloride	48 hr	142	6.8	100% mortality	12,500	Griffitt et al. 2011	Duration
Zebrafish (adult, female), <i>Danio rerio</i>	Aluminum chloride	48 hr	142	6.8	No mortality	5,000	Griffitt et al. 2011	Duration
Smallmouth bass (eyed egg), <i>Micropterus dolomieu</i>	F, M	11 d	15.7	4.8	Survival	100-200 (NOEC-LOEC)	Holtze and Hutchinson 1989	Duration; pH too low
Largemouth bass (juvenile), <i>Micropterus salmoides</i>	Aluminum sulfate	7 d	64-80	6.6- 7.4	0% dead	50,000	Sanborn 1945	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Largemouth bass (eggs/fry), <i>Micropterus salmoides</i>	Aluminum chloride	8 d	93-105	7.2- 7.8	LC50	170	Birge et al. 1978	Duration
Largemouth bass (embryo), <i>Micropterus salmoides</i>	Aluminum chloride	7-12 d	100	7.0- 7.8	LC50	190	Birge et al. 2000	Duration
Striped bass (160 d), <i>Morone saxatilis</i>	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), <i>Morone saxatilis</i>	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), <i>Morone saxatilis</i>	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), <i>Esox lucius</i>	Aluminum sulfate	10 d	18	4	LC50	~160	Vuorinen et al. 1993	Duration, pH too low
Pike (yolk-sac fry), <i>Esox lucius</i>	Aluminum sulfate	10 d	18	4.25	LC50	~325	Vuorinen et al. 1993	Duration, pH too low
Pike (yolk-sac fry), <i>Esox lucius</i>	Aluminum sulfate	10 d	18	4.5	LC50	~600	Vuorinen et al. 1993	Duration, pH too low
Pike (yolk-sac fry), <i>Esox lucius</i>	Aluminum sulfate	10 d	18	4.75	LC50	~1,000	Vuorinen et al. 1993	Duration, pH too low
White sucker (eyed egg), <i>Catostomus commersoni</i>	-	96 hr	15.7	4.8	Survival	100-200 (NOEC-LOEC)	Holtze and Hutchinson 1989	Atypical endpoint; pH too low
Lake whitefish (cleavage egg), <i>Coregonus clupeaformis</i>	-	12 d	15.7	4.8	Survival	300 (NOEC)	Holtze and Hutchinson 1989	Duration; pH too low
Bullfrog (embryo), <i>Rana catesbeiana</i>	Aluminum chloride	10-12 d	100	7.0- 7.8	LC50	80	Birge et al. 2000	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Leopard frog (embryo, 3 hr, Gosner stage 3-4), <i>Rana pipiens</i>	Aluminum chloride	4-5 d	2.0	4.6	LC50	811	Freda and McDonald 1990	pH too low
Leopard frog (embryo, 3 hr, Gosner stage 3-4), <i>Rana pipiens</i>	Aluminum chloride	4-5 d	2.0	4.8	LC50	403	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, Gosner stage 20), <i>Rana pipiens</i>	Aluminum chloride	96 hr	2.0	4.4	LC50	>250	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, Gosner stage 20), <i>Rana pipiens</i>	Aluminum chloride	96 hr	2.0	4.6	LC50	>250	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, 3 wk), <i>Rana pipiens</i>	Aluminum chloride	96 hr	2.0	4.2	LC50	>1,000	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, 3 wk), <i>Rana pipiens</i>	Aluminum chloride	96 hr	2.0	4.4	LC50	>1,000	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, 3 wk), <i>Rana pipiens</i>	Aluminum chloride	96 hr	2.0	4.6	LC50	>1,000	Freda and McDonald 1990	pH too low
Leopard frog (tadpole, 3 wk), <i>Rana pipiens</i>	Aluminum chloride	96 hr	2.0	4.8	LC50	>1,000	Freda and McDonald 1990	pH too low
Leopard frog (embryos), <i>Rana pipiens</i>	Aluminum chloride	96 hr	2.0	4.8	LC50	471	Freda et al. 1990	pH too low
Leopard frog (embryo), <i>Rana pipiens</i>	Aluminum chloride	10-11 d	100	7.0-7.8	LC50	90	Birge et al. 2000	Duration
Wood frog (eggs), <i>Rana sylvatica</i>	-	24 hr	7.78	5.75	Hatch success	20->20 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
Wood frog (eggs), <i>Rana sylvatica</i>	-	24 hr	7.78	4.75	Hatch success	100->100 (NOEC-LOEC)	Clark and LaZerte 1985	Duration

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Wood frog (eggs), <i>Rana sylvatica</i>	-	24 hr	7.78	4.415	Hatch success	10-20 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
Wood frog (eggs), <i>Rana sylvatica</i>	-	24 hr	7.78	4.14- 5.75	Survival	200 (NOEC)	Clark and LaZerte 1985	Duration
Wood frog (larva, Gosner stage 25), <i>Rana sylvatica</i>	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), <i>Pseudacris crucifer</i>	Aluminum chloride	7 d	100	7.0- 7.8	LC50	90	Birge et al. 2000	Duration
Green tree frog (tadpole), <i>Hyla cinerea</i>	Aluminum chloride	96 hr	1.5	5.5	Growth	<150-150 (NOEC-LOEC)	Jung and Jagoe 1995	Atypical endpoint
Green tree frog (tadpole), <i>Hyla cinerea</i>	Aluminum chloride	96 hr	1.5	4.5	Growth	<150-150 (NOEC-LOEC)	Jung and Jagoe 1995	Atypical endpoint
Green tree frog (tadpole), <i>Hyla cinerea</i>	Aluminum chloride	96 hr	1.5	4.5	LC50	277	Jung and Jagoe 1995	pH too low
American toad (eggs), <i>Bufo americanus</i>	-	24 hr	7.78	5.75	Hatch success	20->20 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
American toad (eggs), <i>Bufo americanus</i>	-	24 hr	7.78	4.75	Hatch success	100->100 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
American toad (eggs), <i>Bufo americanus</i>	-	24 hr	7.78	4.14	Hatch success	5-10 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
American toad (eggs), <i>Bufo americanus</i>	-	24 hr	7.78	4.14	Hatch success	<10-10 (NOEC-LOEC)	Clark and LaZerte 1985	Duration
American toad (eggs), <i>Bufo americanus</i>	-	24 hr	7.78	4.14- 5.75	NOEC (survival)	200	Clark and LaZerte 1985	Duration
American toad (tadpoles, Gosner stage 26), <i>Bufo americanus</i>	Aluminum chloride	96 hr	2.0	4.5	LC50	672	Freda et al. 1990	pH too low

Species	Chemical	Duration	Hardness (mg/L as CaCO ₃)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Common toad (spawn, 0-48 hr), <i>Bufo bufo</i>	Aluminum nitrate	7 d	50	6.0	Survival	>320 (NOEC)	Gardner et al. 2002	Duration
Common toad (spawn, 0-48 hr), <i>Bufo bufo</i>	Aluminum nitrate	7 d	50	7.5	Survival	>320 (NOEC)	Gardner et al. 2002	Duration
Fowler's toad (embryo), <i>Bufo fowleri</i>	Aluminum chloride	7 d	100	7.0- 7.8	LC50	280	Birge et al. 2000	Duration
Narrow-mouthed toad (eggs), <i>Gastrophryne carolinensis</i>	Aluminum chloride	7 d	195	7.4	EC50 (death and deformity)	50	Birge 1978	Duration
Narrow-mouthed toad (eggs), <i>Gastrophryne carolinensis</i>	Aluminum chloride	7 d	100	7.0- 7.8	LC50	50	Birge et al. 2000	Duration
Marbled salamander (eggs), <i>Ambystoma opacum</i>	Aluminum chloride	8 d	93-105	7.2- 7.8	EC50 (death and deformity)	2,280	Birge et al. 1978	Duration
Marbled salamander (embryo), <i>Ambystoma opacum</i>	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, <i>Dunaliella tertiolecta</i>	Aluminum nitrate	72 hr	-	8.2	IC25 (inhibit growth)	18,160	Sacan et al. 2007	Duration
Phytoplankton, <i>Dunaliella tertiolecta</i>	Aluminum nitrate	72 hr	-	8.2	SC20 (stimulate growth)	4,660	Sacan et al. 2007	Duration
Polychaete worm, <i>Ctenodrilus serratus</i>	Aluminum chloride	21 d	-	7.6-8	Reproduction	20-40 (NOEC-LOEC)	Petrich and Reish 1979	Unmeasured chronic exposure
Sea urchin (embryo), <i>Paracentrotus lividus</i>	Aluminum sulfate	72 hr	-	-	69.7% developmental effects	539.6	Caplat et al. 2010	Difficult to determine effect concentration
Bay mussel (28.0 mm), <i>Mytilus edulis</i>	Alum (potassium)	24 hr	30	4.4-7.3	LC50	>6,400,000	Robinson and Perkins 1977	Duration
Common winkle (13.3 mm), <i>Littorina littorea</i>	Alum (potassium)	24 hr	30	4.4-7.3	LC50	>6,400,000	Robinson and Perkins 1977	Duration
European shore crab (12.6 mm), <i>Carcinus maenas</i>	Alum (potassium)	24 hr	30	4.4-7.3	LC50	2,500,000	Robinson and Perkins 1977	Duration
Hermit crab (11.4 mm), <i>Eupagurus bernhardus</i>	Alum (potassium)	24 hr	30	4.4-7.3	LC50	250,000	Robinson and Perkins 1977	Duration
Yellow crab (embryo, 4-lobed stage), <i>Cancer anthonyi</i>	-	7 d	34	7.8	Survival	<10,000-10,000 (NOEC-LOEC)	MacDonald et al. 1988	Duration, unmeasured chronic exposure

Species	Chemical	Duration	Salinity (g/kg)	pH	Effect	Concentration (µg/L)	Reference	Reason Other Data
Yellow crab (embryo, 4-lobed stage), <i>Cancer anthonyi</i>	-	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), <i>Palaemonetes pugio</i>	-	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, <i>Mytilus edulis</i> collected offshore from an aluminum smelter industry (Norway)	2008	Bay mussel, <i>Mytilus edulis</i>	-	Not applicable; no aluminum toxicity data
Abdelhamid and El-Ayouty	Effect of catfish (<i>Clarias lazera</i>) composition of ingestion rearing water contaminated with lead or aluminum compounds	1991	Catfish, <i>Clarias lazera</i>	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 (<i>Oreochromis niloticus</i>)	2008	Nile tilapia, <i>Oreochromis niloticus</i>	96 hr LC50=175.9	Dilution water not characterized; lack of exposure details
Abraham et al.	Quantified elemental changes in <i>Aspidisca cicada</i> and <i>Vorticella convallaria</i> after exposure to aluminum, copper, and zinc	1997	Protozoa, <i>Aspidisca cicada</i> Protozoa, <i>Vorticella convallaria</i>	-	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
Al-Aarajy and Al-Saadi	Effect of heavy metals on physiological and biochemical features of <i>Anabaena cylindrica</i>	1998	Blue-green alga, <i>Anabaena cylindrica</i>	-	Only one exposure concentration; lack of exposure details (duration not reported)
Alessa and Oliveira	Aluminum toxicity studies in <i>Vaucheria longicaulis</i> var. <i>macounii</i> (Xanthophyta, Tribophyceae). I. Effects on cytoplasmic organization	2001a	Alga, <i>Vaucheria longicaulis</i> var. <i>macouni</i>	10 hr 2,159 growth ceased	Only one exposure concentration
Alessa and Oliveira	Aluminum toxicity studies in <i>Vaucheria longicaulis</i> var. <i>macounii</i> (Xanthophyta, Tribophyceae). II. Effects on the F-Actin array	2001b	Alga, <i>Vaucheria longicaulis</i> var. <i>macouni</i>	-	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 (<i>Oncorhynchus mykiss</i>)	1999	Rainbow trout, <i>Oncorhynchus mykiss</i>	6 wk 29.2 Reduced appetite	Only one exposure concentration
Allin and Wilson	Effects of pre-acclimation to aluminum on the physiology and swimming behaviour of juvenile rainbow trout (<i>Oncorhynchus mykiss</i>) during a pulsed exposure	2000	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Pulsed exposures to pollutant

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Alquezar et al.	Metal accumulation in the smooth toadfish, <i>Tetractenos glaber</i> , in estuaries around Sydney, Australia	2006	Toadfish, <i>Tetractenos glaber</i>	-	Not North American species; exposed to mixture
Alstad et al.	The significance of water ionic strength on aluminum in brown trout (<i>Salmo trutta</i> L.)	2005	Brown trout, <i>Salmo trutta</i>	650 Survival time =16-34 hr	No acclimation to test water; only one exposure concentration
Amato et al.	Concentrations, sources and geochemistry of airborne particulate 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 <i>Daphnia magna</i> for chlorides of various metals when added to Lake Erie water	1948	Cladoceran, <i>Daphnia magna</i>	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 (<i>Salmo trutta</i> L.)	2012	Brown trout, <i>Salmo trutta</i>	-	Mixture; dilution water is river water
Andren et al.	Effects of pH and aluminum on embryonic and early larval stages of Swedish brown frogs <i>Rana arvalis</i> , <i>R. temporaria</i> and <i>R. dalmatina</i>	1988	Brown frog, <i>Rana arvalis</i> Brown frog, <i>Rana temporaria</i> Brown frog, <i>Rana dalmatina</i>	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
Arain et al.	Total dissolved and bioavailable elements in water and sediment samples and their accumulation in <i>Oreochromis mossambicus</i> of polluted Manchar Lake	2008	Mozambique tilapia, <i>Oreochromis mossambicus</i>	-	Survey
Arthur D. Little Inc.	Water quality criteria data book, volume 2; Inorganic chemical pollution of freshwater	1971	-	-	Review; results of previously published papers

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
ASCI Corp.	Aluminum water-effect ratio for the 3M Middleway plant effluent discharge, Middleway, West virginia	1994	Cladoceran, <i>Daphnia magna</i> Rainbow trout, <i>Oncorhynchus mykiss</i>	-	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, <i>Salmo trutta</i> , juveniles in concentration gradients of pH and Al - a laboratory study	1998	Atlantic salmon, <i>Salmo salar</i>	1 hr 200=avoidance, 70=no avoidance	Only two exposure concentrations
Atland and Barlaup	Avoidance behaviour of Atlantic salmo (<i>Salmo salar</i> L.) fry in waters of low pH and elevated aluminum concentration: laboratory experiments	1996	Atlantic salmon, <i>Salmo salar</i>	1 hr LC20=85, LC40=160	Only two exposure concentrations
Avis et al.	Ultrastructural alterations in <i>Fusarium sambucinum</i> and <i>Heterobasidion annosum</i> treated with aluminum chloride and sodium metabisulfite	2009	Fungus, <i>Fusarium sambucinum</i> Fungus, <i>Heterobasidion annosum</i>	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, <i>Dendraster excentricus</i> Purple urchin, <i>Strongylocentrotus purpuratus</i>	-	Mixture; effluent
Baker	Aluminum toxicity to fish as related to acid precipitation and Adirondack surface water quality	1981	Brook trout, <i>Salvelinus fontinalis</i> White sucker, <i>Catostomus commersoni</i>	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 (<i>Salvelinus fontinalis</i>) in the Catskill Mountains, New York	1997	Brook trout, <i>Salvelinus fontinalis</i>	-	Mixture; fluctuating Catskill mountain stream chemical exposure

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
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 <i>Lymnaea stagnalis</i> in neutral freshwater	2001	Snail, <i>Lymnaea stagnalis</i>	-	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 <i>Leporinus macrocephalus</i> (Anostomidae)	2004	Neotropical fish, <i>Leporinus macrocephalus</i>	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, <i>Salmo trutta</i> L.	1988	Brown trout, <i>Salmo trutta</i>	-	Acclimation too short; too few organisms per concentration
Beattie et al.	The effects of pH, aluminum concentration and temperature on the embryonic development of the European common frog, <i>Rana temporaria</i>	1992	European common frog, <i>Rana temporaria</i>	-	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 <i>Chlorella</i>	1973	Green alga, <i>Chlorella vulgaris</i>	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

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Berg and Burns	The distribution of aluminum in the tissues of three fish species	1985	Channel catfish, <i>Ictalurus punctatus</i> Largemouth bass, <i>Micropterus salmoides</i> Gizzard shad, <i>Dorosoma cepedianum</i>	-	Exposure concentration not known; field accumulation study
Bergman	Development of biologically relevant methods for determination of bioavailable aluminum in surface waters	1992	Rainbow trout, <i>Oncorhynchus mykiss</i> Brook trout, <i>Salvelinus fontinalis</i>	-	Mixture; Al and organic acids
Bergman and Mattice	Lake acidification and fisheries project: adult brook trout (<i>Salvelinus fontinalis</i>) early life stages	1990	Brook trout, <i>Salvelinus fontinalis</i>	-	Review; results of previously published papers
Bergman et al.	Lake acidification and fisheries project: adult brook trout (<i>Salvelinus fontinalis</i>)	1988	Brook trout, <i>Salvelinus fontinalis</i>	-	Review; results of previously published papers
Berntssen et al.	Responses of skin mucous cells to aluminum exposure at low pH in Atlantic salmon (<i>Salmo salar</i>) smolts	1997	Atlantic salmon, <i>Salmo salar</i>	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 (<i>Dreissena polymorpha</i>) to assess the bioavailability of microcontaminants in Flemish surface waters	2005	Zebra mussel, <i>Dreissena polymorpha</i>	-	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 bioassay 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
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, <i>Pimephales promelas</i>	50 Reduced feeding	Only two exposure concentrations
Bjerknes et al.	Aluminum in acidic river water causes mortality of farmed Atlantic salmon (<i>Salmo salar</i> L.) in Norwegian fjords	2003	Atlantic salmon, <i>Salmo salar</i>	-	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 <i>Lemna gibba</i>	1999	Duckweed, <i>Lemna gibba</i>	7 d NOEC(growth)= >29,000	Excessive EDTA used (>200 µg/L)

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Booth et al.	Effects of aluminum and low pH on net ion fluxes and ion balance in the brook trout (<i>Salvelinus fontinalis</i>)	1988	Brook trout, <i>Salvelinus fontinalis</i>	-	Mixture; low pH and Al
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, <i>Rana muscosa</i> Yosemite toad, <i>Bufo canorus</i>	No effect on hatch time or growth at 75; Effect on hatch time and decrease growth at 75	Only one exposure concentration
Brady and Griffiths	Effects of pH and aluminum on the growth and feeding behaviour of smooth and palmate newt larvae	1995	Newt, <i>Triturus helveticus</i> Newt, <i>Triturus vulgaris</i>	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 (<i>Salmo salar</i>) exposed to acidic water and aluminum	1999	Atlantic salmon, <i>Salmo salar</i>	-	Mixture; dilution water is river water
Brodeur et al.	Effects of subchronic exposure to aluminum in acidic water on bioenergetics of Atlantic salmon (<i>Salmo salar</i>)	2001	Atlantic salmon, <i>Salmo salar</i>	36 d Decrease growth, but not food consumption at 50	Only one exposure concentration
Brown	The effects of various cations on the survival of brown trout, <i>Salmo trutta</i> at low pHs	1981a	Brown trout, <i>Salmo trutta</i>	18 d Increase survival time at 250	Only two exposure concentrations
Brown	Effect of calcium and aluminum concentrations on the survival of brown trout (<i>Salmo trutta</i>) at low pH	1983	Brown trout, <i>Salmo trutta</i>	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 (<i>Oncorhynchus mykiss</i>)	1990	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species
Brown et al.	Contaminant effects on the teleost fish thyroid	2004	-	-	Review; results of previously published papers

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Brumbaugh and Kane	Variability of aluminum concentrations in organs and whole bodies of smallmouth bass (<i>Micropterus dolomieu</i>)	1985	Smallmouth bass, <i>Micropterus dolomieu</i>	-	Exposure concentration not known; field accumulation study
Budambula and Mwachiro	Metal status of Nairobi river waters and their bioaccumulation in <i>Labeo cylindricus</i>	2006	Fish, <i>Labeo cylindricus</i>	-	Not North American species; exposure concentration not known; field accumulation study
Buerger 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
Burton and Allan	Influence of pH, aluminum, and organic matter on stream invertebrates	1986	Stonefly, <i>Nemoura</i> sp. Isopod, <i>Asellus intermedius</i> Snail, <i>Physella heterostropha</i> Caddisfly, <i>Lepidostoma liba</i> Caddisfly, <i>Pycnopsyche guttifer</i>	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
Calevro et al.	Toxic effects of aluminum, chromium and cadmium in intact and regenerating freshwater planarians	1998a	Planarian, <i>Dugesia etrusca</i>	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 (Cr ³⁺ , Al ³⁺ , Cd ²⁺)	1998b	Newt, <i>Triturus vulgaris meridionalis</i> Frog, <i>Rana esculenta</i>	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 <i>Pleurodeles waltl</i> and regeneration in the planarian <i>Dugesia etrusca</i>	1999	Planarian, <i>Dugesia etrusca</i>	14 d 100% mortality at 13,490 NOEC (regeneration)=1,349	Not North American species

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Camargo et al.	Osmo-ionic alterations in a neotropical fish acutely exposed to aluminum	2007	Neotropical fish, <i>Prochilodus lineatus</i>	-	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 <i>Prochilus lineatus</i>	2009	Neotropical fish, <i>Prochilodus lineatus</i>	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 (<i>Mogurnda mogurnda</i>)	2003	Australian spotted gudgeon, <i>Mogurnda mogurnda</i>	96 hr LC50=374; LC50=547	Not North American species
Campbell et al.	Effect of aluminum and silica acid on the behavior of the freshwater snail <i>Lymnaea stagnalis</i>	2000	Snail, <i>Lymnaea stagnalis</i>	7 d Reduce behavioral state score (BSS) at 500	Only two exposure concentrations
Cardwell et al.	Toxic substances and water quality effects on larval marine organisms, technical report no. 45	1979	-	-	Not applicable; no aluminum toxicity data
Chamier and Tipping	Effects of aluminum in acid streams on growth and sporulation of aquatic hyphomycetes	1997	Fungi, <i>Tricladium splendens</i> Fungi, <i>Alatospora constricta</i> Fungi, <i>Varicosporium elodea</i>	-	Mixture; low pH and Al
Chang et al.	Response of the mussel <i>Anadonta grandis</i> to acid and aluminum. Comparison of blood ions from laboratory and field results	1988	Mussel, <i>Anadonta grandis</i>	-	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
Chen et al.	Environmental factors affecting settlement of quagga mussel (<i>Dreissena rostriformis bugensis</i>) veligers in Lake Mead, Nevada-Arizona, USA	2011	Quagga mussel, <i>Dreissena rostriformis bugensis</i>	-	Not applicable; no aluminum toxicity data

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Chevalier et al.	Acidity and aluminum effects on osmo-iono-regulation in the brook trout	1987	Brook trout, <i>Salvelinus fontinalis</i>	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, <i>Catostomus commersoni</i> (lacepede)	1971/ 1972	White sucker, <i>Catostomus commersoni</i>	-	In vitro experiment
Christensen and Tucker	Effects of selected water toxicants on the in vitro activity of fish carbonic anhydrase	1976	Channel catfish, <i>Ictalurus punctatus</i>	-	Excised cells
Clark and Hall	Effects of elevated hydrogen ion and aluminum concentrations on the survival of amphibian embryos and larvae	1985	Toad, <i>Bufo americanus</i> Wood frog, <i>Rana sylvatica</i> Spotted salamander, <i>Ambystoma maculatum</i>	-	Exposure concentration not known; field experiment: dosed stream pools
Clark and LaZerte	Intraspecific variation in hydrogen ion and aluminum toxicity in <i>Bufo americanus</i> and <i>Ambystoma maculatum</i>	1987	Toad, <i>Bufo americanus</i> Spotted salamander, <i>Ambystoma maculatum</i>	-	Pre-exposure to pollutant
Cleveland et al.	Interactive toxicity of aluminum and acidity to early life stages of brook trout	1986	Brook trout, <i>Salvelinus fontinalis</i>	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, <i>Salvelinus fontinalis</i>	-	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
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 <i>Somatochlora cingulata</i>	1985	Dragonfly, <i>Somatochlora cingulata</i>	96 hr No change in respiratory rate at 30	Lack of exposure details; dilution water not characterized; too few exposure concentration

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Correa et al.	Oxygen consumption and ammonia excretion in the detritivore caddisfly <i>Limnephillus sp.</i> exposed to low pH and aluminum	1986	Caddisfly, <i>Limnephillus sp.</i>	-	Only one exposure concentration; mixture; low pH and Al
Correia et al.	Aluminum as an endocrine disruptor in female Nile tilapia (<i>Oreochromis niloticus</i>)	2010	Nile tilapia, <i>Oreochromis niloticus</i>	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 <i>Rana temporaria</i> tadpoles	1986	Brown frog, <i>Rana temporaria</i>	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, <i>Salmo trutta</i> L.	1986	Brown trout, <i>Salmo trutta</i>	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
Desouky	Tissue distribution and subcellular localization of trace metals on the pond snail <i>Lymnaea stagnalis</i> with special reference to the role of lysosomal granules in metal sequestration	2006	Snail, <i>Lymnaea stagnalis</i>	-	Bioaccumulation: exposure concentration not measured; inadequate exposure methods
Desouky et al.	Influence of oligomeric silica and humic acids on aluminum accumulation in a freshwater grazing invertebrate	2002	Snail, <i>Lymnaea stagnalis</i>	-	Bioaccumulation: steady state not reached
DeWalle et al.	Episodic flow-duration analysis: a method of assessing toxic exposure of brook trout (<i>Salvelinus fontinalis</i>) to episodic increases in aluminum	1995	-	-	Not applicable; no aluminum toxicity data

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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, <i>Oncorhynchus mykiss</i>	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 (<i>Salmo trutta fario</i> , L.) in a Swiss alpine lake	1989b	Brown trout, <i>Salmo trutta fario</i>	-	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 (<i>Salmo trutta fario</i>) in acid water	1989	Brown trout, <i>Salmo trutta fario</i>	-	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
Driscoll et al.	Effect of aluminum speciation on fish in dilute acidified waters	1980	Brook trout, <i>Salvelinus fontinalis</i>	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, <i>Coregonus albula</i>	Decrease hatch % at 2,100, pH=5.0	Not North American species; only one exposure concentration
Dussault et al.	Effects of sublethal, acidic aluminum exposure on blood ions and metabolites, cardiac output, heart rate and stroke volume of rainbow trout, <i>Oncorhynchus mykiss</i>	2001	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species
Dussault et al.	Effects of chronic aluminum exposure on swimming and cardiac performance in rainbow trout, <i>Oncorhynchus mykiss</i>	2004	Rainbow trout, <i>Oncorhynchus mykiss</i>	6 wk 75% survival at 32	Too few exposure concentrations; too few organisms per concentration

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Dwyer et al.	Use of surrogate 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, <i>Ambloplites rupestris</i> Largemouth bass, <i>Micropterus salmoides</i> Yellow perch, <i>Perca flavescens</i>	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 (<i>Salmo salar</i>) in fresh water and in solutions of metal ions	1983	Atlantic salmon, <i>Salmo salar</i>	1 hr Inhibit perivitelline fluid formation at 26,980	Dilution water not characterized
Eddy and Talbot	Sodium balance in eggs and dechlorinated embryos of the Atlantic salmon <i>Salmo salar</i> L. exposed to zinc, aluminum and acid waters	1985	Atlantic salmon, <i>Salmo salar</i>	-	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 <i>Asellus aquaticus</i> in neutral water	1999	Crustacean, <i>Asellus aquaticus</i>	-	Bioaccumulation: unmeasured concentration in exposure media
Elsebae	Comparative susceptibility of the Alareesh Marine Culture Center shrimp <i>Penaeus japonicus</i> and the brine shrimp <i>Artemia salina</i> to different insecticides and heavy metals	1994	Shrimp, <i>Penaeus japonicus</i>	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 <i>Tipula</i> 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 <i>Gyrodactylus salaris</i>	2009	-	-	Mixture; mixed species exposure; dilution water is river water

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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
Everhart and Freeman	Effect of chemical variations in aquatic environments. Vol. II. Toxic effects of aqueous aluminum to rainbow trout	1973	Rainbow trout, <i>Oncorhynchus mykiss</i>	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, <i>Oncorhynchus mykiss</i>	45 min. Avoidance at 33.73	No acclimation to test water
Exley et al.	Polynuclear aluminum and acute toxicity in the fish	1994	-	-	Inappropriate form of toxicant; polynuclear aluminum
Exley et al.	Kinetic constraints in acute aluminum toxicity in the rainbow trout (<i>Oncorhynchus mykiss</i>)	1996	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Only one exposure concentration; no control group
Exley et al.	Hydroxyaluminosilicates and acute aluminum toxicity to fish	1997	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Mixture; Al and Si
Farag et al. 1993	The effects of low pH and elevated aluminum on yellowstone cutthroat trout (<i>Oncorhynchus clarki bouvieri</i>)	1993	Yellowstone cutthroat trout, <i>Oncorhynchus clarki bouvieri</i>	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- <i>Ctenopharingodon idella</i>)	2012	Grass carp, <i>Ctenopharingodon idella</i>	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 (<i>Salmo salar</i> L.) and brown trout (<i>Salmo trutta</i> L.): Mortality and physiological response	1984	Atlantic salmon, <i>Salmo salar</i>	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
Fok et al.	Determination of 3,5,3"-triiodo-L-thyronine (T3) levels in tissues of rainbow trout (<i>Salmo gairdneri</i>) and the effects of low ambient pH and aluminum.	1990	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Inappropriate form of toxicant (AlKSO ₄); surgically altered test species

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Folsom et al.	Comparative study of aluminum and copper transport and toxicity in an acid-tolerant freshwater green alga	1986	Green alga, <i>Chlorella saccharophila</i>	-	Lack of details; cannot determine effect concentration
France and Stokes	Influence of manganese, calcium, and aluminum on hydrogen ion toxicity to the amphipod <i>Hyalella azteca</i>	1987	Amphipod, <i>Hyalella azteca</i>	-	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, <i>Oncorhynchus mykiss</i>	-	Pre-exposure to pollutant
Frick and Herrmann	Aluminum accumulation in a lotic mayfly at low pH - a laboratory study	1990	Mayfly, <i>Heptagenia sulphurea</i>	-	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, <i>Escherichia coli</i> Protozoa, <i>Tetrahymena thermophila</i> Protozoa, <i>Euglena gracilis</i>	-	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, <i>Salvelinus fontinalis</i> Mottled sculpin, <i>Cottus bairdi</i> Slimy sculpin, <i>Cottus cognatus</i>	-	Mixture; exposure concentration varied over time; dilution water is river water
Galindo et al.	Genotoxic effects of aluminum on the neotropical fish <i>Prochilodus lineatus</i>	2010	Neotropical fish, <i>Prochilodus lineatus</i>	96 hr Increase COMET score and number of damaged nucleoids at 438	Not North American species, only one exposure concentration
Gallon et al.	Hydroponic study of aluminum accumulation by aquatic plants: effects of fluoride and pH	2004	Five aquatic plants	-	Bioaccumulation: steady state not reached
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

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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 (<i>Cyprinus carpio</i>)	2010	Common carp, <i>Cyprinus carpio</i>	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 (<i>Cyprinus carpio</i>)	2011	Common carp, <i>Cyprinus carpio</i>	96 hr DNA damage: T/N index at 50	Too few exposure concentrations, dilution water not characterized
Gardner and Al-Hamdani	Interactive effects of aluminum and humic substances on <i>Salvinia</i>	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 (<i>Rana sylvatica</i>) eggs and tadpoles	1987	Wood frog, <i>Rana sylvatica</i>	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 (<i>Pimephales promelas</i>) Volume V	1990	Fathead minnows, <i>Pimephales promelas</i>	-	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 <i>Asterionella ralfsii</i> var. <i>americana</i> (Bacillariophyceae).	1990	Diatom, <i>Asterionella ralfsii</i> var. <i>americana</i>	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 <i>Asterionella ralfsii</i> var. <i>americana</i>	1991a	Diatom, <i>Asterionella ralfsii</i> var. <i>americana</i>	-	Review of Gensemer 1989 thesis
Gensemer	The effects of aluminum on phosphorus and silica-limited growth in <i>Asterionella ralfsii</i> var. <i>americana</i>	1991b	Diatom, <i>Asterionella ralfsii</i> var. <i>americana</i>	-	Growth stimulation study, not toxicity
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 <i>Asterionella ralfsii</i> var. <i>americana</i> (Bacillariophyceae)	1993	Diatom, <i>Asterionella ralfsii</i> var. <i>americana</i>	-	Only one exposure concentration; cannot determine effect concentration

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Gensemer et al.	Interactions of pH and aluminum on cell length reduction in <i>Asterionella ralfsii</i> var. <i>americana</i> Korn	1994	Diatom, <i>Asterionella ralfsii</i> var. <i>americana</i>	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, <i>Cosmarium melanosporum</i> Blue-green alga, <i>Schizothrix calcicola</i> Diatom, <i>Achnanthes minutissima</i> Diatom, <i>Naviculoids</i>	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 (<i>Carassius auratus</i>)	1987	Goldfish, <i>Carassius auratus</i>	-	Surgically altered test species
Goossenaerts et al.	A microanalytical study of the gills of aluminum-exposed rainbow trout (<i>Salmo gairdneri</i>)	1988	Rainbow trout, <i>Oncorhynchus mykiss</i>	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 <i>Hydroides elegans</i>	2007	Polychaete, <i>Hydroides elegans</i>	-	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, <i>Salmo gairdneri</i>	1988	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered fish
Greger et al.	Aluminum effects on <i>Scenedesmus obtusiusculus</i> with different phosphorus status. I. Mineral uptake	1992a	Green alga, <i>Scenedesmus obtusiusculus</i>	-	Excessive EDTA in growth media (108 µm Na ₂ EDTA)
Greger et al.	Aluminum effects on <i>Scenedesmus obtusiusculus</i> with different phosphorus status. II. Growth, photosynthesis and pH	1992b	Green alga, <i>Scenedesmus obtusiusculus</i>	-	Excessive EDTA in growth media (108 µm Na ₂ EDTA)
Guerold et al.	Occurrence of aluminum in chloride cells of <i>Perla marginata</i> (Plecoptera) after exposure to low pH and elevated aluminum concentration	1995	Stonefly, <i>Perla marginata</i>	-	Not North American species; Bioaccumulation: steady state not reached

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Gunn and Keller	Spawning site water chemistry and lake trout (<i>Salvelinus namaycush</i>) sac fry survival during spring snow melt	1984	Lake trout, <i>Salvelinus namaycush</i>	-	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 (<i>Salvelinus namaycush</i>) alevins	1987	Lake trout, <i>Salvelinus namaycush</i>	5 d LOEC (growth)=<100	Only two exposure concentrations
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
Hall et al.	Mortality of striped bass larvae in relation to contaminants and water quality in a Chesapeake Bay tributary	1985	Striped bass, <i>Morone saxatilis</i>	-	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
Handy and Eddy	Surface absorption of aluminium by gill tissue and body mucus of rainbow trout, <i>Salmo gairdneri</i> , at the onset of episodic exposure	1989	Rainbow trout, <i>Oncorhynchus mykiss</i>	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, <i>Mya arenaria</i> American oyster, <i>Crassostrea virginica</i>	-	Dilution water not characterized, inappropriate form of Al
Harry and Aldrich	The distress syndrome in <i>Taphius glabratus</i> (Say) as a reaction to toxic concentrations of inorganic ions	1963	Snail, <i>Taphius glabratus</i>	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

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Havens	Aluminum binding to ion exchange sites in acid-sensitive versus acid tolerant cladocerans	1990	Cladoceran, <i>Daphnia galeata mendotae</i> Cladoceran, <i>Daphnia retrocurva</i> Cladoceran, <i>Bosmina longirostris</i>	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, <i>Daphnia galeata mendotae</i> Cladoceran, <i>Bosmina longirostris</i>	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
Havens	Acid and aluminum effects on osmoregulation and survival of the freshwater copepod <i>Skistodiaptomus oregonensis</i>	1993b	Copepod, <i>Skistodiaptomus oregonensis</i>	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 (<i>Salmo salar</i>) exposed to mixtures of copper, aluminum and gamma radiation	2012	Atlantic salmon, <i>Salmo salar</i>	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, <i>Oncorhynchus mykiss</i>	-	Surgically altered fish

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
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, <i>Danio rerio</i>	-	Review
Hockett and Mount	Use of metal chelating agents to differentiate among sources of acute aquatic toxicity	1996	Cladoceran, <i>Ceriodaphnia dubia</i>	-	Mixture; EDTA, thiosulfate and Al
Hofler	Action of aluminum salts on <i>Spirogyra</i> and <i>Zygnema</i>	1958	-	-	Text in foreign language
Horne and Dunson	Exclusion of the Jefferson salamander, <i>Ambystoma jeffersonianum</i> , from some potential breeding ponds in Pennsylvania: effects of pH, temperature, and metals on embryonic development	1994	Jefferson salamander, <i>Ambystoma jeffersonianum</i>	-	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, <i>Ambystoma jeffersonianum</i>	1995a	Jefferson salamander, <i>Ambystoma jeffersonianum</i>	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, <i>Rana sylvatica</i> Jefferson salamander, <i>Ambystoma jeffersonianum</i>	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
Hunn et al.	Influence of pH and aluminum on developing brook trout in a low calcium water	1987	Brook trout, <i>Salvelinus fontinalis</i>	45 d Reduced growth and some behaviors at 283	Only one exposure concentration
Husaini and Rai	pH dependent aluminum toxicity to <i>Nostoc linckia</i> : Studies on phosphate uptake, alkaline and acid phosphatase activity, ATP content, and photosynthesis and carbon fixation	1992	Blue-green alga, <i>Nostoc linckia</i>	14 d Reduce photosynthetic O ₂ evolution at 53,336	Only three exposure concentrations

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Husaini et al.	Impact of aluminum, fluoride and fluoroaluminate on ATPase activity of <i>Nostoc linckia</i> and <i>Chlorella vulgaris</i>	1996	Blue-green alga, <i>Nostoc linckia</i> Green alga, <i>Chlorella vulgaris</i>	-	Mixture
Hutchinson and Sprague	Toxicity of trace metal mixtures to American flagfish (<i>Jordanella floridae</i>) in soft, acidic water and implications for cultural acidification	1986	American flagfish, <i>Jordanella floridae</i>	-	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, <i>Crassostrea virginica</i>	-	Exposure concentration not known; field accumulation study
Hyne and Wilson	Toxicity of acid-sulphate soil leachate and aluminum to the embryos and larvae of Australian bass (<i>Macquaria novemaculeata</i>) in estuarine water	1997	Australian bass, <i>Macquaria novemaculeata</i>	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 et al.	Epidermal response to pH, aluminum, and calcium exposure in brook trout (<i>Salvelinus fontinalis</i>) fry	1990b	Brook trout, <i>Salvelinus fontinalis</i>	-	Only two exposure concentrations; too few test organisms per concentration
Jagoe and Haines	Changes in gill morphology of Atlantic salmon (<i>Salmo salar</i>) smolts due to addition of acid and aluminum to stream water	1997	Atlantic salmon, <i>Salmo salar</i>	-	Only one exposure concentration, increasing Al concentration over time
Jancula et al.	Effects of polyaluminium chloride on the freshwater invertebrate <i>Daphnia magna</i>	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 <i>Steinernema carpocapsae</i> and <i>Heterohabditis bacteriophora</i> entomopathogenic nematodes under laboratory conditions	1999	Nematode, <i>Steinernema carpocapsae</i>	-	Distilled water without proper salts added
Jaworska et al.	Effect of metal ions under laboratory conditions on the entomopathogenic <i>Steinernema carpocapsae</i> (Rhabditida: steinernematidae)	1996	Nematode, <i>Steinernema carpocapsae</i>	-	Distilled water without proper salts added; infected test organism
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, <i>Astacus astacus</i> , exposed to soft, acid water with and without aluminum	1990	Crayfish, <i>Astacus astacus</i>	21 d No effect on haemolymph haemocyanin concentration at 675	Not North American species, only one exposure concentration

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
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, <i>Tinca tinca</i>	-	Surgically altered test species
Jones	The relation between the electrolytic solution pressures on the metals and their toxicity to the stickleback (<i>Gasterosteus aculeatus</i> L.)	1939	Threespine stickleback, <i>Gasterosteus aculeatus</i>	-	Lack of details; review
Jones	A further study of the relation between toxicity and solution pressure, with <i>Polycelis nigra</i> as test animals	1940	Planarian, <i>Polycelis nigra</i>	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
Juhel et al.	Alumina nanoparticles enhance growth of <i>Lemna minor</i>	2011	Duckweed, <i>Lemna minor</i>	-	Inappropriate form of toxicant; nanoparticles
Kadar et al.	Avoidance responses to aluminum in the freshwater bivalve, <i>Anodonta cygnea</i>	2001	Swan mussel, <i>Anodonta cygnea</i>	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 <i>Anodonta cygnea</i> L. At Neutral Ph	2002	Swan mussel, <i>Anodonta cygnea</i>	15 d Duration of siphon activity at 241.3	Not North American species, only two exposure concentrations
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, <i>Salmo trutta</i> L.	1986a	Brown trout, <i>Salmo trutta</i>	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, <i>Salmo trutta</i> L.	1986b	Brown trout, <i>Salmo trutta</i>	-	Bioaccumulation: survey; exposure concentration not measured over time
Keinanen et al.	Ion regulation in whitefish (<i>Coregonus lavaretus</i> L.) yolk-sac fry exposed to low pH and aluminum at low and moderate ionic strength	1998	Whitefish, <i>Coregonus lavaretus</i>	-	Not North American species; cannot determine effect concentration
Keinanen et al.	Comparison of the responses of the yolk-sac fry of pike (<i>Esox lucius</i>) and roach (<i>Rutilus rutilus</i>) to low pH and aluminum: sodium influx, development and activity	2000	Pike, <i>Esox lucius</i> Roach, <i>Rutilus rutilus</i>	10 d NOEC (growth)=600 at pH=5.0; 9 d LOEC (survival)=100 at pH=5.25	Too few exposure concentrations

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Keinanen et al.	Fertilization and embryonic development of whitefish (<i>Coregonus lavaretus lavaretus</i>) in acidic low-ionic strength water with aluminum	2003	Whitefish, <i>Coregonus lavaretus lavaretus</i>	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, <i>Esox lucius</i>	-	Mixture; dilution water is lake water
Khargarot and Das	Acute toxicity of metals and reference toxicants to a freshwater ostracod, <i>Cypris subglobosa</i> Sowerby, 1840 and correlation to EC50 values of other test models	2009	Ostracod, <i>Cypris subglobosa</i>	-	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 (<i>Tanichthys albonubes</i> and <i>Neocaridina denticulata</i>) and the hardness of the test solution	1990	White cloud mountain minnow, <i>Tanichthys albonubes</i>	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, <i>Salmo gairdneri</i>	1988	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species
Klauda and Palmer	Responses of blueback herring eggs and larvae to pulses of aluminum	1987	Blueback herring, <i>Alosa aestivalis</i>	-	Pulsed exposures to pollutant
Kline	The effects of organic complexation on aluminum toxicity to rainbow trout (<i>Oncorhynchus mykiss</i>)	1992	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Only two exposure concentrations; effect for inorganic Al not total Al
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 <i>Polycelis felina</i> (Daly.)	2009a	Planarian, <i>Polycelis felina</i>	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

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Kroglund et al.	Exposure to moderate acid water and aluminum reduces Atlantic salmon post-smolt survival	2007	Atlantic salmon, <i>Salmo salar</i>	-	Dilution water not characterized; mixture
Kroglund et al.	Water quality limits for Atlantic salmon (<i>Salmo salar</i> L.) exposed to short term reductions in pH and increased aluminum simulating episodes	2008	Atlantic salmon, <i>Salmo salar</i>	-	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, <i>Salmo salar</i>	-	Only one exposure concentration; no control group
Kure et al.	Molecular responses to toxicological stressors: Profiling microRNAs in wild Atlantic salmon (<i>Salmo salar</i>) exposed to acidic aluminum-rich water	2013	Atlantic salmon, <i>Salmo salar</i>	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, <i>Salmo salar</i>	-	Mixture; Al and citrate
Laitinen and Valtonen	Cardiovascular, ventilatory and haematological responses of brown trout (<i>Salmo trutta</i> L.), to the combined effects of acidity and aluminum in humic water at winter temperatures	1995	Brown trout, <i>Salmo trutta</i>	-	Mixture; dilution water is river water
Lange	Toxicity of aluminum to selected freshwater invertebrates in water of pH 7.5	1985	Fingernail clam, <i>Sphaerium sp.</i>	4 d LC50=2,360	High control mortality (26.7%)
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, <i>Micropterus salmoides</i>	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, <i>Pimephales promelas</i>	1988	Fathead minnow, <i>Pimephales promelas</i>	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, <i>Pimephales promelas</i>	-	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, <i>Ctenopharingodon idella</i>	4 d LC50=260	Lack of exposure details; text in foreign language
Li et al.	Responses of <i>Ceriodaphnia dubia</i> to TiO ₂ and Al ₂ O ₃ nanoparticles: A dynamic nano-toxicity assessment of energy budget distribution	2011	Cladoceran, <i>Ceriodaphnia dubia</i>	-	Inappropriate form of toxicant (nanoparticles)

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
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, <i>Chlorella sp.</i> Green alga, <i>Scenedesmus sp.</i>	-	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
Macova et al.	Polyaluminium chloride (PAX-18) - acute toxicity and toxicity for early development stages of common carp (<i>Cyprinus carpio</i>)	2009	Common carp, <i>Cyprinus carpio</i>	-	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 (<i>Danio rerio</i>)	2010	Zebrafish, <i>Danio rerio</i>	-	Inappropriate form of toxicant, PAX-18 (9% Al)
Madigosky et al.	Concentrations of aluminum in gut tissue of crayfish (<i>Procambarus clarkii</i>), purged in sodium chloride	1992	Crayfish, <i>Procambarus clarkii</i>	-	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 (<i>Salmo trutta</i>) in headwater streams recovering from acidification	2012	Brown trout, <i>Salmo trutta</i>	-	Survey
Malley and Chang	Effects of aluminum and acid on calcium uptake by the crayfish <i>Orconectes virilis</i>	1985	Crayfish, <i>Orconectes virilis</i>	-	No aluminum toxicity data; calcium uptake with Al treatment
Malley et al.	Changes in the aluminum content of tissues of crayfish held in the laboratory and in experimental field enclosures	1986	Crayfish, <i>Orconectes virilis</i>	-	Mixture; sediment
Malley et al.	Effects on ionic composition of blood tissues of <i>Anodonta grandis grandis</i> (Bivalvia) of an addition of aluminum and acid to a lake	1988	Mussel, <i>Anodonta grandis grandis</i>	-	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, <i>Oncorhynchus mykiss</i>	-	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, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Mao et al.	Assessment of sacrificial anode impact by aluminum accumulation in mussel <i>Mytilus edulis</i> : a large-scale laboratory test	2011	Bay mussel, <i>Mytilus edulis</i>	-	Inappropriate form of toxicant; Al anode
Markarian et al.	Toxicity of nickel, copper, zinc and aluminum mixtures to the white sucker (<i>Catostomus commersoni</i>)	1980	White sucker, <i>Catostomus commersoni</i>	-	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, <i>Mytilus edulis</i> , from San Francisco Bay, California	1984	Bay mussel, <i>Mytilus edulis</i>	-	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 (<i>Micropterus salmoides</i>) exposed to low pH and elevated aluminum at low temperature in soft water	1992	Largemouth bass, <i>Micropterus salmoides</i>	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 embryonic-larval development of the fathead minnow in soft water	1989	Fathead minnow, <i>Pimephales promelas</i>	4 d 38% hatch at 49 and pH=5.5; 94% hatch at 66 and pH=7.5	Only two exposure concentrations
McCormick et al.	Thresholds for short-term acid and aluminum impacts on Atlantic salmon smolts	2012	Atlantic salmon, <i>Salmo salar</i>	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, <i>Lymnaea stagnalis</i>	-	Dilution water not characterized; lack of exposure details
McDonald and Milligan	Sodium transport in the brook trout, <i>Salvelinus fontinalis</i> : effects of prolonged low pH exposure in the presence and absence of aluminum	1988	Brook trout, <i>Salvelinus fontinalis</i>	-	Only one exposure concentration; pre-exposure to pollutant
McDonald et al.	Nature and time course of acclimation to aluminum in juvenile brook trout (<i>Salvelinus fontinalis</i>). I. Physiology	1991	Brook trout, <i>Salvelinus fontinalis</i>	-	Exposure concentration varied over time; changed dose mid experiment

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
McKee and Wolf	Water quality criteria. 2 nd Edition	1963	-	-	Review; results of previously published papers
Mehta et al.	Relative toxicity of some non-insecticidal chemicals to the free living larvae guinea-worm (<i>Dracunculus medinensis</i>)	1982	Guinea worm (larvae), <i>Dracunculus medinensis</i>	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, <i>Rutilus rutilus</i>	-	Not North American species; exposure concentration not known; field accumulation study
Meland et al.	Exposure of brown trout (<i>Salmo trutta</i> L.) to tunnel wash water runoff -- Chemical characterisation and biological impact	2010	Brown trout, <i>Salmo trutta</i>	-	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
Michailova et al.	Functional and structural rearrangements of salivary gland polytene chromosomes of <i>Chironomus riparius</i> Mg. (Diptera, Chironomidae) in response to freshly neutralized aluminum	2003	Midge, <i>Chironomus riparius</i>	24-25 d Higher frequency of numerous somatic aberrations at 500	Only one exposure concentration
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, <i>Selenastrum capricornutum</i>	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
Monette	Impacts of episodic acid and aluminum exposure on the physiology of Atlantic salmon, <i>Salmo salar</i> , smolt development	2007	Atlantic salmon, <i>Salmo salar</i>	-	Only one exposure concentration; pulse exposures
Monette and McCormick	Impacts of short-term acid and aluminum exposure on Atlantic salmon (<i>Salmo salar</i>) physiology: a direct comparison of parr and smolts	2008	Atlantic salmon, <i>Salmo salar</i>	-	Review of Monette 2007
Monette et al.	Effects of short-term acid and aluminum exposure on the parr-smolt transformation in the Atlantic salmon (<i>Salmo salar</i>): disruption of seawater tolerance and endocrine status	2008	Atlantic salmon, <i>Salmo salar</i>	-	Review of Monette 2007

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Monette et al.	Physiological, molecular, and cellular mechanisms of impaired seawater tolerance following exposure of Atlantic salmon, <i>Salmo salar</i> , smolts to acid and aluminum	2010	Atlantic salmon, <i>Salmo salar</i>	6 d NOEC (mortality)=43; LOEC=71	Only two exposure concentrations;
Morgan et al.	A plant toxicity test with the moss <i>Physcomitrella patens</i> (Hedw.) B.S.G.	1990	Moss, <i>Physcomitrella patens</i>	-	Lack of details; toxicity information not discernible
Morgan et al.	An aquatic toxicity test using the moss <i>Physcomitrella patens</i> (Hedw.) B.S.G.	1993	Moss, <i>Physcomitrella patens</i>	-	Lack of details; toxicity information not discernible
Mount et al.	Effect of long-term exposure to acid, aluminum, and low calcium in adult brook trout (<i>Salvelinus fontinalis</i>). 1. survival, growth, fecundity, and progeny survival	1988a	Brook trout, <i>Salvelinus fontinalis</i>	-	Mixture; low pH and Al
Mount et al.	Effect of long-term exposure to acid, aluminum, and low calcium in adult brook trout (<i>Salvelinus fontinalis</i>). 2. vitellogenesis and osmoregulation	1988b	Brook trout, <i>Salvelinus fontinalis</i>	-	Mixture; low pH and Al
Mount et al.	Response of brook trout (<i>Salvelinus fontinalis</i>) fry to fluctuating acid, aluminum, and low calcium exposures	1990	Brook trout, <i>Salvelinus fontinalis</i>	-	Pre-exposure to pollutant; only two exposure concentrations
Mueller et al.	Nature and time course of acclimation to aluminum in juvenile brook trout (<i>Salvelinus fontinalis</i>). II. Gill histology	1991	Brook trout, <i>Salvelinus fontinalis</i>	-	Only one exposure concentration; exposure concentration varied over time
Mukai	Effects of chemical pretreatment on the germination of statoblasts of the freshwater bryozoan, <i>Pectinatella gelatinosa</i>	1977	Bryozoa, <i>Pectinatella gelatinosa</i>	-	Not applicable; no aluminum toxicity data
Mulvey et al.	Effects of potassium aluminium sulphate (alum) used in an <i>Aeromonas salmonicida</i> bacterin on Atlantic salmon, <i>Salmo salar</i>	1995	Atlantic salmon, <i>Salmo salar</i>	-	Inject toxicant; inappropriate form of toxicant (potassium aluminum sulphate)
Muniz and Leivestad	Toxic effects of aluminum on the brown trout, <i>Salmo trutta</i> L.	1980b	Brown trout, <i>Salmo trutta</i>	-	Mixture; dilution water is breakwater
Muramoto	Influence of complexans (NTA, EDTA) on the toxicity of aluminum chloride and sulfate to fish at high concentrations	1981	Common carp, <i>Cyprinus carpio</i>	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, <i>Notropis sp.</i>	96 hr Whole fish tissue = 0.78 mg/g (dry weight) at 5,000	Lack of details, exposure methods unknown

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Musibono and Day	Active uptake of aluminum, copper, and manganese by the freshwater amphipod <i>Paramelita nigroculus</i> in acidic waters	2000	Amphipod, <i>Paramelita nigroculus</i>	-	Not North American species; mixture
Naskar et al.	Aluminum toxicity induced poikilocytosis in an air-breathing telost, <i>Clarias batrachus</i> (Linn.)	2006	Catfish, <i>Clarias batrachus</i>	5 d Some membrane abnormalities with red blood cells at 165,000	Only two exposure concentrations; non-wild population test animals
Neave et al.	The transcriptome and proteome are altered in marine polychaetes (Annelida) exposed to elevated metal levels	2012	Polychaete, <i>Ophelina sp.</i>	-	Mixture; field study: exposure concentration not known
Neville	Physiological response of juvenile rainbow trout, <i>Salmo gairdneri</i> , to acid and aluminum - prediction of field responses from laboratory data	1985	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	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, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species
Nilsen et al.	Atlantic salmon (<i>Salmo salar</i> L.) smolts require more than two weeks to recover from acidic water and aluminum exposure	2013	Atlantic salmon, <i>Salmo salar</i>	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 (<i>Phoxinus phoxinus</i> L.) at different pH levels	1991	Minnow, <i>Phoxinus phoxinus</i>	48 d No effect on mortality at 174 and pH=7.1; Increase mortality at 168 and pH=5.9	Only one exposure concentration
Odonnell et al.	A review of the toxicity of aluminum in fresh water	1984	-	-	Review
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
OSU (Oregon State University)	Chronic toxicity of aluminum, at pH6, to the freshwater duckweed, <i>Lemna minor</i>	2012d	Duckweed, <i>Lemna minor</i>	-	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

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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
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, <i>Lepomis macrochirus</i> Fathead minnow, <i>Pimephales promelas</i> Channel catfish, <i>Ictalurus punctatus</i>	Exposure concentrations overlapped (all over the place)	Exposure concentrations overlapped
Panda and Khan	Lipid peroxidation and oxidative damage in aquatic duckweed (<i>Lemna minor</i> L.) in response to aluminum toxicity	2004	Duckweed, <i>Lemna minor</i>	-	Cannot determine effect concentration, dilution media not defined; no statistical analysis
Parent et al.	Influences of natural dissolved organic matter on the interaction of aluminum with the microalga <i>Chlorella</i> : a test of free-ion model of trace metal toxicity	1996	Green alga, <i>Chlorella pyrenoidosa</i>	-	Mixture; Al and soil fluvic acid
Parkhurst et al.	Inorganic monomeric aluminum and pH as predictors of acidic water toxicity to brook trout (<i>Salvelinus fontinalis</i>)	1990	Brook trout, <i>Salvelinus fontinalis</i>	-	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, <i>Ceriodaphnia dubia</i> Fathead minnow, <i>Pimephales promela</i>	-	Mixture; power plant effluent
Pauwels	Some effects of exposure to acid and aluminum on several lifestages of the Atlantic salmon (<i>Salmo salar</i>)	1990	Atlantic salmon, <i>Salmo salar</i>	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, <i>Scenedesmus bijgva</i>	-	Lack of details; duration and exposure methods not provided
Pettersson et al.	Physiological and structural responses of the cyanobacterium <i>Anabaena cylindrica</i> to aluminum	1985a	Blue-green alga, <i>Anabaena cylindrica</i>	-	Excessive EDTA used (672.52 µg/L)
Pettersson et al.	Accumulation of aluminum by <i>Anabaena cylindrica</i> into polyphosphate granules and cell walls: an X-ray energy-dispersive microanalysis study	1985b	Blue-green alga, <i>Anabaena cylindrica</i>	-	Bioaccumulation: not renewal or flow-through

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Pettersson et al.	Aluminum uptake by <i>Anabaena cylindrica</i>	1986	Blue-green alga, <i>Anabaena cylindrica</i>	-	Bioaccumulation: not renewal or flow-through; steady state not reached
Pettersson et al.	Aluminum effects on uptake and metabolism of phosphorus by the cyanobacterium <i>Anabaena cylindrica</i>	1988	Blue-green alga, <i>Anabaena cylindrica</i>	-	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, <i>Coregonus lavaretus</i>	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 <i>Daphnia magna</i> Straus (Crustacea, Cladocera)	2010	Cladoceran, <i>Daphnia magna</i>	-	Inappropriate form of toxicant, PIX 113 and PAX 18
Playle	Physiological effects of aluminum on rainbow trout in acidic soft water, with emphasis on the gill micro-environment	1989	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species
Playle and Wood	Mechanisms of aluminum extraction and accumulation at the gills of rainbow trout, <i>Oncorhynchus mykiss</i> (Walbaum), in acidic soft water	1991	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species
Playle et al.	Physiological disturbances in rainbow trout during acid and aluminum exposures	1988	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species
Playle et al.	Physiological disturbances in rainbow trout (<i>Salmo gairdneri</i>) during acid and aluminum exposures in soft water of two calcium concentrations	1989	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species
Poleo	Temperature as a major factor concerning fish mortality in acidic Al-rich waters: Experiments with young stage Atlantic salmon (<i>Salmo salar</i> L.)	1992	Atlantic salmon, <i>Salmo salar</i>	-	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, <i>Salmo salar</i>	1993	Atlantic salmon, <i>Salmo salar</i>	LT50=49 hr at 271 (1°C); LT50=21 hr at 272 (10°C)	Only one exposure concentration; no control group

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Poleo et al.	The influence of temperature on aqueous aluminum chemistry and survival of Atlantic salmon (<i>Salmo salar</i> L.) fingerlings	1991	Atlantic salmon, <i>Salmo salar</i>	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, <i>Carassius carassius</i> , exposed to a high low-molecular weight inorganic aluminum challenge	1995	Crucian carp, <i>Carassius carassius</i>	-	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 <i>Gyrodactylus salaris</i> (Plathyrlminthes, Monogenea) infections in Atlantic salmon (<i>Salmo salar</i>)	2004	Parasite, <i>Gyrodactylus salaris</i> Atlantic salmon, <i>Salmo salar</i>	-	Two species tested with one exposure; not sure how much exposure to the parasite
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, <i>Salmo salar</i>	-	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 <i>Spirogyra decimina</i> in response to heavy metals exposure: I. the effect of cadmium	2005	Green alga, <i>Spirogyra decimina</i>	-	Not applicable; cadmium study
Pynnonen	Aluminum accumulation and distribution in the freshwater clams (Unionidae)	1990	Mussel, <i>Anodonta anatina</i> Mussel, <i>Unio pictorum</i>	-	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 (<i>Chlamydomonas-Daphnia</i>) 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 <i>Lemna minor</i> L.	2010	Duckweed, <i>Lemna minor</i>	15 d NOEC (relative growth rate)=4,047; LOEC=8,094	

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Rajesh	Toxic effect of aluminum in <i>Oreochromis mossambicus</i> (Peters)	2010	Mozambique tilapia, <i>Oreochromis mossambicus</i>	4 d LC50=8,000	Dilution water not characterized
Ramamoorthy	Effect of pH on speciation and toxicity of aluminum to rainbow trout (<i>Salmo gairdneri</i>)	1988	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Mixture
Reader et al.	Growth, mineral uptake and skeletal calcium deposition in brown trout, <i>Salmo trutta</i> L., yolk-sac fry exposed to aluminum and manganese in soft acid water	1988	Brown trout, <i>Salmo trutta</i>	-	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, <i>Salmo trutta</i> L.	1989	Brown trout, <i>Salmo trutta</i>	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, <i>Salmo trutta</i> L.	1991	Brown trout, <i>Salmo trutta</i>	-	No control group
Reid et al.	Acclimation to sublethal aluminum: modification of metal - gill surface interactions of juvenile rainbow trout (<i>Oncorhynchus mykiss</i>)	1991	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	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 <i>Amoeba proteus</i>	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 <i>Asterionella</i>	1991	Diatom, <i>Asterionella ralfsii</i> Diatom, <i>Asterionella formosa</i>	-	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 <i>D. magna</i>	2005	Cladoceran, <i>Daphnia magna</i>	-	Not applicable; no aluminum toxicity data
Robertson and Liber	Bioassays with caged <i>Hyaella azteca</i> to determine in situ toxicity downstream of two Saskatchewan, Canada, uranium operations	2007	Amphipod, <i>Hyaella azteca</i>	-	Mixture; downstream exposure of uranium mining operation
Robinson and Deano	The synergistic effects of acidity and aluminum on fish (Golden shiners) in Louisiana	1985	Golden shiner, <i>Notemigonus crysoleucas</i>	-	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, <i>Notemigonus crysoleucas</i>	-	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, <i>Salmo salar</i> Brown trout, <i>Salmo trutta</i> Brook trout, <i>Salvelinus fontinalis</i>	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
Royset et al.	Diffusive gradients in thin films sampler predicts stress in brown trout (<i>Salmo trutta</i> L.) exposed to aluminum in acid fresh waters	2005	Brown trout, <i>Salmo trutta</i>	-	Mixture; dilution water is river water
Rueter et al.	Indirect aluminum toxicity to the green alga <i>Scenedesmus</i> through increased cupric ion activity	1987	Green alga, <i>Scenedesmus quadricauda</i>	-	Mixture; Al and Cu
Sacan and Balcioglu	Bioaccumulation of aluminium in <i>Dunaliella tertiolecta</i> in natural seawater: Aluminium-metal (Cu, Pb, Se) interactions and influence of pH	2001	Phytoplankton, <i>Dunaliella tertiolecta</i>	-	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, <i>Salmo trutta</i>	7 d NOEC (specific growth rate)=18.87 at pH=5.5; LOEC=30.04 at pH=5.5	Too few exposure concentrations; duration
Sadler and Lynam	The influence of calcium on aluminum-induced changes in the growth rate and mortality of brown trout, <i>Salmo trutta</i> L.	1988	Brown trout, <i>Salmo trutta</i>	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

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Salbu et al.	Environmentally relevant mixed exposures to radiation and heavy metals induce measurable stress responses in Atlantic salmon	2008	Atlantic salmon, <i>Salmo salar</i>	-	Only one exposure concentration; mixture
Sauer	Heavy metals in fish scales: accumulation and effects on cadmium regulation in the mummichog, <i>Fundulus heteroclitus</i> L.	1986	Mummichog, <i>Fundulus heteroclitus</i>	-	Not applicable; no aluminum toxicity data
Sayer	Survival and subsequent development of brown trout, <i>Salmo trutta</i> L., subjected to episodic exposures of acid, aluminum and copper in soft water during embryonic and larval stages	1991	Brown trout, <i>Salmo trutta</i>	-	Only one exposure concentration; mixture; low pH and Al
Sayer et al.	Embryonic and larval development of brown trout, <i>Salmo trutta</i> L.: exposure to aluminum, copper, lead or zinc in soft, acid water	1991a	Brown trout, <i>Salmo trutta</i>	700 d 13% mortality at 161.8	Only one exposure concentration
Sayer et al.	Embryonic and larval development of brown trout, <i>Salmo trutta</i> L.: exposure to trace metal mixtures in soft water	1991b	Brown trout, <i>Salmo trutta</i>	-	Only two exposure concentrations; mixture
Sayer et al.	Effects of six trace metals on calcium fluxes in brown trout (<i>Salmo trutta</i> L.) in soft water	1991c	Brown trout, <i>Salmo trutta</i>	-	Only two exposure concentrations; mixture
Sayer et al.	Mineral content and blood parameters of dying brown trout (<i>Salmo trutta</i> L.) exposed to acid and aluminum in soft water	1991d	Brown trout, <i>Salmo trutta</i>	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 (<i>Salvelinus fontinalis</i>) in acidified waters	1980	Brook trout, <i>Salvelinus fontinalis</i>	-	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, <i>Salmo trutta</i> , in low pH water	1988	Brown trout, <i>Salmo trutta</i>	5d Decrease weight and length at 230	Only one exposure concentration
Senger et al.	Aluminum exposure alters behavioral parameters and increases acetylcholinesterase activity in zebrafish (<i>Danio rerio</i>) brain	2011	Zebrafish, <i>Danio rerio</i>	4 d Increase AChE activity in brain at 10.12 at pH=5.8 but not pH=6.8	Only one exposure concentration

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
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 <i>Anabaena oryzae</i> and <i>Aulosira fertilissima</i>	1986a	-	-	Lack of details; cannot determine effect concentration
Shabana et al.	Studies on the effects of some heavy metals on the biological activities of some phytoplankton species. III. Effects Al ³⁺ , Cr ³⁺ , Pb ²⁺ and Zn ²⁺ on heterocyst frequency, nitrogen and phosphorus metabolism of <i>Anabaena oryzae</i> and <i>Aulosira fertilissima</i>	1986b	-	-	Lack of details; cannot determine effect concentration
Shuhaimi-Othman et al.	Toxicity of eight metals to Malaysian freshwater midge larvae <i>Chironomus javanus</i> (Diptera, Chironomidae)	2011b	Midge, <i>Chironomus javanus</i>	4 d LC50=1,430	Not North American species
Shuhaimi-Othman et al.	Toxicity of metals to tadpoles of the common Sunda toad, <i>Duttaphrynus melanostictus</i>	2012	Sunda toad, <i>Duttaphrynus melanostictus</i>	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 acid mine drainage streams	2005	-	-	Sediment exposure
Sivakumar and Sivasubramanian	FT-IR study of the effect of aluminum on the muscle tissue of <i>Cirrhinus mrigala</i>	2011	Carp hawk, <i>Cirrhinus mrigala</i>	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, <i>Salmo salar</i> L., at low levels of aluminum in acidic softwater	1986	Atlantic salmon, <i>Salmo salar</i>	-	Mixture; dilution water is lake water
Soleng et al.	Toxicity of aqueous aluminum to the ectoparasitic monogenean <i>Gyrodactylus salaris</i>	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 Sø	1978	-	-	Not applicable; no aluminum toxicity data
Sparling and Lowe	Environmental hazards of aluminum to plants, invertebrates, fish and wildlife	1996a	-	-	Review; results of previously published papers

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Sparling and Lowe	Metal concentrations of tadpoles in experimental ponds	1996b	-	-	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, <i>Salmo salar</i>	1993	Atlantic salmon, <i>Salmo salar</i>	-	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 <i>Cyclops viridis</i> (Crustacea, Copepoda) and <i>Gammarus pulex</i> (Crustacea, Amphipoda)	1992	Copepod, <i>Cyclops viridis</i> Amphipod, <i>Gammarus pulex</i>	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 <i>Daphnia magna</i> and <i>Vibrio fischeri</i>	2009	Cladoceran, <i>Daphnia magna</i>	-	Inappropriate form of toxicant, nanoparticles
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 <i>Cloeon triangulifer</i> McDunnough (Ephemeroptera: Baetidae)	1991	Mayfly, <i>Cloeon triangulifer</i>	No effect on hatch success at 100 and pH=5.5	Only two exposure concentrations
Taneeva	Toxicity of some heavy metals for hydrobionts	1973	Barnacle, <i>Balanus eburneus</i>	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, <i>Margaritifera margaritifera</i>	2011	Pearl mussel, <i>Margaritifera margaritifera</i>	-	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
Terhaar et al.	Toxicity of photographic processing chemicals to fish	1972	-	-	Mixture; no aluminum toxicity data

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Thomas	Effects of certain metallic salts upon fishes	1915	Mummichog, <i>Fundulus heteroclitus</i>	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
Thomsen et al.	Effect of aluminum and calcium ions on survival and physiology of rainbow trout <i>Salmo gairdneri</i> (Richardson) eggs and larvae exposed to acid stress	1988	Rainbow trout, <i>Oncorhynchus mykiss</i>	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, <i>Salmo salar</i>	-	Only two exposure concentrations; surgically altered test species (outfitted with acoustic transmitters)
Tietge et al.	Morphometric changes in gill secondary lamellae of brook trout (<i>Salvelinus fontinalis</i>) after long-term exposure to acid and aluminum	1988	Brook trout, <i>Salvelinus fontinalis</i>	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. <i>Daphnia magna</i>	1995a	Cladoceran, <i>Daphnia magna</i>	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 <i>Bulinus globosus</i>	1995b	Snail, <i>Bulinus globosus</i>	96 hr 100% mortality at 10,000; 1% mortality at 3,000	Not North American species
Troilo et al.	Biochemical responses of <i>Prochilodus lineatus</i> after 24-h exposure to aluminum	2007	Sabalo, <i>Prochilodus lineatus</i>	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 <i>Lymnaea stagnalis</i>	1995	Snail, <i>Lymnaea stagnalis</i>	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 <i>Astacus leptodactylus</i>	2013	Crayfish, <i>Astacus leptodactylus</i>	-	Field bioaccumulation study: exposure concentration not know; not North American species

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
van Coillie and Rousseau	Mineral composition of the scales of <i>Catostomus commersoni</i> from two different waters: Studies using electron microprobe analysis	1974	White sucker, <i>Catostomus commersoni</i>	-	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
Vazquez et al.	Effects of water acidity and metal concentrations on accumulation and within-plant distribution of metals in the aquatic bryophyte <i>Fontinalis antipyretica</i>	2000	Bryophyte, <i>Fontinalis antipyretica</i>	-	Exposure concentration not known; field accumulation study
Velzeboer et al.	Aquatic ecotoxicity tests of some nanomaterials	2008	-	-	Inappropriate form of toxicant, nanoparticles
Verboost et al.	The toxic mixing zone of neutral and acidic river water: acute aluminum toxicity in brown trout (<i>Salmo trutta</i> L.)	1995	Brown trout, <i>Salmo trutta</i>	-	Mixture; dilution water is lake water
Vieira et al.	Effects of aluminum on the energetic substrates in neotropical freshwater <i>Astyanax bimaculatus</i> (Teleostei: Characidae) females	2013	Two spot astyanax, <i>Astyanax bimaculatus</i>	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 (<i>Paralichthys olivaceus</i>)	2013	Olive flounder, <i>Paralichthys olivaceus</i>	-	Injected toxicant
Vincent et al.	Accumulation of Al, Mn, Fe, Cu, Zn, Cd, and Pb by the bryophyte <i>Scapania undulata</i> in three upland waters of different pH	2001	Bryophyte, <i>Scapania undulata</i>	-	Exposure concentration not known; field accumulation study
Vuorinen et al.	The sensitivity to acidity and aluminum of newly-hatched perch (<i>Perca fluviatilis</i>) originating from strains from four lakes with different degrees	1994a	Perch, <i>Perca fluviatilis</i>	7 d LC50=>1,000	Not North American species
Vuorinen et al.	The sensitivity to acidification of pike (<i>Esox lucius</i>), whitefish (<i>Coregonus lavaretus</i>) and roach (<i>Rutilus rutilus</i>): 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 (<i>Coregonus albula</i> L.) in long-term exposure to acidity to aluminum	2003	Vendace, <i>Coregonus albula</i>	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

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Walker et al.	Effects of low pH and aluminum on ventilation in the brook trout (<i>Salvelinus fontinalis</i>)	1988	Brook trout, <i>Salvelinus fontinalis</i>	-	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 (<i>Salvelinus fontinalis</i>)	1991	Brook trout, <i>Salvelinus fontinalis</i>	-	Pre-exposure to pollutant
Wallen et al.	Toxicity to <i>Gambusia affinis</i> of certain pure chemicals in turbid waters	1957	Western mosquitofish, <i>Gambusia affinis</i>	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, <i>Lymnaea stagnalis</i>	2009	Snail, <i>Lymnaea stagnalis</i>	steady state not reached	Lack of details; steady state not reached
Ward et al.	Influences of aqueous aluminum on the immune system of the freshwater crayfish <i>Pacifastacus leniusculus</i>	2006	Crayfish, <i>Pacifastacus leniusculus</i>	-	Only one exposure concentration; test organism injected with bacteria
Waring and Brown	Ionoregulatory and respiratory responses of brown trout, <i>Salmo trutta</i> , exposed to lethal and sublethal aluminum in acidic soft waters	1995	Brown trout, <i>Salmo trutta</i>	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 (<i>Salmo trutta</i>) exposed to lethal and sublethal aluminum in acidic soft waters	1996	Brown trout, <i>Salmo trutta</i>	-	Surgically altered test species
Waterman	Effect of salts of heavy metals on development of the sea urchin, <i>Arbacia punctulata</i>	1937	Sea urchin, <i>Arbacia punctulata</i>	-	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 (<i>Salmo trutta</i> L.) in relation to aluminum speciation in upland Welsh streams	1990	Brown trout, <i>Salmo trutta</i>	-	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, <i>Lymnaea stagnalis</i>	-	Mixture, Al and Si

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Whitehead and Brown	Endocrine responses of brown trout, <i>Salmo trutta</i> L., to acid, aluminum and lime dosing in a Welsh hill stream	1989	Brown trout, <i>Salmo trutta</i>	-	Mixture, field experiment-dosed stream
Wilkinson and Campbell	Aluminum bioconcentration at the gill surface of juvenile Atlantic salmon in acidic media	1993	Atlantic salmon, <i>Salmo salar</i>	-	Bioaccumulation: steady state not reached
Wilkinson et al.	Surface complexation of aluminum on isolated fish gill cells	1993	Largemouth bass, <i>Micropterus salmoides</i>	-	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
Wilson and Hyne	Toxicity of acid-sulfate soil leachate and aluminum to embryos of the Sydney Rock Oyster	1997	Sydney rock oyster, <i>Accostrea commercialis</i>	48 hr EC50 (development)=222; EC50=227	Not North American species
Wilson and Wood	Swimming performance, whole body ions, and gill Al accumulation during acclimation to sublethal aluminum in juvenile rainbow trout (<i>Oncorhynchus mykiss</i>)	1992	Rainbow trout, <i>Oncorhynchus mykiss</i>	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 (<i>Oncorhynchus mykiss</i>). 1: Acclimation specificity, resting physiology, feeding, and growth	1994a	Rainbow trout, <i>Oncorhynchus mykiss</i>	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 (<i>Oncorhynchus mykiss</i>). 2: Gill morphology, swimming performance, and aerobic scope	1994b	Rainbow trout, <i>Oncorhynchus mykiss</i>	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 (<i>Oncorhynchus mykiss</i>)	1996	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	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 (<i>Oncorhynchus mykiss</i>)	2005	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Bioaccumulation: not renewal or flow-through exposure; high control mortality
Witters	Acute acid exposure of rainbow trout, <i>Salmo gairdneri</i> Richardson: effects of aluminum and calcium on ion balance and haematology	1986	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species; only one exposure concentration

Author	Title	Date	Organism(s)	Concentration (µg/L)	Reason Unused
Witters et al.	Interference of aluminum and pH on the Na-influx in an aquatic insect <i>Corixa punctata</i> (Illig.)	1984	Waterbug, <i>Corixa punctata</i>	-	Mixture; low pH and Al
Witters et al.	Ionoregulatory and haematological responses of rainbow trout <i>Salmo gairdneri</i> Richardson to chronic acid and aluminum stress	1987	Rainbow trout, <i>Oncorhynchus mykiss</i>	48 hr ~50% mortality at 200	Only one exposure concentration
Witters et al.	Haematological disturbances and osmotic shifts in rainbow trout, <i>Oncorhynchus mykiss</i> (Walbaum) under acid and aluminum exposure	1990a	Rainbow trout, <i>Oncorhynchus mykiss</i>	2.5 d ~53% mortality at 200	Only one exposure concentration
Witters et al.	The effect of humic substances on the toxicity of aluminum to adult rainbow trout, <i>Oncorhynchus mykiss</i> (Walbaum)	1990b	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species
Witters et al.	Adrenergic response to physiological disturbances in rainbow trout, <i>Oncorhynchus mykiss</i> , exposed to aluminum at acid pH	1991	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species
Witters et al.	Physicochemical changes of aluminum in mixing zones: Mortality and physiological disturbances in brown trout (<i>Salmo trutta</i> L.)	1996	Brown trout, <i>Salmo trutta</i>	48 hr 60% mortality at 184.0	Only one exposure concentration
Wold	Some effects of aluminum sulfate and arsenic sulfide on <i>Daphnia pulex</i> and <i>Chironomus tentans</i>	2001	Cladoceran, <i>Daphnia pulex</i> Midge, <i>Chironomus tentans</i>	-	Inadequate exposure methods; chronic was a static, unmeasured exposure; pre-exposure to pollutant
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 (<i>Salvelinus fontinalis</i>) under acid/aluminum exposure	1988a	Brook trout, <i>Salvelinus fontinalis</i>	-	Only one exposure concentration; surgically altered test species
Wood et al.	Physiological evidence of acclimation to acid/aluminum stress in adult brook trout (<i>Salvelinus fontinalis</i>). 1. Blood composition and net sodium fluxes	1988b	Brook trout, <i>Salvelinus fontinalis</i>	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 (<i>Salvelinus fontinalis</i>). 2. Blood parameters by cannulation	1988c	Brook trout, <i>Salvelinus fontinalis</i>	-	Only one exposure concentration; surgically altered test species
Wood et al.	Whole body ions of brook trout (<i>Salvelinus fontinalis</i>) alevins: responses of yolk-sac and swim-up stages to water acidity, calcium, and aluminum, and recovery effects	1990a	Brook trout, <i>Salvelinus fontinalis</i>	-	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 (<i>Salvelinus fontinalis</i>) continuously exposed from fertilization to swim-up: a study by instrumental neutron activation analysis	1990b	Brook trout, <i>Salvelinus fontinalis</i>	-	Lack of details; cannot determine effect concentration
Wooldridge and Wooldridge	Internal damage in an aquatic beetle exposed to sublethal concentrations of inorganic ions	1969	Aquatic beetle, <i>Tropisternus lateralis nimbatus</i>	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.	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
Youson and Neville	Deposition of aluminum in the gill epithelium of rainbow trout (<i>Salmo gairdneri</i> Richardson) subjected to sublethal concentrations of the metal	1987	Rainbow trout, <i>Oncorhynchus mykiss</i>	-	Surgically altered test species
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 (<i>Danio rerio</i>) early developmental stage	2008	Zebrafish, <i>Danio rerio</i>	-	Inappropriate form of toxicant, nanoparticles

Appendix K CRITERIA FOR VARIOUS WATER CHEMISTRY CONDITIONS

Table K-1. Freshwater CMC at DOC of 0.5 mg/L and Various Water Hardness Levels and pHs.

Hardness	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 8.5		pH 9.0	
25	5.3	a	30	a	130	b	360	d	750	d	1,200	b	1,200	a	940	a	530	a
50	9.7	a	50	a	190	b	470	d	880	d	1,300	d	1,300	g	920	a	470	a
75	14	a	68	a	250	c	550	d	930	d	1,400	d	1,400	b	900	a	430	a
100	18	a	85	a	290	d	600	d	960	e	1,400	d	1,400	b	890	a	410	a
150	26	a	110	a	370	d	680	d	1,000	f	1,300	e	1,400	d	870	a	380	a
200	26	a	110	a	370	d	680	d	1,000	f	1,300	e	1,400	d	870	a	380	a
250	26	a	110	a	370	d	680	d	1,000	f	1,300	e	1,400	d	870	a	380	a
300	26	a	110	a	370	d	680	d	1,000	f	1,300	e	1,400	d	870	a	380	a
350	26	a	110	a	370	d	680	d	1,000	f	1,300	e	1,400	d	870	a	380	a
400	26	a	110	a	370	d	680	d	1,000	f	1,300	e	1,400	d	870	a	380	a

Bolded values indicate where the 2017 criteria are lower than the 1988 criteria magnitude within the 1988 pH range applied of 6.5-9.0.

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Daphnia, Ceriodaphnia, Stenocypris, Crangonyx

b Daphnia, Ceriodaphnia, Oncorhynchus, Micropterus

c Daphnia, Oncorhynchus, Ceriodaphnia, Micropterus

d Daphnia, Oncorhynchus, Micropterus, Ceriodaphnia

e Daphnia, Oncorhynchus, Micropterus, Salmo

f Oncorhynchus, Daphnia, Micropterus, Salmo

g Daphnia, Ceriodaphnia, Stenocypris, Oncorhynchus

h Oncorhynchus, Micropterus, Daphnia, Salmo

Table K-2. Freshwater CCC at DOC of 0.5 mg/L and Various Water Hardness Levels and pHs.

Hardness	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 8.5		pH 9.0	
25	2.3	a	14	b	69	c	160	f	350	f	620	i	540	b	410	a	230	a
50	4.3	a	24	b	100	d	170	f	310	f	630	f	670	j	400	a	200	a
75	6.1	a	33	b	130	e	180	f	290	f	530	f	730	i	390	a	190	a
100	7.8	a	41	b	150	e	190	f	280	g	460	f	770	c	390	a	180	a
150	11	a	55	b	180	f	200	g	270	h	390	g	650	f	430	b	170	a
200	11	a	55	b	180	f	200	g	270	h	390	g	650	f	430	b	170	a
250	11	a	55	b	180	f	200	g	270	h	390	g	650	f	430	b	170	a
300	11	a	55	b	180	f	200	g	270	h	390	g	650	f	430	b	170	a
350	11	a	55	b	180	f	200	g	270	h	390	g	650	f	430	b	170	a
400	11	a	55	b	180	f	200	g	270	h	390	g	650	f	430	b	170	a

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Lampsilis, Ceriodaphnia, Hyalella, Brachionus

b Lampsilis, Ceriodaphnia, Hyalella, Salmo

c Lampsilis, Salmo, Ceriodaphnia, Salvelinus

d Salmo, Lampsilis, Ceriodaphnia, Salvelinus

e Salmo, Lampsilis, Salvelinus, Ceriodaphnia

f Salmo, Salvelinus, Lampsilis, Ceriodaphnia

g Salmo, Salvelinus, Lampsilis, Danio

h Salmo, Salvelinus, Danio, Lampsilis

i Lampsilis, Ceriodaphnia, Salmo, Salvelinus

j Lampsilis, Ceriodaphnia, Salmo, Hyalella

Table K-3. Freshwater CMC at DOC of 1.0 mg/L and Various Water Hardness Levels and pHs.

Hardness	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 8.5		pH 9.0	
25	7.6	a	43	a	180	b	510	d	1,100	d	1,700	b	1,800	a	1,400	a	760	a
50	14	a	72	a	280	c	680	d	1,300	d	1,900	d	1,900	g	1,300	a	670	a
75	20	a	98	a	350	c	780	d	1,300	d	2,000	d	2,000	b	1,300	a	620	a
100	26	a	120	a	420	d	860	d	1,400	e	2,000	d	2,000	b	1,300	a	590	a
150	37	a	160	a	530	d	970	d	1,500	f	1,900	e	2,100	d	1,300	a	550	a
200	37	a	160	a	530	d	970	d	1,500	f	1,900	e	2,100	d	1,300	a	550	a
250	37	a	160	a	530	d	970	d	1,500	f	1,900	e	2,100	d	1,300	a	550	a
300	37	a	160	a	530	d	970	d	1,500	f	1,900	e	2,100	d	1,300	a	550	a
350	37	a	160	a	530	d	970	d	1,500	f	1,900	e	2,100	d	1,300	a	550	a
400	37	a	160	a	530	d	970	d	1,500	f	1,900	e	2,100	d	1,300	a	550	a

Bolded values indicate where the 2017 criteria are lower than the 1988 criteria magnitude within the 1988 pH range applied of 6.5-9.0.

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Daphnia, Ceriodaphnia, Stenocypris, Crangonyx

b Daphnia, Ceriodaphnia, Oncorhynchus, Micropterus

c Daphnia, Oncorhynchus, Ceriodaphnia, Micropterus

d Daphnia, Oncorhynchus, Micropterus, Ceriodaphnia

e Daphnia, Oncorhynchus, Micropterus, Salmo

f Oncorhynchus, Daphnia, Micropterus, Salmo

g Daphnia, Ceriodaphnia, Stenocypris, Oncorhynchus

h Oncorhynchus, Micropterus, Daphnia, Salmo

Table K-4. Freshwater CCC at DOC of 1.0 mg/L and Various Water Hardness Levels and pHs.

Hardness	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 8.5		pH 9.0	
25	3.3	a	21	b	99	c	220	f	490	f	900	i	780	b	590	a	330	a
50	6.1	a	35	b	150	e	250	f	440	f	890	f	960	j	580	a	290	a
75	8.8	a	47	b	180	e	260	f	410	f	740	f	1,100	i	570	a	270	a
100	11	a	59	b	210	e	270	f	390	g	650	f	1,100	c	560	b	260	a
150	16	a	80	b	250	f	280	g	380	h	540	g	910	f	620	b	240	a
200	16	a	80	b	250	f	280	g	380	h	540	g	910	f	620	b	240	a
250	16	a	80	b	250	f	280	g	380	h	540	g	910	f	620	b	240	a
300	16	a	80	b	250	f	280	g	380	h	540	g	910	f	620	b	240	a
350	16	a	80	b	250	f	280	g	380	h	540	g	910	f	620	b	240	a
400	16	a	80	b	250	f	280	g	380	h	540	g	910	f	620	b	240	a

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Lampsilis, Ceriodaphnia, Hyalella, Brachionus

b Lampsilis, Ceriodaphnia, Hyalella, Salmo

c Lampsilis, Salmo, Ceriodaphnia, Salvelinus

d Salmo, Lampsilis, Ceriodaphnia, Salvelinus

e Salmo, Lampsilis, Salvelinus, Ceriodaphnia

f Salmo, Salvelinus, Lampsilis, Ceriodaphnia

g Salmo, Salvelinus, Lampsilis, Danio

h Salmo, Salvelinus, Danio, Lampsilis

i Lampsilis, Ceriodaphnia, Salmo, Salvelinus

j Lampsilis, Ceriodaphnia, Salmo, Hyalella

Table K-5. Freshwater CMC at DOC of 2.5 mg/L and Various Water Hardness Levels and pHs.

Hardness	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 8.5		pH 9.0	
25	12	a	70	a	290	b	820	d	1,700	d	2,700	b	2,800	a	2,200	a	1,200	a
50	23	a	120	a	450	c	1,100	d	2,000	d	3,100	d	3,000	g	2,100	a	1,100	a
75	32	a	160	a	570	d	1,200	d	2,100	d	3,200	d	3,200	b	2,100	a	1,000	a
100	42	a	200	a	680	d	1,400	d	2,200	e	3,100	d	3,300	b	2,100	a	960	a
150	60	a	270	a	860	d	1,500	e	2,400	h	3,000	e	3,300	d	2,000	a	890	a
200	60	a	270	a	860	d	1,500	e	2,400	h	3,000	e	3,300	d	2,000	a	890	a
250	60	a	270	a	860	d	1,500	e	2,400	h	3,000	e	3,300	d	2,000	a	890	a
300	60	a	270	a	860	d	1,500	e	2,400	h	3,000	e	3,300	d	2,000	a	890	a
350	60	a	270	a	860	d	1,500	e	2,400	h	3,000	e	3,300	d	2,000	a	890	a
400	60	a	270	a	860	d	1,500	e	2,400	h	3,000	e	3,300	d	2,000	a	890	a

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Daphnia, Ceriodaphnia, Stenocypris, Crangonyx

b Daphnia, Ceriodaphnia, Oncorhynchus, Micropterus

c Daphnia, Oncorhynchus, Ceriodaphnia, Micropterus

d Daphnia, Oncorhynchus, Micropterus, Ceriodaphnia

e Daphnia, Oncorhynchus, Micropterus, Salmo

f Oncorhynchus, Daphnia, Micropterus, Salmo

g Daphnia, Ceriodaphnia, Stenocypris, Oncorhynchus

h Oncorhynchus, Micropterus, Daphnia, Salmo

Table K-6. Freshwater CCC at DOC of 2.5 mg/L and Various Water Hardness Levels and pHs.

Hardness	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 8.5		pH 9.0	
25	5.4	a	34	b	160	c	350	f	770	f	1,500	i	1,300	b	960	a	540	a
50	9.9	a	57	b	230	e	390	f	690	f	1,400	f	1,600	j	930	a	470	a
75	14	a	77	b	290	e	410	f	640	f	1,200	f	1,700	i	920	a	440	a
100	18	a	96	b	330	e	420	f	620	g	1,000	f	1,800	d	920	b	420	a
150	26	a	130	b	390	f	450	g	590	h	860	g	1,400	f	1,000	b	390	a
200	26	a	130	b	390	f	450	g	590	h	860	g	1,400	f	1,000	b	390	a
250	26	a	130	b	390	f	450	g	590	h	860	g	1,400	f	1,000	b	390	a
300	26	a	130	b	390	f	450	g	590	h	860	g	1,400	f	1,000	b	390	a
350	26	a	130	b	390	f	450	g	590	h	860	g	1,400	f	1,000	b	390	a
400	26	a	130	b	390	f	450	g	590	h	860	g	1,400	f	1,000	b	390	a

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Lampsilis, Ceriodaphnia, Hyalella, Brachionus

b Lampsilis, Ceriodaphnia, Hyalella, Salmo

c Lampsilis, Salmo, Ceriodaphnia, Salvelinus

d Salmo, Lampsilis, Ceriodaphnia, Salvelinus

e Salmo, Lampsilis, Salvelinus, Ceriodaphnia

f Salmo, Salvelinus, Lampsilis, Ceriodaphnia

g Salmo, Salvelinus, Lampsilis, Danio

h Salmo, Salvelinus, Danio, Lampsilis

i Lampsilis, Ceriodaphnia, Salmo, Salvelinus

j Lampsilis, Ceriodaphnia, Salmo, Hyalella

Table K-7. Freshwater CMC at DOC of 5.0 mg/L and Various Water Hardness Levels and pHs.

Hardness	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 8.5		pH 9.0	
25	18	a	100	a	420	b	1,200	d	2,500	d	3,900	b	4,100	a	3,200	a	1,800	a
50	33	a	170	a	640	c	1,500	d	2,900	d	4,400	d	4,400	g	3,100	a	1,600	a
75	47	a	230	a	820	d	1,800	d	3,000	d	4,500	d	4,600	b	3,000	a	1,500	a
100	60	a	280	a	970	d	1,900	d	3,100	e	4,500	d	4,700	b	3,000	a	1,400	a
150	86	a	380	a	1,200	d	2,200	e	3,400	h	4,300	e	4,700	d	2,900	a	1,300	a
200	86	a	380	a	1,200	d	2,200	e	3,400	h	4,300	e	4,700	d	2,900	a	1,300	a
250	86	a	380	a	1,200	d	2,200	e	3,400	h	4,300	e	4,700	d	2,900	a	1,300	a
300	86	a	380	a	1,200	d	2,200	e	3,400	h	4,300	e	4,700	d	2,900	a	1,300	a
350	86	a	380	a	1,200	d	2,200	e	3,400	h	4,300	e	4,700	d	2,900	a	1,300	a
400	86	a	380	a	1,200	d	2,200	e	3,400	h	4,300	e	4,700	d	2,900	a	1,300	a

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Daphnia, Ceriodaphnia, Stenocypris, Crangonyx

b Daphnia, Ceriodaphnia, Oncorhynchus, Micropterus

c Daphnia, Oncorhynchus, Ceriodaphnia, Micropterus

d Daphnia, Oncorhynchus, Micropterus, Ceriodaphnia

e Daphnia, Oncorhynchus, Micropterus, Salmo

f Oncorhynchus, Daphnia, Micropterus, Salmo

g Daphnia, Ceriodaphnia, Stenocypris, Oncorhynchus

h Oncorhynchus, Micropterus, Daphnia, Salmo

Table K-8. Freshwater CCC at DOC of 5.0 mg/L and Various Water Hardness Levels and pHs.

Hardness	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 8.5		pH 9.0	
25	7.7	a	49	b	230	c	500	f	1,100	f	2,100	c	1,900	b	1,400	a	770	a
50	14	a	82	b	330	e	540	f	970	f	2,000	f	2,200	j	1,300	a	680	a
75	20	a	110	b	410	e	570	f	900	f	1,600	f	2,500	i	1,300	a	640	a
100	26	a	140	b	460	f	590	f	880	g	1,400	f	2,500	d	1,300	b	600	a
150	38	a	190	b	550	f	630	g	840	h	1,200	g	2,000	f	1,500	b	560	a
200	38	a	190	b	550	f	630	g	840	h	1,200	g	2,000	f	1,500	b	560	a
250	38	a	190	b	550	f	630	g	840	h	1,200	g	2,000	f	1,500	b	560	a
300	38	a	190	b	550	f	630	g	840	h	1,200	g	2,000	f	1,500	b	560	a
350	38	a	190	b	550	f	630	g	840	h	1,200	g	2,000	f	1,500	b	560	a
400	38	a	190	b	550	f	630	g	840	h	1,200	g	2,000	f	1,500	b	560	a

Ranking of four most sensitive genera (Rank 1-Rank 4).

a Lampsilis, Ceriodaphnia, Hyalella, Brachionus

b Lampsilis, Ceriodaphnia, Hyalella, Salmo

c Lampsilis, Salmo, Ceriodaphnia, Salvelinus

d Salmo, Lampsilis, Ceriodaphnia, Salvelinus

e Salmo, Lampsilis, Salvelinus, Ceriodaphnia

f Salmo, Salvelinus, Lampsilis, Ceriodaphnia

g Salmo, Salvelinus, Lampsilis, Danio

h Salmo, Salvelinus, Danio, Lampsilis

i Lampsilis, Ceriodaphnia, Salmo, Salvelinus

j Lampsilis, Ceriodaphnia, Salmo, Hyalella

Appendix L ACUTE TO CHRONIC RATIOS

As stated in **Section 2.7.3** the chronic criterion can be calculated in one of two ways. Since, the freshwater chronic data were supplemented with a chronic value for an amphibian from the “Other Data” all eight MDRs were met. The freshwater chronic criterion is derived using the same method as the acute criterion, employing chronic values (e.g., EC₂₀) estimated from acceptable toxicity tests. However, if this were not the case (fewer chronic data are available), the chronic criterion can be derived by determining an appropriate acute-chronic ratio (ACR), described below.

The ACR is a way of relating the acute and chronic toxicities of a material to aquatic organisms. Acute-chronic ratios can be used to derive chronic criteria with data for species of aquatic animals provided that at least three of the minimum data requirements are met and that:

- at least one is a fish
- at least one is an invertebrate
- at least one is an acutely sensitive freshwater species (or estuarine/marine species if estuarine/marine criteria are being derived); the other two species data may be freshwater or estuarine/marine as appropriate to the derivation.

ACRs are calculated by dividing the acute toxicity test values by a “paired” (same lab, same dilution water) chronic test value. Comparisons of ACRs across taxa may elucidate differences and similarities in taxa response. If variability is greater than ten-fold among calculated ACRs, and no explainable trend exists, then a chronic criterion should not be derived, per the 1985 Guidelines. The Final ACR (FACR) is then derived by calculating the geometric mean of all acceptable ACRs. The Final Chronic Value (FCV) is then estimated by dividing the FAV by the FACR. This serves as the basis for the chronic criterion. Aluminum ACRs could be calculated for four freshwater species, a mussel, a cladoceran, an amphipod and a fish. No estuarine/marine ACRs could be calculated.

The chronic toxicity of aluminum to the freshwater unionid mussel, *Lampsilis siliquoidea*, was evaluated by Wang et al. (2016, 2017). The calculated biomass EC₂₀ was 169 µg/L; division of the 96-hr LC₅₀ of >6,302 µg/L also reported by Wang et al. (2016, 2017) resulted in an ACR of >37.29 for the species (**Table L-1**).

Two chronic aluminum studies were conducted in separate laboratories with the cladoceran, *Ceriodaphnia dubia* (ENSR 1992b; McCauley et al. 1986). 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. The EC₂₀ and MATC were estimated to be 1,780 and <1,100 µg/L, respectively. Division of the 48-hr LC₅₀s (1,900 and 1,500 µg/L) (**Appendix A**) by the two chronic values from the same study resulted in ACRs of 1.067 and <1.364, respectively.

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 CaCO₃ and pH of 7.3, 7.5, 7.9 and 8.1, respectively. The mean number of young produced per female was the most sensitive endpoint and division of the *C. dubia* 48-hr LC₅₀ from another study conducted in the same dilution water by the same laboratory (ENSR 1992d) resulted in ACRs of 0.4624, 2.325, 3.758 and >145.7 (**Table L-1**).

Wang et al. (2016, 2017) also conducted a *H. azteca* chronic test where 7-day old juvenile amphipods were exposed under flow-through measured conditions for 28 days. The calculated biomass EC₂₀ was 425 µg/L, and division of the *H. azteca* 96-hr LC₅₀ of >5,997 µg/L also reported by Wang et al. (2016, 2017) resulted in an ACR of >14.11 for the species.

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. Biomass was more sensitive than percent hatchability, growth and survival to the aluminum exposures, with a resulting EC₂₀ of 6,194 µg/L. Division of the 96-hr LC₅₀ value of 35,000 µg/L obtained from a fed acute exposure in the same study resulted in an ACR of 5.651 (**Table L-1**).

Table L-1. Acute to Chronic Ratios.

Species	Acute Hardness (mg/L as CaCO ₃)	Chronic Hardness (mg/L as CaCO ₃)	pH	Acute Value (µg/L)	Chronic Value (µg/L)	Ratio	Species Acute-Chronic Ratio	Reference
Freshwater Species								
Fatmucket, <i>Lampsilis siliquoidea</i>	106 (104-108)	105.5 (105-106)	5.95-6.13	>6,302	169	>37.29	>37.29	Wang et al. 2016, 2017
Cladoceran, <i>Ceriodaphnia dubia</i>	50	50	7.15-7.42	1,900	1,780	1.067	-	McCauley et al. 1986
Cladoceran, <i>Ceriodaphnia dubia</i>	50.5	50.5	7.61-7.86	1,500	<1,100	<1.364	-	McCauley et al. 1986
Cladoceran, <i>Ceriodaphnia dubia</i>	26	26	7.3-7.5	720	1,557	0.4624	-	ENSR 1992b; 1992d

Species	Acute Hardness (mg/L as CaCO ₃)	Chronic Hardness (mg/L as CaCO ₃)	pH	Acute Vale (µg/L)	Chronic Value (µg/L)	Ratio	Species Acute-Chronic Ratio	Reference
Cladoceran, <i>Ceriodaphnia dubia</i>	46	46	7.5-7.6	1,880	808.7	2.325	-	ENSR 1992b; 1992d
Cladoceran, <i>Ceriodaphnia dubia</i>	96	96	7.8-7.9	2,450	651.9	3.758	-	ENSR 1992b; 1992d
Cladoceran, <i>Ceriodaphnia dubia</i>	194	194	8.1	>99,600	683.6	>145.7 ^a	1.425	ENSR 1992b; 1992d
Amphipod, <i>Hyalella azteca</i>	106 (103-108)	106 (105-107)	5.92-6.16	>5,997 ^b	425	>14.11	>14.11	Wang et al. 2016, 2017
Fathead minnow, <i>Pimephales promelas</i>	220	220	7.27-7.34	35,000 ^b	6,194	5.651	5.651	Kimball 1978

^a Not used to calculate *C. dubia* ACR because value is considered an outlier.

^b Acute study was fed.

While there are four freshwater species ACRs, there are no ACRs available for estuarine/marine species. If the requirement for an estuarine/marine species ACR is ignored, the FACR, calculated as the geometric mean of the four species ACRs, is 8.068 (**Table L-1**). While it is possible to use the FACR to develop this alternate FCV, this value is considered too conservative, i.e., the FCV based on division of the FAV of 2,741 µg/L by the FACR of 8.068 is 340 µg/L and is 1.5 times lower than the lowest GMCV (*Salmo*, 508.5 µg/L) (**Figure L-1**).

However, this result demonstrates that the chronic criterion of 390 µg/L total aluminum at pH 7, hardness of 100 mg/L as CaCO₃ and DOC of 1.0 mg/L, derived via the use of a sensitivity distribution of empirical chronic data is supported via calculations by this other, more indirect ACR-based chronic criterion calculation. Additional estuarine/marine toxicity data would reduce this uncertainty.

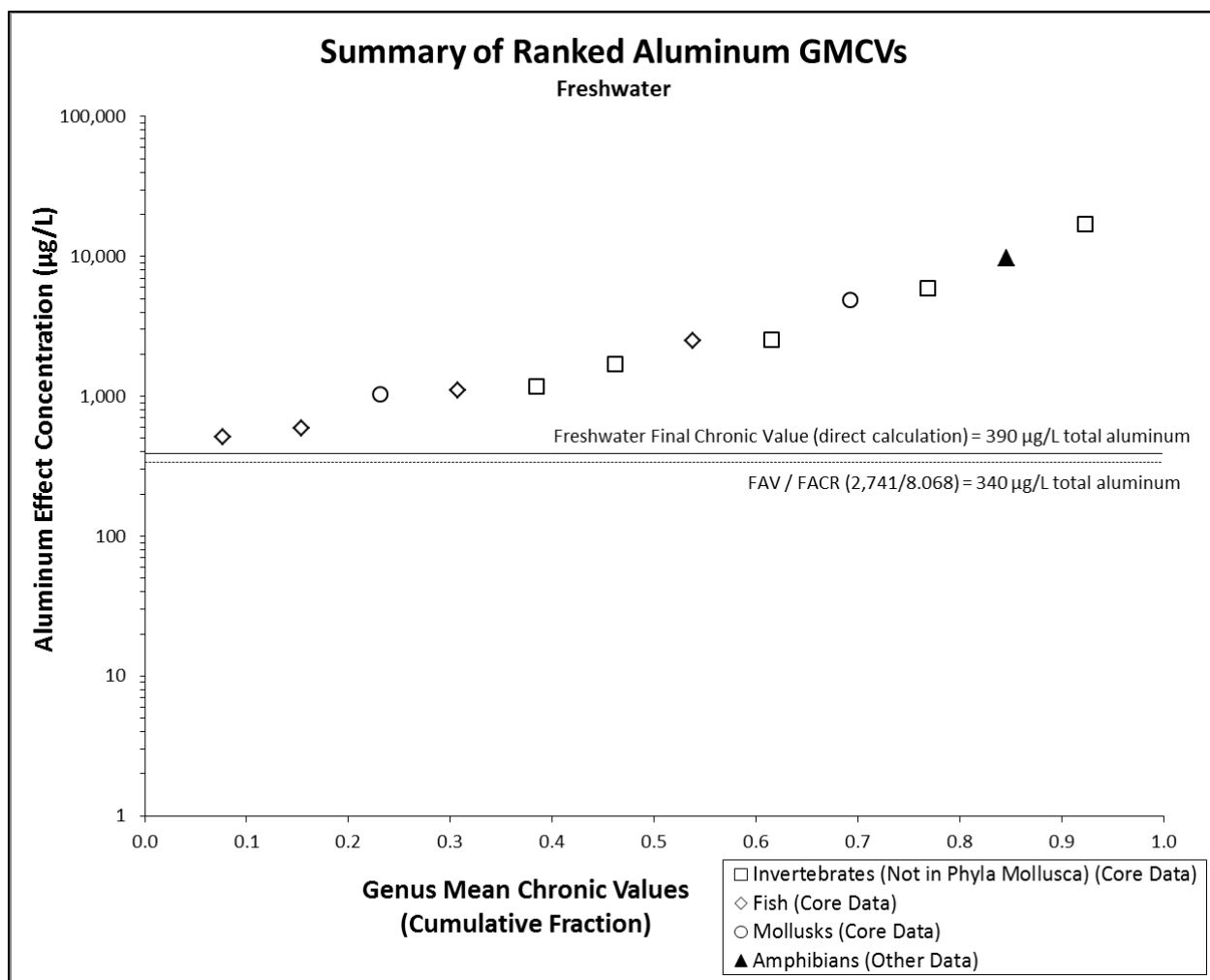


Figure L-1. Ranked Summary of Total Aluminum Genus Mean Chronic Values (GMCVs) at pH 7, Hardness of 100 mg/L, and DOC of 1 mg/L.