Procedures for Deriving Refuge-Specific Water Quality Targets for the Protection of Natural Resources on National Wildlife Refuges

Prepared for:

National Wildlife Refuge System
U.S. Fish and Wildlife Service

Prepared – *December, 2014* – by:

MacDonald Environmental Sciences Ltd.
#24 - 4800 Island Highway North
Nanaimo, British Columbia V9T 1W6

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ENVIRONMENTAL SCIENCES LTD.

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D.D. MacDonald, J.A. Sinclair, A. Schein, M.E. Wainwright, H.J. Prencipe, and M.L. Haines
MacDonald Environmental Sciences Ltd.
#24 - 4800 Island Highway North
Nanaimo, British Columbia V9T 1W6

Preface

Mike Higgins and Kevin Kilbride, National Wildlife Refuge System, U.S. Fish and Wildlife Service

Assessing Water Quality on National Wildlife Refuges: An Overview

Water is the lifeblood of the National Wildlife Refuge System (NWRS); maintaining adequate supplies of clean, fresh water is essential to achieving the mission of the NWRS. Protecting refuge water quality requires identifying existing and potential sources of contamination, monitoring water quality to document baseline conditions and detect changes, and assessing potential effects that contaminants may have on wildlife and habitats. In addition, it is imperative that refuge staff have access to these information sources to help them manage refuge water supplies to safeguard fish, wildlife, and habitats.

To determine if water quality on a refuge is sufficient to support fish and wildlife resources in order to meet refuge purposes and the NWRS mission, the following questions need to be answered:

- What are the threats to water quality?
- What pollutants are in the water?
- Are the concentrations of these pollutants harmful to refuge biota?

Tools, including this current project, have been developed to help answer these questions and to provide broader access to the information necessary to assess water quality on refuges. This section provides a brief overview of these tools and how they relate to one another. The available tools are:

- Contaminant Assessment Process (CAP) application;
- Water Resource Inventory and Assessment (WRIA) application;
- Water Quality Information System (WQIS) application;
- Biosolids Handbook and associated Rapid Assessment Tool (MacDonald *et al.* 2014); and,
- Refuge-Specific Water Quality Target Report and associated Water Quality Assessment Tool (current project).

Contaminant Assessment Process (CAP)

The CAP is a standardized procedure for identifying threats to refuge resources from environmental contaminants, where the results are stored in an online application. This process is broader than water resources; it also assesses potential contaminant threats to air and soil. A CAP conducted for a particular refuge will: 1) identify potential sources of pollution, both point and non-point, on and off the refuge; 2) evaluate transport pathways for these pollutants by examining the geophysical and hydrological (surface and ground water) characteristics of the refuge, including prevailing wind patterns; and 3) determine "potential areas of contamination" and "areas subject to spill" on or near the refuge that could impact refuge resources. In short, the CAP addresses the question of "What are the threats to refuge water quality?" To a lesser extent, a CAP may also address what pollutants are in refuge water supplies by identifying known and suspected contaminants, and if these pollutants are potentially harmful to refuge resources by identifying susceptible aquatic receptors (i.e., plants and animals).

Water Resource Inventory and Assessment (WRIA)

Like CAP, the WRIA is both a process and a centralized database application. The WRIA procedure collects existing information about refuge water resources (the "inventory"), including data relating to water features, monitoring sites, infrastructure, hydroclimate, water quality, and water rights. Information on refuge water quality is gleaned from multiple sources, including a CAP, Environmental Protection Agency (EPA) impaired waters, and others. The application does not store actual monitoring data; however, it allows users to summarize monitoring results. In addition, the WRIA application allows users to identify and associate water-related threats and needs, and identify recommendations (the "assessment"). As a process, hydrologists with assistance from other Fish and Wildlife Service (FWS) staff prepare a narrative WRIA report that summarizes the findings and presents recommendations. The report is a valuable resource for refuge staff. The utility of the WRIA application is as a centralized repository for water-related information for the entire NWRS. As a relational database, it can be queried, and data can be aggregated and sorted to help manage NWRS water resources at the refuge, regional, and national levels.

Water Quality Information System (WQIS)

The WQIS application is a reporting tool developed out of a multi-year partnership with the NWRS, EPA and the U.S. Geological Survey. The WQIS is a stand-

alone application that identifies Clean Water Act (CWA) 303(d) impaired waters and TMDLs (Total Maximum Daily Loads) on refuges in the contiguous United States (it does not include Alaska or Hawaii). Impairments and TMDLs are identified for streams within refuges, and these data can be sorted to produce reports at the refuge, region, and national levels. This information is important in helping to address the question of what pollutants are in the water, and if any TMDLs have been developed for a particular stream that could affect refuge water management. That said, the WQIS does not include water quality information regarding wetlands, ponds, and lakes (nonlinear features), and it must be manually updated as EPA releases new data sets on impaired waters. The EPA is moving toward "catchment-based indexing" to process and report 303(d)-listed waters, and this will not be compatible with the WQIS. The FWS is currently working with the EPA to develop more dynamic solutions to obtaining refuge-related EPA CWA data (including polygon data) and serving these through WRIA.

Biosolids Handbook and Rapid Assessment Tool

The Biosolids Handbook was developed for addressing risks to fish and wildlife associated with the placement of water, treated wastewater, stormwater, sediment, soil, biosolids, or other materials on units of the NWRS. The project resulted in the development of a step-wise framework that would enable FWS staff to evaluate the risks to natural resources associated with the use of candidate materials on refuges. Therefore, a conceptual decision framework and a series of associated tools were developed for determining if candidate materials can be applied on refuge lands without adversely affecting fish, wildlife, plants, or the aquatic, riparian, and terrestrial habitats upon which they depend. The framework consists of four main elements including:

- Material Placement Proposal;
- Preliminary Screening of Proposal;
- Rapid (Tier 1) Assessment; and,
- Detailed (Tier 2) Assessment.

The framework is structured in a manner that enables the Review Team (a team consisting of refuge staff, FWS environmental contaminants specialists, or other specialists) to evaluate candidate materials using the Rapid (Tier 1) Assessment process (which includes the Excel-Based Rapid Assessment Tool). If it is determined (either through the preliminary screening of the proposal or as a result

of the Rapid [Tier 1] Assessment) that a more detailed evaluation is needed, Refuge Managers may: (1) reject the request to place the candidate material on a refuge; or, (2) invite the Applicant to complete a Detailed (Tier 2) Assessment for the candidate materials.

Refuge-Specific Water Quality Target Report and Water Quality Assessment Tool

The Water Quality Assessment Tool provides the framework for determining if levels of pollutants in the water are harmful to refuge biota. Though EPA has developed generic water quality benchmarks with numeric water quality criteria for U.S. surface waters, they may or may not be protective of all species or all life stages that may be present on a refuge. If sensitive species or life stages are present, the refuge staff would seek to safeguard these waters through anti-degradation regulations of the CWA, even if these waters are already below the numeric EPA criteria. An important component of this tool, therefore, is that it is contextual; there may not be one single benchmark to target, but it will depend on the refuge resources in need of protection.

Such an analysis of concentrations of pollutants requires quantitative data on what constituents are in the water, and if these are changing over time. Appendix 5 of this document is devoted to describing how to develop a rigorous baseline monitoring program for a refuge. The reader will note that undertaking such rigorous monitoring will be expensive and, thus, may be impractical to implement Refuge System-wide. Still, it may be possible, and perhaps preferable, to initiate pilot monitoring projects at a few refuges using the monitoring design described in this report.

Integrating the Tools

Each tool provides a unique set of information to assess the quality of fresh water on refuges. The CAP, WQIS, and the Water Quality Assessment Tool are designed to provide specific information about contaminants existing or threatening refuge water supplies, and the WRIA process provides a mechanism to store and access this information in a centralized location. The Biosolids Handbook provides guidance for evaluating the potential for acceptance and use of water, treated wastewater, stormwater, sediment, soil, biosolids, or other materials on a refuge. Monitoring water quality on or near refuges is essential to establishing baseline conditions and detecting changes. While CWA data from

EPA is useful at a coarse level to identify impairments, regular on-site monitoring of refuge waters can offer near real-time data on water quality conditions to safeguard refuge resources. Integration of all of these tools into an assessment of water quality on a refuge would:

- Assess existing and potential threats to refuge water quality (CAP);
- Examine existing data sets for information on refuge water quality (WQIS; EPA impaired waters and TMDL data);
- Monitor existing and proposed refuge water supplies to establish baseline conditions and detect changes in water quality (using sampling design described in this document);
- Determine if candidate materials (including water, treated wastewater, stormwater, sediment, soil, and biosolids) can be accepted on a refuge without adversely affecting fish, wildlife, plants, or the habitats upon which they depend (Biosolids Handbook and Rapid Assessment Tool). This step is optional and is only necessary when refuge staff want to bring a new material onto the refuge;
- Determine if one or more pollutants identified through monitoring are at concentrations that would likely be harmful to refuge resources (Water Quality Assessment Tool); and,
- Access refuge water quality information from a centralized database and identify threats and needs (WRIA).

Each tool has unique features that are designed to provide specific information. Using multiple tools will make it easier for refuge staff to document water quality conditions and protect designated water uses on a refuge. Refuge staff can use whichever combination of these tools is most appropriate for their refuge.

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List of Acronyms

2,4-D	-	2,4-Dichlorophenoxyacetic acid
ACZA	-	ammoniacal copper zinc arsenate
Ag	-	silver
Al	-	aluminum
As	-	arsenic
AWQC	-	ambient water quality criteria
BTEX	-	benzene, toluene, ethylbenzene, and xylene
CAP	-	Contaminants Assessment Process
CCA	-	chromated copper arsenate
CCP	-	comprehensive conservation plan
Cd	-	cadmium
COPC	-	chemical of potential concern
Cr	-	chromium
Cu	-	copper
DDAC	-	didecyldimethyl ammonium chloride
DDT	-	dichlorodiphenyltrichloroethane
DOI	-	Department of the Interior
DQO	-	data quality objective
EPA	-	Environmental Protection Agency
Fe	-	iron
FWS	-	Fish and Wildlife Service
HCB	-	hexachlorobenzene
Hg	-	mercury
I&M	-	Inventory and Monitoring
IPBC	-	3-iodo-2propynyl butyl carbamate
Mo	-	molybdenum
Ni	-	nickel
NWR	-	National Wildlife Refuge
NWRS	-	National Wildlife Refuge System
PAH	-	polycyclic aromatic hydrocarbon
Pb	-	lead
PBDE	-	polybrominated diphenyl ether
PCB	-	polychlorinated biphenyl
PCDD	-	polychlorinated dibenzo-*p*-dioxins
PCDF	-	polychlorinated dibenzofurans
PFOA	-	perfluorooctanoic acid
PFOS	-	perfluorooctanesulfonate
RSWQT	-	refuge-specific water quality target

Se	-	selenium
TCDD	-	tetrachlorodibenzo-*p*-dioxin
TDS	-	total dissolved solids
TSS	-	total suspended solids
UCL	-	upper confidence limit
WCS	-	water classification system
WQG	-	water quality guideline
WQO	-	water quality objective
WQS	-	water quality standard
WQT	-	water quality target
WRIA	-	Water Resources Inventory and Assessment
Zn	-	zinc

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1.0 Introduction

Water quality and water quantity are important issues throughout the United States. Not surprisingly, National Wildlife Refuges (NWRs) are facing increasing challenges in terms of ensuring that water supplies of sufficient quality and quantity are available to conserve and protect fish and wildlife, as well as the habitats upon which they depend. In some cases, the National Wildlife Refuge System (NWRS) may need to meet this challenge by utilizing water from non-traditional sources, including wastewater (i.e., from municipalities, agriculture, and light industry) and stormwater. Because wastewaters and stormwaters have the potential to contain elevated levels of contaminants, the NWRS requires a process for assessing potential risks to fish, wildlife, and environmental quality associated with exposure to water supplies used on refuges, both now and in the future.

The Fish and Wildlife Service (FWS) has responded to this challenge by developing a framework for assessing the acceptability of wastewater, stormwater, and biosolids that provides a basis for evaluating risks to ecological receptors associated with exposure to contaminants. The *Handbook for Assessing Risks to Fish and Wildlife Associated with the Potential Use of Water, Treated Wastewater, Stormwater, Sediment, Soil, Biosolids, or Other Materials on Units of the National Wildlife Refuge System* (the *Handbook*; MacDonald *et al.* 2014), and the associated Excel-Based Assessment Tool, are intended to provide users with guidance for conducting expedited and detailed assessments of these materials to guide decisions that could affect environmental quality conditions on NWRs.

The *Handbook* and Excel-Based Assessment Tool provide procedures and guidance that are appropriate and relevant for conducting assessments of potential water supplies. The work conducted to develop the framework serves as a foundation for extending the framework to evaluate existing environmental quality conditions on NWRs. While the *Handbook* is appropriate and relevant for conducting assessments of potential water supplies, an assessment tool for

evaluating existing refuge water supplies needs to have a higher level of site-specificity than the framework described in the *Handbook* to ensure that decisions related to the management of water resources explicitly address the priority resources of concern that use habitats on NWRs, including threatened and endangered species and/or major taxa of concern to the Department of the Interior (DOI). Accordingly, a step-wise approach to the formulation of a more specific water quality assessment tool was developed to support comprehensive assessments of existing surface water and groundwater supplies used for resource management on refuge lands. This approach includes the following steps:

- Step 1: Identification of key chemicals of potential concern (COPCs);
- Step 2: Identification of taxa of concern;
- Step 3: Acquisition, evaluation, and compilation of toxicological data on the COPCs;
- Step 4: Evaluation of the protectiveness of Environmental Protection Agency (EPA) ambient water quality criteria (AWQC; USEPA 2014a) for taxa of concern on NWRs;
- Step 5: Development of procedures for establishing refuge-specific water quality targets (RSWQTs);
- Step 6: Development of an Excel-Based Water Quality Assessment Tool; and,
- Step 7: Preparation of a guidance document to support assessments of water resources on NWRs.

During a workshop convened in February of 2013, FWS personnel and consultants identified key COPCs and taxa of concern on NWRs. As such, the work that has culminated in this report provides the procedures and results of Steps 3 through 7 that focus on the identified COPCs and taxa of concern.

This document is intended to provide FWS personnel with detailed guidance for evaluating the quality of refuge water supplies relative to the potential for impacts (risks) on the resources being managed and protected. More specifically, this report describes a water classification system (WCS) that enables users to determine the sensitivity of refuge waters to changes in water quality conditions associated with land or water use activities within and outside refuge boundaries. In addition, this document describes procedures for establishing RSWQTs that can be used to evaluate water quality relative to the conditions required to protect the receptors that use aquatic habitats within the NWRS. For this project, RSWQTs are defined as the short-term and long-term concentrations of COPCs that should not be exceeded to support and protect designated water uses within the NWRS. An accompanying Excel-Based Water Quality Assessment Tool was developed to provide a convenient way for refuge staff to develop appropriate RSWQTs and to determine whether the waters on a NWR are likely to be protective of aquatic life.

Figure 1 provides an overview of the decision framework for assessing potential risks to fish, wildlife, and environmental quality on NWRs. This figure illustrates the framework presented in both the *Handbook* and this document to outline the methods used to assess current water quality conditions (i.e., using RSWQTs) or to evaluate potential water supplies (i.e., rapid or detailed assessment process).

1.1 Overview of Report

This report describes a WCS and the procedures for deriving RSWQTs. Section 2 of this report provides background information on sources of COPCs to the environment and on the process that was used to identify high priority COPCs relative to the NWRS. Taxa of concern utilizing aquatic habitats within the NWRS are identified in Section 3. The system for classifying surface waters on NWRs is described in Section 4, while Section 5 of the document outlines the process of deriving numerical RSWQTs for the three classes of waters that may apply to a NWR. Additional information on the procedures for developing

RSWQTs is provided in the appendices, along with case studies that illustrate their application. A discussion of various candidate approaches for designing water quality monitoring programs for assessing attainment of RSWQTs is presented in Section 6, while specific recommendations for applying RSWQTs on NWRs are offered in Section 7. This report provides a framework for establishing RSWQTs for a variety of COPCs; ammonia and cadmium are used as examples to illustrate the process.

2.0 Identification of Priority Chemicals of Potential Concern

Identification of COPCs represents a key step in the overall water quality assessment process. For this project, the COPCs selected to illustrate the RSWQTs development process were identified using a 3-step process. Development of an inventory of COPCs based on an evaluation of the potential sources of chemicals to NWRs was the first step in this process. Next, FWS Contaminants Specialists throughout the United States were asked to identify priority COPCs, based on their understanding of pervasive water quality issues and concerns within their regions. Finally, two priority COPCs were selected to illustrate the RSWQTs derivation process based on an evaluation of the toxicological datasets that could be efficiently assembled for each of the priority COPCs.

2.1 Inventory of Chemicals of Potential Concern for the National Wildlife Refuge System

There are a wide variety of land- and water-use activities that have the potential to adversely affect aquatic habitats within the NWRS. Such anthropogenic activities have the potential to release a wide range of chemicals, including both toxic and bioaccumulative substances, into waters within the NWRS. Natural sources of

such substances include weathering and erosion of terrestrial soils, bacterial decomposition of vegetation and animal matter, and long-range transport of substances originating from forest fires or other natural combustion sources. In addition to these natural sources, there are a number of anthropogenic point and non-point sources of toxic and/or bioaccumulative substances that have the potential to influence surface-water and groundwater quality conditions within the NWRS, including (MacDonald *et al.* 2011):

Point Sources

- Pulp and paper mills;
- Sawmills, plywood mills, and particle board mills;
- Wood preservation facilities;
- Cement and concrete plants;
- Seafood processing facilities;
- Operating and abandoned mines;
- Oil and gas developments;
- Bulk storage and shipping facilities;
- Other manufacturing facilities;
- Contaminated sites and chemical spills;
- Municipal wastewater treatment facilities; and/or,
- Municipal and industrial landfills.

Non-Point Sources

- Runoff from forest management areas;
- Runoff from agricultural operations;
- Runoff of municipal stormwater; and/or,
- Runoff from linear developments.

Atmospheric Sources

- Natural sources of atmospheric pollutants (forest fires and volcanoes); and/or,
- Anthropogenic sources of atmospheric pollutants (i.e., vehicle emissions, industrial emissions, agricultural emissions, and long-range transport of atmospheric pollutants).

These and other natural and anthropogenic sources have the potential to release a variety of chemicals into surface waters and groundwaters within or upstream of NWRs. In so doing, these sources pose potential risks to aquatic organisms and aquatic-dependent wildlife using habitats within the NWRS. Some of the substances that could, potentially, be released to surface waters and groundwaters from these sources include the following (MacDonald *et al.* 2011):

- Conventional variables (e.g., pH, alkalinity, biological oxygen demand, chemical oxygen demand, total suspended solids [TSS]);
- Microbiological variables (e.g., fecal coliforms, enterococci);
- Major ions (e.g., total dissolved solids [TDS], calcium, chlorides, potassium, sodium, sulfates, sulfides);
- Nutrients (i.e., nitrate, nitrite, ammonia, urea, phosphorus);
- Trace elements (i.e., aluminum, arsenic, barium, boron, cadmium, copper, chromium, cobalt, iron, lead, mercury, manganese, molybdenum, nickel, selenium, silver, strontium, vanadium, zinc);
- Organometallics (e.g., methylmercury, organotins);
- Cyanides;
- Monoaromatic hydrocarbons (i.e., benzene, toluene, ethylbenzene, and xylene [BTEX]);

- Polycyclic aromatic hydrocarbons (PAHs; i.e., individual parent PAHs, alkylated PAHs, total low molecular weight PAHs, total high molecular weight PAHs, total PAHs);
- Petroleum hydrocarbons (e.g., oil and grease, diesel range organics, lube oils, alkanes);
- Phenolic compounds (i.e., phenol, cresol);
- Chlorinated phenolic compounds (i.e., chlorophenols, chloroguaiacols, chlorocatechols);
- Polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (PCDD/PCDF; total 2,3,7,8-tetrachlorodibenzo-*p*-dioxins [TCDD] toxic equivalents, 210 congeners);
- Polychlorinated biphenyls (PCBs; i.e., dioxin-like PCB congeners evaluated as total 2,3,7,8-TCDD toxic equivalents; total PCBs as sum of congeners, sum of homologs, or sum of Aroclors);
- Resin acids (e.g., abietic acid);
- Fatty acids (e.g., palmitic acid);
- Legacy organochlorine pesticides (i.e., aldrin, chlordane, dichlorodiphenyltrichloroethane [DDT], dieldrin, endrin, endosulfan, heptachlor, heptachlor epoxide, hexachlorobenzene [HCB], lindane, methoxychlor, nonachlor, toxaphene);
- In-use herbicides (e.g., atrazine, 2,4-Dichlorophenoxyacetic acid [2,4-D], ethalfluralin, glyphosate, mineral oil, paraquat, pendimethalin, picloram, simazine, triallate, triclopyr, trifluralin);
- In-use insecticides (e.g., azinphosmethyl, *Bacillis thuringiensis*, chlorpyrifos, diazinon, malathion, mineral oil, parathion, pyrethroids);
- In-use fungicides (i.e., captan, chlorothalonil, copper, dazomet, mancozeb, metam, metiram, lime sulfur);
- Other pesticides (i.e., formaldehyde, formalin);

- Wood preservatives (i.e., creosote, chromated copper arsenate [CCA], ammoniacal copper zinc arsenate [ACZA], pentachlorophenol);
- Anti-sapstain chemicals (i.e., didecyldimethyl ammonium chloride [DDAC], 3-iodo-2propynyl butyl carbamate [IPBC]);
- Surfactants (i.e., alkylphenolethoxylates, fluorosurfactants);
- Fire retardants (i.e., polybrominated diphenyl ethers [PBDEs; 209 congeners and 10 homolog groups], perfluorooctanesulfonate [PFOS], perfluorooctanoic acid [PFOA], diammonium sulfate, diammonium phosphate, ammonium sulfate, ammonium phosphate, ammonium polyphosphate);
- Plastic-related compounds (i.e., phthalate esters, bisphenol A);
- Steroids, hormones, and hormone-mimicking substances (e.g., 17β-estradiol, estrone, 17α-ethinylestradiol, plant sterols, phytoestrogen metabolites);
- Pharmaceuticals (e.g., antibiotics, antihypertensives, anticonvulsants, antidepressants, anti-acid reflux, anti-inflammatory, antifungal, analgesic compounds);
- Personal care products (e.g., fragrances, insect repellants, detergents, antimicrobials, fungicides, surfactants, stimulants);
- Disinfectants (i.e., bromine, residual chlorine, iodine), disinfection byproducts (e.g., trihalomethanes, haloacetic acids); and,
- Nanoparticles.

All of these substances were considered to be COPCs for the NWRS. Hence, NWR Managers need tools to enable them to evaluate the hazards that these substances pose to resources of concern and to support decisions on the management of surface-water and groundwater resources.

2.2 Identification of Regional Water Quality Issues and Concerns

The inventory of COPCs for the NWRS provides a detailed list of substances that could, potentially, be released into surface waters from point and non-point sources. Recognizing that it would not be possible to evaluate all of the COPCs included in the inventory, the FWS conducted an internal review of priorities to support identification of the COPCs that should be considered to support refinement of the water quality assessment tool on NWRs (Mike Higgins, FWS Region 9, 2013, personal communication). The input provided by FWS Contaminants Specialists was reviewed and evaluated to identify the substances that were considered to represent pervasive hazards to aquatic organisms and/or aquatic-dependent wildlife utilizing habitats within the NWRS. The results of this review indicated that the highest priority COPCs for consideration in refinement of the water quality assessment tool include:

- Ammonia;
- Sulfate/Major Ions (e.g., chlorine; TDS);
- Cadmium;
- Chromium (III/VI);
- Copper;
- Lead;
- Mercury; and,
- Selenium.

2.3 Selection of Chemicals of Potential Concern to Illustrate Procedures for Deriving Refuge-Specific Water Quality Targets

Based on the identified priorities, two COPCs were selected to evaluate candidate procedures for deriving RSWQTs: ammonia and cadmium. These COPCs were selected because they represent frequently identified water quality issues for refuges, because substantial datasets are available to evaluate their toxicity to freshwater organisms, and because EPA AWQC are available for both of them (USEPA 2014a). Detailed information on the toxicity of these substances to aquatic organisms and/or aquatic dependent wildlife is provided in Appendices 1 and 2. In addition, toxicity data for copper were compiled as a starting point to assist FWS Contaminants Specialists and others in evaluating RSWQTs that are developed for copper. These data are presented in Appendix 3. Toxicity data on bioaccumulative substances (e.g., selenium) were not compiled. However, information on managing bioaccumulative substances is provided in Appendix 4.

3.0 Identification of Taxa of Concern Using Aquatic Habitats on National Wildlife Refuges

The NWRS has been established to administer a national network of lands and waters for the conservation, management and, where necessary and appropriate, restoration of the fish, wildlife, and plant resources and their habitats within the United States for the benefit of present and future generations of Americans. To help guide the development of comprehensive conservation plans (CCPs) and to support the administration, management, and growth of the NWRS, the following goals have been established for the NWRS (USFWS 2006):

- Conserve a diversity of fish, wildlife, and plants and their habitats, including species that are endangered or threatened with becoming endangered;
- Develop and maintain a network of habitats for migratory birds, anadromous and inter-jurisdictional fish, and marine mammal populations that is strategically distributed and carefully managed to meet important life history needs of these species across their ranges;
- Conserve those ecosystems, plant communities, wetlands of national or international significance, and landscapes and seascapes that are unique, rare, declining, or under-represented in existing protection efforts;
- Provide and enhance opportunities to participate in compatible wildlife-dependent recreation (hunting, fishing, wildlife observation and photography, and environmental education and interpretation); and,
- Foster understanding and instill appreciation of the diversity and inter-connectedness of fish, wildlife, and plants, and their habitats.

In addition, the National Wildlife Refuge System Improvement Act (1997) states that "the Secretary [of the Interior] shall...ensure the biological integrity, diversity, and environmental health of the National Wildlife Refuge System are maintained..." and "...assist in the maintenance of adequate water quantity and quality to fulfill the mission of the System and the purposes of each refuge..."

These goals emphasize the essential role that the NWRS plays in the conservation and protection of fish, wildlife, plants, and their habitats throughout the United States. As such, decisions regarding the management of these areas have the potential to influence the status and use of these natural resources, both now and in the future. While effective management of NWRs necessarily involves a broad range of initiatives and activities, decisions regarding the management of surface waters are critical because water quality conditions are important relative to the maintenance or restoration of fish and wildlife habitats. In areas where water

shortages have the potential to limit the productivity or viability of fish, wildlife, or plant species, refuge staff may be forced to consider a variety of water management options that require balancing concerns related to water quality and water availability. For this reason, the FWS needs effective and efficient tools to support informed decisions regarding surface-water and groundwater management on NWRs.

Recommended national EPA AWQC (USEPA 2014a), state water quality standards (WQSs; e.g., WDOE 2012), and generic water quality guidelines (WQGs; e.g., BCMOE 2014a; CCME 2014) provide relevant scientific information to support water management decisions. Table 1 provides a comparison of these different types of water quality benchmarks. The acceptance levels and rejection levels developed from the available water quality benchmarks provide NWRS-specific tools for evaluating candidate water sources that could be used on NWRs (MacDonald *et al*. 2014). However, application of such tools requires an understanding of the water uses that need to be protected and the ecological receptors that may require special consideration in the water quality assessment process. To facilitate identification of taxa of concern on NWRs, the FWS convened a workshop in Arlington, VA in February, 2013. Workshop participants were charged with the task of identifying the ecological receptors that use aquatic habitats within the NWRS. Based on the workshop results, the taxa of concern relative to NWRs are likely to include:

- Aquatic-dependent mammals (e.g., mink; otters);
- Migratory birds (e.g., shorebirds; wading birds; water fowl; colonial water birds; raptors; grassland birds);
- Amphibians;
- Reptiles;
- Fishes (e.g., warm-water fish; cold-water fish; food fish);

- Aquatic invertebrates (e.g., benthic invertebrates [bird food]; nektonic invertebrates; insects; oligochaetes; crayfish; crustaceans; mussels; gastropods [e.g., snails]); and,
- Aquatic plants (e.g., phytoplankton; periphyton; aquatic macrophytes).

Depending on the NWR under consideration, all or a portion of these ecological receptors need to be conserved and protected to achieve the defined purpose of the refuge. Because certain receptors are more sensitive to contaminant challenges than others, water quality requirements may differ among refuges or among water bodies within a refuge. Effective management of water resources requires an understanding of these requirements and tools that enable managers to make informed management decisions.

The RSWQTs developed in this document are for the protection of aquatic life. Water bodies may support other designated uses (e.g., wildlife, recreation, aesthetics, shellfish harvesting, agriculture [livestock and irrigation], drinking water). For example, some wildlife may be more sensitive to certain COPCs (e.g., molybdenum). Refuge staff should identify each of the designated uses that are applicable to the NWR. Then, information on protective concentrations for each of the identified COPCs, for each designated use, should be compiled and considered to determine whether they should be adopted as RSWQTs for the NWR.

4.0 Classification of Surface Waters for Waters Within the National Wildlife Refuge System

The NWRS is characterized by an abundance of freshwater habitats, including a diversity of wetlands, streams, rivers, ponds, and lakes. Managing these diverse water resources represents a daunting challenge because each of these systems has unique characteristics that must be considered in decisions related to water

resources management. In general, management of aquatic habitat and the need to mitigate degradation of water quality is the primary focus within the NWRS. To assist refuge staff in attaining this goal, the FWS has developed a WCS for the NWRs that provides a systematic basis for classifying receiving water bodies relative to their importance and sensitivity to disturbance (this document). The three classes of surface waters defined by the WCS, and the narrative objectives that apply to each class of surface water, are described below:

- *Waters of Special Significance* – such waters meet the following characteristics:
    - Provide critical habitat for state or federally listed endangered species;
    - Support listed or endangered species with the potential for extinction;
    - Include habitats that support listed or endangered species through their entire life cycle;
    - Support aquatic-obligate listed or endangered species; or,
    - Include designated or proposed wilderness/natural areas.

  For these waters, a primary water management goal is to maintain and protect the quality of these special waters and the associated water uses (i.e., water quality conditions should not be degraded or impaired by human activities). Information on how to design baseline monitoring programs in order to establish background conditions is provided in Appendix 5.
- *Sensitive Waters* - such waters support sensitive species or taxa of concern. For these waters, a primary water management goal is to protect all life stages of sensitive species or taxa of concern (which may include listed or endangered species with limited exposure to the water body of interest), as well as the occupied habitats upon which they depend, from adverse effects associated with exposure to a chemical or

a chemical mixture for an indefinite period of time (i.e., entire life cycles). EPA AWQC may or may not offer the level of protection needed to protect sensitive species utilizing these waters (Appendix 6). Appendix 7 describes in detail the rationale and methods for deriving RSWQTs for Sensitive Waters.

- *Typical Waters* - such waters support other resources of concern. For these waters, a primary water management goal is to protect the designated uses of surface water resources, including protection of aquatic life and aquatic-dependent wildlife. An additional goal is the recovery of waters that have been degraded so that they are able to support designated uses, including the protection of aquatic life and aquatic-dependent wildlife.

The WCS is designed to be a simple decision-support tool that assists water managers in identifying issues and concerns relative to the quality of receiving water bodies. In addition, the WCS provides a mechanism for compiling and evaluating the existing data and information on a water body and, in so doing, identifying any critical data gaps that may exist. Furthermore, the WCS provides a basis for establishing numerical RSWQTs for the diversity of water bodies within the NWRS that reflect their specific sensitivity and importance.

In order to classify the waters on a particular NWR, background information about the refuge must be collected, collated, and considered. First, background water quality data on the COPCs in the NWR must be compiled. Then the information on the aquatic organisms and aquatic-dependent wildlife species present on the refuge must be collected. Sensitive taxa of concern specific to the NWR should be identified. It is important to document habitat use by threatened or endangered species, as well as other sensitive taxa of concern, on the refuge at various times of year. The refuge staff can choose whether to put the NWR into the same class for the entire year or to perform the classification on a seasonal or monthly basis, according to which species are present in each season or month. A checklist for

determining the classification of a water body on a NWR is provided in Table 2. Appendix 8 provides guidance on the application of the checklist in the water classification process for NWRs.

If aquatic-obligate threatened or endangered species are only present during certain months of the year (e.g., May - August), refuge staff could consider classifying the water bodies as Waters of Special Significance to ensure such RSWQTs can be met when threatened or endangered species utilize the water body. As Waters of Special Significance should not be degraded relative to background conditions, it is necessary to estimate the background concentrations of COPCs in the NWR to support RSWQTs development. Details on the methods for estimating background concentrations of COPCs in aquatic ecosystems are described in Appendix 5.

Water bodies are classified as Sensitive Waters if they support sensitive species or taxa of special concern (as identified by refuge staff), or support listed or endangered species with limited exposure to the water body of interest. Sensitive species are those that are known to be particularly sensitive to certain COPCs (e.g., freshwater mussels are known to be particularly sensitive to ammonia and copper). As these species are more sensitive than most aquatic organisms, they may not be protected by the EPA AWQC (i.e., if the derivation of the EPA AWQC did not include toxicity data for these species or key endpoints related to these species). Therefore, the lowest of the available EPA AWQC, WQSs, and WQGs would be selected as the RSWQTs for Sensitive Waters (Appendix 7). If these RSWQTs are not expected to be protective of sensitive species or if generic EPA AWQC, WQSs, or WQGs do not exist for certain COPCs, then *de novo* RSWQTs can be developed for the water body under consideration, using the methods outlined in Appendix 7. The RSWQTs should be compared to background concentrations on the NWR to ensure that they are applicable to that location (i.e., not lower than natural conditions).

Water bodies are classified as Typical Waters if they contain none of the characteristics outlined for Waters of Special Significance or Sensitive Waters. As Typical Waters support typical aquatic communities, they should be adequately protected by the EPA AWQC. Nonetheless, data on background concentrations of COPCs should be compiled, so that they can be compared to EPA AWQC to ensure that the EPA AWQC are applicable to the particular NWR in question. Such background water quality data also provide the information needed to adapt the EPA AWQC to site conditions.

Once the waters on a NWR have been classified according to the species present, the applicable methods can be used to derive RSWQTs for those water bodies. The process for developing RSWQTs for Waters of Special Significance is explained in Section 5.1 and Appendix 5. The procedures for deriving RSWQTs for Sensitive Waters are explained in Section 5.2 and Appendix 7. The methods for developing RSWQTs for Typical Waters are described in Section 5.3. Case studies illustrating the procedures for all three classes of water are presented in Appendix 8.

5.0 Derivation of Numerical Refuge-Specific Water Quality Targets for Waters of the National Wildlife Refuge System

In the United States, a variety of tools are available to support water quality assessments, including EPA AWQC and state WQSs. Such tools provide science-based information on the concentrations of COPCs that need to be achieved to protect the designated uses of receiving waters. Although EPA AWQC and state WQSs provide a consistent basis for evaluating water quality conditions, they may not provide adequate protection for threatened or endangered species, sensitive species, or taxa of concern using aquatic habitats on NWRs on seasonal or continuous bases (see Appendix 6 for an evaluation of EPA AWQC for ammonia and cadmium). For this reason, refuge staff require consistent procedures for

establishing RSWQTs that will provide a basis for protecting biological resources on NWRs. While all water bodies on NWRs should meet EPA AWQC for the identified COPCs, certain water bodies may require additional protection. As such, different approaches have been established for developing numerical RSWQTs for each class of surface waters, as follows:

- *Waters of Special Significance* - The background-concentration procedure is recommended to support the derivation of numerical RSWQTs for Waters of Special Significance (i.e., numerical RSWQTs are established to avoid degradation of water quality conditions);
- *Sensitive Waters* - The enhanced use-protection strategy is applied to support the derivation of numerical RSWQTs for Sensitive Waters (i.e., numerical RSWQTs are established at levels that are protective of sensitive species or taxa of special concern); and,
- *Typical Waters* - The use-protection strategy is applied to support the derivation of numerical RSWQTs for Typical Waters (i.e., numerical RSWQTs are established at levels that are protective of typical aquatic and aquatic-dependent communities during the entire year).

The procedures that are recommended for deriving numerical RSWQTs for the three classes of refuge waters are described in the following sections of this document.

5.1 Derivation of Numerical Refuge-Specific Water Quality Targets for Waters of Special Significance

For Waters of Special Significance, numerical RSWQTs are established to avoid degradation of water quality conditions. To do so, numerical RSWQTs should be derived using the background-concentration procedure. The background-concentration procedure involves determination of the natural background

concentrations of COPCs in water, with the resultant data used to define acceptable water quality conditions at the site under consideration. Natural background conditions are those that have not been affected by substantial land or water use activities. In cases where habitat management efforts have already been implemented, baseline characterization should be informed by the collection of data and information from hydrologically and biogeochemically similar water bodies in or nearby the NWR that have not been anthropogenically influenced. Application of the background-concentration procedure is based on the premise that surface water systems that support critical habitats for threatened or endangered species should not be degraded.

For the purpose of deriving numerical RSWQTs using the background-concentration procedure, there is a need to collect sufficient quantities of water chemistry data, representative of background conditions, for all of the water bodies for which RSWQTs are required. Because background levels of water quality variables can vary substantially over time and space, baseline monitoring programs need to be designed to collect spatially and temporally relevant data for assessing background concentrations of water quality variables. Such sampling should be conducted at stations located upstream of known point-source discharges and/or located in appropriately selected reference areas (BCMOE 2013). At minimum, baseline monitoring programs should include monthly sampling at each monitoring location and two 5-in-30-day sampling events each year (i.e., 5 samples collected at six-day intervals over a 30-day period, targeting high flow and low flow periods; BCMOE 2012a). While BCMOE (2012a) recommends baseline monitoring for an absolute minimum of one year, it is recommended that a minimum of three years of baseline data are collected to assess inter-annual variation in water quality (Appendix 5). Because the concentrations of many water quality variables are influenced by the presence of suspended sediments, baseline monitoring programs should include collection of data on the total and dissolved concentrations of COPCs. Generally, numerical RSWQTs for metals and nutrients should be based on the dissolved fraction to address the high variability of total concentrations of these classes of water quality

variables. Additional guidance on the design of baseline water quality monitoring programs is provided in Appendix 5.

Derivation of numerical RSWQTs using the background-concentration procedure requires determination of both the central tendency and upper limit of background concentrations of the selected COPCs. The estimate of central tendency of the background concentrations is used to establish the chronic (i.e., 30-d average) RSWQT, while the upper limit of background conditions is used to establish the acute (i.e., maximum) RSWQT for each water quality variable. The chronic RSWQT is calculated for each month of the year by determining the 95% upper confidence limit (UCL) of the mean concentration using all of the available data on the concentrations of a water quality variable for that month (if 10 or more measurements are available for the month) or the arithmetic mean concentration (if fewer than 10 measurements are available for the month). The acute RSWQT for each month of the year is calculated by determining the 95th percentile concentration for each water quality variable. As an alternative to determining monthly RSWQTs, RSWQTs may be derived for specific stages of the hydrograph (e.g., low flow conditions, ascending limb of hydrograph, high flow conditions) using the water chemistry data that were collected during that flow condition. The same mathematical procedures would be applied to derive the RSWQTs. More specifically, numerical RSWQTs for Waters of Special Significance should be derived using the following procedures:

Step 1: Determine baseline water quality conditions for the water body under consideration. As indicated above, baseline monitoring programs should be designed to obtain not less than three years of data and be sufficient to evaluate the temporal and spatial variability of water quality conditions.

Step 2: Determine preliminary RSWQTs based on an analysis of the baseline water quality data. As water quality conditions in Waters of Special Significance should not be materially altered by point-source discharges or other anthropogenic activities (with the exception of long-range

transport of atmospheric chemicals), numerical RSWQTs are established by determining the central tendency (i.e., 95% UCL of the mean) and upper limit (95^{th} percentile) of natural background concentrations for the chronic (i.e., long-term average) RSWQT and acute (i.e., short-term maximum) RSWQT, respectively, for each water quality variable each month (or flow period).

Using the background-concentration procedure, numerical RSWQTs are typically established for conventional variables (e.g., pH, hardness, alkalinity, dissolved oxygen, TSS, turbidity), major ions (e.g., chloride, sulfate, TDS), nutrients (i.e., ammonia, nitrate, nitrite, phosphorus), and metals (i.e., Al, As, Cd, Cr, Cu, Fe, Pb, Hg, Mo, Ni, Se, Ag, Zn). In addition, RSWQTs may be established for any other substances that have the potential to be discharged to the receiving environment as a result of anthropogenic activities within the watershed. Furthermore, interim RSWQTs could be set for the water body of interest during the collection of baseline data to support the derivation of final RSWQTs. To develop interim RSWQTs, the results of preliminary or impact surveys conducted in the NWR could be used to support calculation of estimated background conditions. The recommended procedures for deriving RSWQTs for Waters of Special Significance are illustrated using a case study for ammonia (see Appendix 8).

5.2 Derivation of Numerical Refuge-Specific Water Quality Targets for Sensitive Waters

Sensitive Waters are waters that are considered to support species having high sensitivity to chemical challenges or taxa of special concern, including listed or endangered species with limited exposure to the water bodies of interest. For Sensitive Waters, water quality conditions should be maintained such that the most sensitive designated water use(s) is afforded an enhanced level of protection. For

Sensitive Waters, numerical RSWQTs should be derived using the following procedures (Figure 2):

Step 1: Determine baseline water quality conditions for the water body under consideration. Baseline monitoring programs should be designed to obtain not less than three years of data and be sufficient to evaluate the temporal and spatial variability of water quality conditions.

Step 2: Identify the designated uses of each surface water body under investigation.

Step 3: Compile EPA AWQC, WQSs, and WQGs for all of the designated water uses of the receiving water body for each of the substances for which numerical RSWQTs are required. A systematic process must be used in the compilation of water quality benchmarks, using, at minimum, the following sources:

- EPA AWQC (USEPA 2014a);
- State WQSs for the state in which the NWR is present;
- Canadian WQGs (CCME 2014); and,
- Approved and working WQGs from British Columbia (Nagpal *et al.* 2006; BCMOE 2014a).

In addition, WQGs from other jurisdictions (i.e., outside of North America) may be considered. See Table 3 for compiled benchmarks for the protection of aquatic life for selected COPCs.

Step 4: Adjust the EPA AWQC, WQSs, and WQGs to account for the site-specific water quality characteristics of each month (i.e., using conservative estimates of the concentrations of the relevant water quality variables; e.g., the 5th percentile for water hardness each month

when deriving the site-adapted water quality targets [WQTs] for certain metals).

Step 5: Identify the lowest site-adapted WQT for each water quality variable (i.e., among the EPA AWQC, WQSs, and WQGs compiled from the various sources for the various water uses) and select those values as the preliminary RSWQTs.

Step 6: Evaluate the applicability of the preliminary RSWQTs to the site under consideration by comparing them to natural background levels of the various water quality variables in the water body (i.e., compare the chronic preliminary RSWQT to the 95% UCL of the mean of background concentrations for each month and the acute preliminary RSWQT to the 95^{th} percentile for each month). Natural background conditions are those that have not been affected by substantial land or water use activities. In cases where habitat management efforts have already been implemented, baseline characterization should be informed by the collection of data and information from hydrologically and biogeochemically similar water bodies in or nearby the NWR that have not been anthropogenically influenced. If a baseline monitoring program to determine natural background conditions has not been done, the comparison of preliminary RSWQTs to background concentrations cannot be made and the preliminary RSWQT should be selected as the RSWQT.

Step 7: Select an alternative procedure for deriving preliminary RSWQTs for one or more of the water quality variables, if required (i.e., based on the results of the assessment of RSWQT applicability). For example, if the RSWQTs are lower than background levels of the COPC under investigation, then the background levels should be selected as RSWQTs. If generic water quality benchmarks are not available for the substance under consideration or are not expected to be protective of sensitive species on the NWR (i.e., based on comparisons of the benchmarks to toxicity thresholds for sensitive taxa that utilize habitats

on the NWR), a preliminary RSWQT may be derived *de novo*, provided the requisite aquatic toxicity data are available.

The following steps outline the process for deriving *de novo* RSWQTs (Figure 2):

Step 1: Determine baseline water quality conditions for the water body under consideration. Baseline monitoring programs should be designed to obtain not less than three years of data and be sufficient to evaluate the temporal and spatial variability of water quality conditions.

Step 2: Identify the designated uses of each surface water body under investigation.

Step 3: Compile all the relevant toxicity data for each of the substances for which numerical RSWQTs are required. Include toxicity data for sensitive species that are present on the NWR if possible (see Augspurger [2013] for an example of the procedures for compiling and evaluating toxicity data for taxa of special concern).

Step 4: Use BCMOE (2012b) methods for deriving WQGs (i.e., the procedure for deriving *de novo* RSWQTs for Sensitive Waters, as described in Appendix 7) to derive preliminary RSWQTs using the compiled toxicity data.

Step 5: Evaluate the applicability of the preliminary RSWQTs to the site under consideration by comparing them to natural background levels of the various water quality variables in the water body (i.e., compare the chronic preliminary RSWQT to the 95% UCL of the mean of background concentrations for each month and the acute preliminary RSWQT to the 95^{th} percentile for each month). If the RSWQTs are lower than background levels of the COPC under investigation, then the background levels should be selected as RSWQTs. Natural background conditions are those that have not been affected by substantial land or water use activities. In cases where habitat management efforts have already been implemented, baseline characterization should be informed by the collection of data and information from hydrologically and

biogeochemically similar water bodies in or nearby the NWR that have not been anthropogenically influenced. If a baseline monitoring program to determine natural background conditions has not been done, the comparison of preliminary RSWQTs to background concentrations cannot be made and the preliminary RSWQT should be selected as the RSWQT.

Numerical RSWQTs are typically established for conventional variables (e.g., pH, hardness, alkalinity, dissolved oxygen, TSS, turbidity), major ions (e.g., chloride, sulfate, TDS), nutrients (i.e., ammonia, nitrate, nitrite, phosphorus), and metals (i.e., Al, As, Cd, Cr, Cu, Fe, Pb, Hg, Mo, Ni, Se, Ag, Zn). Numerical RSWQTs may also be established for any other substances that have the potential to be discharged to the receiving environment as a result of project-related activities. The methods used to determine the recommended procedures for deriving RSWQTs for Sensitive Waters are illustrated in Appendix 7, using ammonia as an example. A case study that illustrates the recommended procedures to derive RSWQTs for ammonia in a specific refuge is presented in Appendix 8.

5.3 Derivation of Numerical Refuge-Specific Water Quality Targets for Typical Waters

Typical Waters are those waters that are considered to support species having typical sensitivity to chemical challenges (i.e., typical aquatic communities). For Typical Waters, water quality conditions must be maintained such that all of the designated water uses are afforded an adequate level of protection during all times of the year. For Typical Waters, numerical RSWQTs should be derived using the following procedures (Figure 3):

Step 1: Determine baseline water quality conditions for the water body under consideration. Baseline monitoring programs should be designed to

obtain not less than three years of data and be sufficient to evaluate the temporal and spatial variability of water quality conditions.

Step 2: Identify the designated uses of each surface water body under investigation.

Step 3: Compile WQSs and EPA AWQC for all of the designated water uses of the receiving water body for each of the substances for which numerical RSWQTs are required, including:

- State WQSs for the state in which the NWR is present; and,
- EPA AWQC (USEPA 2014a).

If WQSs for the state in which the NWR is present are available for a substance, these standards should be used in place of the EPA AWQC.

***Step 4*:** Adjust the state WQSs or EPA AWQC to account for the site-specific water quality characteristics of each month (i.e., using conservative estimates of the concentrations of the relevant water quality variables; e.g., the 5th percentile for water hardness each month when deriving the site-adapted benchmarks for certain metals).

Step 5: Identify the lowest site-adapted WQT for each water quality variable (i.e., among the site-adapted values compiled for the various water uses) and select those values as the preliminary RSWQTs.

Step 6: Evaluate the applicability of the preliminary RSWQTs to the site under consideration by comparing them to natural background levels of the various water quality variables in the water body (i.e., compare the chronic preliminary RSWQT to the 95% UCL of the mean of background concentrations for each month and the acute preliminary RSWQT to the 95th percentile for each month). Natural background conditions are those that have not been affected by substantial land or water use activities. In cases where habitat management efforts have

already been implemented, baseline characterization should be informed by the collection of data and information from hydrologically and biogeochemically similar water bodies in or nearby the NWR that have not been anthropogenically influenced. If a baseline monitoring program to determine natural background conditions has not been done, the comparison of preliminary RSWQTs to background concentrations cannot be made and the preliminary RSWQT should be selected as the RSWQT.

Step 7: Select an alternative procedure for deriving preliminary RSWQTs for one or more of the water quality variables, if required (i.e., based on the results of the assessment of RSWQT applicability). For example, if the RSWQTs are lower than background levels of the COPC under investigation, then the background levels should be selected as RSWQTs. If benchmarks are not available for the substance under consideration, a preliminary RSWQT may be derived *de novo* using the procedures in Stephan *et al.* (1985), provided the requisite aquatic toxicity data are available. Alternatively, WQGs from other jurisdictions (e.g., Canada, Canadian provinces, Europe) may be selected and adapted to the site of interest.

Numerical RSWQTs are typically established for conventional variables (e.g., pH, hardness, alkalinity, dissolved oxygen, TSS, turbidity), major ions (e.g., chloride, sulfate, TDS), nutrients (i.e., ammonia, nitrate, nitrite, phosphorus), and metals (i.e., Al, As, Cd, Cr, Cu, Fe, Pb, Hg, Mo, Ni, Se, Ag, Zn). Numerical RSWQTs may also be established for any other substances that have the potential to be discharged to the receiving environment as a result of project-related activities. The recommended procedures for deriving RSWQTs for Typical Waters are illustrated in Appendix 8, using ammonia as a case study.

A summary of the recommended procedures for all water classifications and proposed RSWQTs for Sensitive and Typical Waters for selected COPCs are presented in Table 4.

5.4 Management of Bioaccumulative Substances on National Wildlife Refuges

Sections 5.1 through 5.3 describe procedures for establishing RSWQTs that can be used to evaluate water quality relative to the conditions required to protect the receptors that use aquatic habitats within the NWRS. However, a different approach to the development of RSWQTs is required for bioaccumulative substances (e.g., mercury and selenium) because the primary exposure pathway for these substances is typically through the diet (Neely *et al*. 1974). Therefore, these substances are typically evaluated using benchmarks for invertebrate and/or fish tissues (CCME 2000; BCMOE 2014b; USEPA 2014b). It is recommended that these tissue-based criteria are adopted for use as RSWQTs in the NWRS (Table 5) to ensure that these receptors will be protected.

However, there may be valid reasons for monitoring of bioaccumulative substances in the water column. For example, there may be regulatory requirements to measure certain substances (e.g., dissolved selenium) in the water column to support loading calculations (Toll *et al*. 2005; Presser and Luoma 2010). While the factors that influence bioaccumulation are highly site-specific and may not be easily predicted, water quality guidelines or criteria have been promulgated for certain bioaccumulative substances, such as mercury, PCBs, and selenium (e.g., BCMOE 2014a; CCME 2014; USEPA 2014a; Table 4). However, in aquatic ecosystems with a high potential for bioaccumulation or where sensitive receptors are present (i.e., Waters of Special Significance or Sensitive Waters) generic criteria may not be protective. In these situations, RSWQTs for the water column may be derived. To support such an approach, tools have been developed, validated, and applied to determine protective concentrations of bioaccumulative substances in the water column using information on site-specific factors or empirical data (e.g., Presser and Luoma 2010). Appendix 4 provides additional information on the selection and derivation of RSWQTs for bioaccumulative substances.

5.5 Application of Procedures for Deriving Refuge-Specific Water Quality Targets

Recognizing that there is a virtually limitless number of water bodies and water quality variables for which targets could be established, numerical RSWQTs should be developed on a priority basis for water quality characteristics that may be affected by human activities conducted on or near the NWR under consideration, either now or in the foreseeable future. In cases where many RSWQTs are needed for individual refuges or refuge complexes, priorities for RSWQT development should be identified by refuge staff prior to developing RSWQTs. Factors that should be included in the prioritization criteria include:

- Resources available for RSWQT development;
- Classification of water bodies of interest;
- Availability of appropriate EPA AWQC, WQSs, and WQGs;
- Extent of critical habitat; and,
- Consideration of the potential risk to aquatic life.

In addition, NWRs may have multiple water bodies that require different classifications, depending on the aquatic community and water uses. Thus, refuge staff may need to prioritize the development of RSWQTs within a refuge. In some cases, different sections of the same water body may require multiple designations; however, in these cases, it may be more efficient to use the precautionary principle (i.e., apply the most protective designation) in order to establish a single classification for the entire water body. Permanent RSWQTs are established when sufficient scientific information is available; however, provisional targets may be established when insufficient data exist to develop permanent targets. The provisional targets are deliberately conservative and accompanied by a recommended monitoring or study program that will lead to the establishment of permanent targets. A monitoring program is also recommended

with the permanent targets to determine the level of attainment and to identify situations where designated water uses may be endangered.

The RSWQTs developed using the recommended procedures are intended to support water quality assessments conducted on NWRs for a number of purposes. For example, the RSWQTs are directly relevant for conducting water quality assessments under the FWS Contaminants Assessment Process (CAP) or the FWS Water Resources Inventory and Assessment (WRIA) initiative. Similarly, the RSWQTs provide a scientific basis for interpreting water quality data collected under the FWS Inventory and Monitoring (I&M) Initiative. The RSWQTs can also provide a basis for evaluating the adequacy of total allowable daily loads of COPCs established under the Clean Water Act.

6.0 Monitoring to Assess Attainment of Refuge-Specific Water Quality Targets

To be effective, a monitoring program must have both a well-defined purpose and an objective that supports effective management of water resources (Ward 1979; Schilperoort and Groot 1983). Whitfield (1988) summarized the reasons for conducting water quality monitoring into five categories, including:

- Assessment of compliance with water quality objectives (WQOs; termed WQTs in this report);
- Trend assessment;
- Estimation of mass transport;
- Environmental impact; and/or,
- General surveillance.

Whitfield and Clark (2001) developed a systematic method for optimizing the design of water quality monitoring programs, and demonstrated the cost-effectiveness of monitoring programs designed to target key ecosystem characteristics likely to be responsive to specific types of interventions. This method relies on knowledge of the forces that drive change, in conjunction with signal analysis, to focus monitoring programs on the data most likely to yield information on the sensitivity and resilience of the ecosystem (Whitfield ***et al.*** 1999). This approach is consistent with the data quality objectives (DQOs) process described by USEPA (2006) and summarized in Clark ***et al***. (2010). DQOs optimize the collection of water quality data since only data needed to support the decision are collected. Additionally, DQOs provide a high level of transparency in decisions related to monitoring program design.

Water quality conditions are known to vary substantially both temporally and spatially. This underlying variability in water quality data makes it challenging to distinguish patterns in water quality conditions from the apparent noise in the system. Potential sources of variability and strategies to address them are summarized in Table 6 (from MacDonald ***et al.*** 2009). Acquisition and evaluation of data characterizing sources of variability in water quality conditions provide a means of designing and optimizing sampling programs for assessing status and trends.

One of the principal objectives of status assessment monitoring programs is to determine whether or not specific water quality targets (e.g., WQOs, RSWQTs) are being met (Whitfield 1988). The effectiveness of compliance monitoring programs is often expressed as the ratio of detected violations to actual violations of the targets (Schilperoort and Groot 1983), with the true frequency of exceedance established through continuous monitoring or intensive surveys of water quality. Whitfield (1988) identified two monitoring approaches that could be used to cost-effectively assess compliance with WQOs, including sequential sampling and Markovian sampling (which is a type of exceedance-driven sampling).

Sequential sampling is a hypothesis testing-driven approach that involves random or stratified sampling, with decisions related to future sampling determined by the monitoring results. More specifically, the sampling data are used to determine if the system is in compliance (null hypothesis; H_o; i.e., WQO has not been exceeded), out of compliance (alternate hypothesis; H_a; i.e., WQO has been exceeded), or the outcome is uncertain (i.e., the result is within the range of uncertainty for the measurement; e.g., WQO $\pm$ 20%). In the case of the third option, the water quality assessment is continued by making additional observations.

Markovian sampling is an approach that involves collection of samples at a variable frequency, depending on the status of the system under investigation. That is, infrequent sampling is undertaken when the system is in control and more frequent sampling is conducted when the system is tending towards non-compliance. In this approach, water quality at a particular station is viewed as a continuous process that can be scaled into levels of acceptability. For example, the possible range of outcomes for a water quality variable can be divided into multiple categories based on proximity to the WQO value (e.g., <0.1 x WQO = *safe*; 0.1 - <0.5 x WQO = *marginal*; 0.5 - 0.99 x WQO = *alert*; and, $\geq$WQO = *non-compliance*). Decisions about the frequency of sampling are then made based on the measured concentrations of each analyte and the period of time that the analyte concentration has been within a particular range. Where a suite of different variables need be analyzed on each sampling occasion, the frequency is determined by those variables closest to non-compliance, or most often non-compliant.

In general, exceedance-driven sampling is considered to be the most appropriate for assessing compliance with acute-type WQOs or WQTs, while fixed-frequency sampling is most relevant for assessing compliance with chronic-type WQOs or WQTs. One advantage of the fixed-frequency sampling approach is that the number of samples and, hence, costs, can be determined prior to program implementation. This is not the case for exceedance-driven sampling. One of the

advantages of the exceedance-driven approach is that it supports determination of the optimum number of samples before implementing the program, if sufficient information exists to estimate the probability of observing outcomes in each category. However, incomplete knowledge of the true variability in water quality conditions can negate this advantage. In addition, the amount of time needed to analyze the samples can render the exceedance driven approach difficult to implement.

7.0 Application of Refuge-Specific Water Quality Targets

Monitoring to assess attainment of WQOs (in this case, RSWQTs) is an important part of the overall WQOs (i.e., RSWQTs) process and is necessary to guide management decisions (BCMOE 2013). Regular sampling must occur to ensure that the recommended acute (i.e., short-term maximum) and chronic (i.e., long-term average) RSWQTs are met. Monthly sampling, as well as two 5-in-30 day sampling events (i.e., 5 samples collected at six-day intervals over a 30 day period, targeting high flow and low flow periods), should occur at appropriate monitoring locations on the NWRs to evaluate attainment of the RSWQTs. For Waters of Special Significance, if one monthly sample exceeds the acute RSWQT or two consecutive monthly samples exceed the chronic RSWQT, then an additional 5-in-30 day sampling event should be triggered in order to obtain a better understanding of the water quality at that time, and to determine if the chronic RSWQT is exceeded by the average of the five samples collected in 30 days. It is acceptable for one out of twenty monthly samples to exceed the acute RSWQT and still be characteristic of baseline conditions. If the acute RSWQT is exceeded more frequently, or if the chronic RSWQT is exceeded at least once (by the average of five samples collected over 30 days), then mitigative actions should be taken to improve the water quality so that there is attainment of the RSWQTs. For Sensitive Waters and Typical Waters, any exceedance of the acute or chronic

RSWQTs should result in an increase in monitoring frequency and/or the application of mitigation measures, as deemed appropriate on the NWR.

8.0 References

Augspurger, T. 2013. Site-specific ammonia limits for an endangered mussel. U.S. Fish and Wildlife Service, Raleigh, NC. Poster RP99, presented at the Society of Environmental Toxicology and Chemistry 34th Annual Meeting, November 21, 2013, Nashville, TN.

BCMOE (British Columbia Ministry of Environment). 2012a. Water and air baseline monitoring guidance document for mine proponents and operators. Written by B. Carmichael, P. Hudson, G. Matscha, C. Schell, C. Stewart, D. Tamblyn, G. Tamblyn, B. Weinstein, B. Wilkes, and C. van Geloven. Edited by V. Carmichael.176 p.

BCMOE (British Columbia Ministry of Environment). 2012b. Derivation of water quality guidelines to protect aquatic life in British Columbia. Water Protection and Sustainability Branch, Environmental Sustainability and Strategic Policy Division, British Columbia Ministry of Environment.34 p.

BCMOE (British Columbia Ministry of Environment). 2013. Guidance for the derivation and application of water quality objectives in British Columbia. Water Protection and Sustainability Branch. Ministry of Environment.140 pp + vii.

BCMOE (British Columbia Ministry of Environment). 2014a. Water Quality: Water Quality Guidelines (Criteria) Reports. Approved Water Quality Guidelines. Environmental Protection Division. Available at http://www.env.gov.bc.ca/wat/wq/wq_guidelines.html.

BCMOE (British Columbia Ministry of Environment). 2014b. Ambient Water Quality Guidelines for Selenium: Technical Report Update. Prepared By: Water Protection and Sustainability Branch, Environmental Sustainability and Strategic Policy Division, British Columbia Ministry of Environment.

CCME (Canadian Council of Ministers of the Environment). 2000. Canadian tissue residue guidelines for the protection of wildlife consumers of aquatic biota: Methylmercury. In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg.

CCME (Canadian Council of Ministers of the Environment). 2007. A protocol for the derivation of water quality guidelines for the protection of aquatic life 2007. In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, 1999, Winnipeg, Manitoba.

CCME (Canadian Council of Ministers of the Environment). 2014. Canadian Environmental Quality Guidelines Summary Table. Water quality guidelines for the protection of aquatic life. Canadian Environmental Quality Guidelines. Winnipeg, Manitoba. Available at http://st-ts.ccme.ca/en/index.html?chems=all&chapters=1

Clark, M.J.R., D.D. MacDonald, P.H. Whitfield, and M.P. Wong. 2010. Designing monitoring programs for water quality based on experience in Canada. Part II - Monitoring Tools - Problem Characterization and Data Quality Objectives. Trends in Analytical Chemistry 29(5):385-398.

MacDonald, D.D., M.J.R. Clark, P.H. Whitfield, and M.P. Wong. 2009. Designing monitoring programs for water quality based on experience in Canada I. Theory and framework. Trends in Analytical Chemistry 28(2): 204-213.

MacDonald, D.D., J. Sinclair, M. Crawford, H. Prencipe and M. Meneghetti. 2011. Potential effects of contaminants on Fraser River sockeye salmon. MacDonald Environmental Sciences Ltd. Cohen Commission Tech. Rep. 2: 164p & appendices. Vancouver, B.C. Available at www.cohencommission.ca.

MacDonald, D.D., M.A. Crawford, H.J. Prencipe, J.A. Sinclair, A. Schein, and M.B. Meneghetti. 2014. Handbook for Assessing Risks to Fish and Wildlife Associated with the Potential Use of Water, Treated Wastewater, Stormwater, Sediment, Soil, Biosolids, or Other Materials on Units of the National Wildlife Refuge System. Volumes I-IV. Prepared for U.S. Fish and Wildlife Service, Vancouver, Washington. Prepared by MacDonald Environmental Sciences Ltd., Nanaimo, British Columbia.

Nagpal, N.K., L.W. Pommen, and L.G. Swain. 2006. Water Quality: A compendium of working water quality guidelines for British Columbia. Prepared for British Columbia Ministry of Environment. Environmental Protection Division. Science and Information Branch. Available at http://www.env.gov.bc.ca/wat/wq/BCguidelines/working.html.

National Wildlife Refuge System Improvement Act. 1997. National Wildlife Refuge System Improvement Act of 1997. Public Law 105-57 - Oct. 9, 1997. Available at http://www.gpo.gov/fdsys/pkg/PLAW-105publ57/pdf/PLAW-105publ57.pdf.

Neely, W.B., D.R. Branson, and G.E. Blau. 1974. Partition coefficient to measure bioconcentration potential of organic chemicals in fish. Environmental Science and Technology 3:1113 – 1115.

Presser, T.S. and S.N. Luoma. 2010. A methodology for ecosystem-scale modelling of selenium. Integrated Environmental Assessment and Management 6(4): 685-710.

Schilperoort, T. and S. Groot. 1983. Design and optimization of water quality monitoring networks. Paper presented at the International Symposium on Methods and Instrumentation for the Investigation of Groundwater Systems (MIIGS), Noordwijkerhout, the Netherlands, May 1982. Publication No. 286.Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman and W.A. Brungs. 1985. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. PB85-227049.National Technical Information Service, Springfield, VA.

Toll, J.E., L.M. Tear, D.K. DeForest, K.V. Brix, and W.J. Adams. 2005. Setting site-specific water-quality standards by using tissue residue criteria and bioaccumulation data. Part 1. Methodology. Environmental Toxicology and Chemistry 24(1):224-230.

USEPA (United States Environmental Protection Agency). 1986. Quality Criteria for Water 1986. EPA 440/5-86-001. Office of Water Regulations and Standards. Washington, District of Columbia. Available at http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/upload/2009_01_13_criteria_goldbook.pdf.

USEPA (United States Environmental Protection Agency). 2006. Guidance on systematic planning using the data quality objectives process. EPA QA/G-4.EPA/240/B-06/001.Office of Environmental Information, Washington, DC.

USEPA (United States Environmental Protection Agency). 2012. Water Quality Standards Handbook: Second Edition. EPA-823-B-12-002.Available at http://water.epa.gov/scitech/swguidance/standards/handbook/.

USEPA (United States Environmental Protection Agency). 2013. Aquatic life ambient water quality criteria for ammonia - freshwater. EPA 822-R-13-001. Office of Water; Office of Science and Technology. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 2014a. National Recommended Water Quality Criteria. Office of Water. Office of Science and Technology. Washington, D.C. Available at http://water.epa.gov/scitech/swguidance/standards/criteria/current/index.cfm.

USEPA (United States Environmental Protection Agency). 2014b. External Peer Review Draft Aquatic Life Ambient Water Quality Criterion for Selenium – Freshwater 2014. Prepared by: USEPA, Office of Water, Office of Science and technology, Washington, DC. EPA 822-P-14-0001. May 2014. 637 pp.

USEPA (United States Environmental Protection Agency). 2014c. Ecoregional criteria documents. Nutrient policy data. Washington, District of Columbia. Available at http://www2.epa.gov/nutrient-policy-data/ecoregional-criteria-documents.

USFWS (United States Fish and Wildlife Service). 2006. National Wildlife Refuge System Mission and Goals and Refuge Purposes. 601 FW 1. Division of Conservation, Planning and Policy. Available at http://www.fws.gov/policy/601fw1.html.

Ward, R.C. 1979. Regulatory water quality monitoring: a systems perspective. Water Resources Bulletin 15(2): 369-380. (As cited in Dixon and Chiswell 1996).

WDOE (Washington Department of Ecology). 2012. Water quality standards for surface waters of the State of Washington. Chapter 173-201A WAC. Watershed Management Section, Water Quality Program. Olympia, Washington. Available at https://fortress.wa.gov/ecy/publications/publications/0610091.pdf.

Whitfield, P.H. 1988. Goals and data collection designs for water quality monitoring. Water Resources Bulletin 24(4):775-780.

Whitfield, P.H. and M.J.R. Clark. 2001. Using force analysis to target collection and analysis of environmental information. Environmental Management 28(1):75-85.

Whitfield, P.H., M.J.R. Clark, and A. Cannon. 1999. Signals and noise in environmental data-characterization of non-random uncertainty in environmental monitoring. p. 86-95. *In*: Environmental modeling. Proceedings of the International Conference on Water, Environment, Ecology, Socio-economics and Health Engineering (WEESHE). October 18-21, 1999. Eds. Singh, V.P., I.W. Seo, and J.H. Sonu. ISBN Number 1-887201-23-8.Water Resources Publications, LLC. Highlands Ranch, Colorado.

Tables

Tables

Table 1. A comparison of different types of water quality benchmarks.

Type of Water Quality Benchmark	Method for Derivation of Acute Water Quality Benchmark	Method for Derivation of Chronic Water Quality Benchmark
Environmental Protection Agency Ambient Water Quality Criteria (EPA AWQC)[1]	- Compile available toxicity test data (use LC_{50} and EC_{50} values). - Requires data from a minimum of eight diverse taxonomic groups (see Stephan *et al.* 1985 for details). - Calculate SMAVs (geometric mean of values from same species) & GMAVs (geometic mean of SMAVs from same genus). - Create species sensitivity distribution (SSD; rank GMAVs from most to least sensitive). - Use the four genera closest to the 5th percentile of the distribution to caclulate the FAV (see Stephan *et al.* 1985 for details). - Divide FAV by two to obtain the CMC.	- Compile available toxicity test data (use MATC [2] or EC_{20} values). - If data from the minimum eight diverse taxonomic groups are available, calculate CCC using procedures similar to those used to - If data are not available from eight diverse taxonomic groups, divide the FAV by the Acute-Chronic Ratio (ACR) to obtain the FCV (see Stephan *et al.* 1985 for details). - The FCV is used directly as the CCC.
Water Quality Standards (WQSs)[3]	- States generally adopt the EPA AWQC. - If a State develops its own WQSs they must be at least as protective as the EPA AWQC and must meet the requirements of the Clean Water - Methods used by States to develop more stringent WQSs are described in their WQSs.	- States generally adopt the EPA AWQC. - If a State develops its own WQSs they must be at least as protective as the EPA AWQC and must meet the requirements of the Clean Water - Methods used by States to develop more stringent WQSs are described in their WQSs.
Canadian Water Quality Guidelines (WQGs)[4]	- Compile available toxicity test data. Classify data as primary, secondary, or unacceptable according to their quality. Minimum data requirements (e.g., three fish species, including one salmonid and one non-salmonid) must be met using primary and secondary data (see CCME 2007 for more details). - Use LC_{50} or EC_{50} values. If there is more than one comparable value for a species, take the geometric mean of these values. - Place the selected toxicity values into a cumulative SSD. - The estimated concentration corresponding to the 5th percentile of evaluated species (based on the fitted SSD) is selected as the WQG.	- Compile available toxicity test data. Classify data as primary, secondary, or unacceptable according to their quality. Minimum data requirements (e.g., three fish species, including one salmonid and one non-salmonid) must be met using primary and secondary data (see CCME 2007 for more details). - Select the most sensitive effect/endpoint combination for each species, preferably a no-effect value. If there is more than one comparable value for a species, take the geometric mean of these values. - Place the selected toxicity values into a cumulative SSD. - The estimated concentration corresponding to the 5th percentile of evaluated species (based on the fitted SSD) is selected as the WQG.

Table 1. A comparison of different types of water quality benchmarks.

Type of Water Quality Benchmark	Method for Derivation of Acute Water Quality Benchmark	Method for Derivation of Chronic Water Quality Benchmark
British Columbia Water Quality Guidelines (WQGs)[5]	- Compile available toxicity test data. Classify data as primary, secondary, or unacceptable according to their quality. A minimum number of primary studies based on toxicity tests with fish, invertebrates, and plants is required to derive a WQG. - From the primary studies, the lowest reliable LC_{50} or EC_{50} from a short-term test is selected as the basis for the short-term maximum WQG. - An uncertainty factor (usually between 2 and 10) is applied to the lowest toxicity value to derive the short-term WQG.	- Compile available toxicity test data. Classify data as primary, secondary, or unacceptable according to their quality. A minimum number of primary studies based on toxicity tests with fish, invertebrates, and plants is required to derive a WQG. - From the primary studies, the lowest reliable low-effects threshold EC_x from a long-term study is selected as the basis of the long-term average WQG. - An uncertainty factor (usually between 2 and 10) is applied to the lowest toxicity threshold to derive the long-term WQG.

AWQC = ambient water quality criteria; BCMOE = British Columbia Ministry of Environment; CCC = criterion continuous concentration; CCME = Canadian Council of Ministers of the Environment; CMC = criterion maximum concentration; EC = effect concentration; EPA = Environmental Protection Agency; FAV = final acute value; FCV = final chronic value; GMAV = genus mean acute value; LC = lethal concentration; MATC = maximum acceptable toxicant concentration; SMAV = species mean acute value; SSD = species sensitivity distribution; WQG = water quality guideline; WQS = water quality standard.

[1] USEPA (2014a).

[2] The MATC (maximum acceptable toxicant concentration) is equal to the geometric mean of the NOEC (no observed effect concentration) and LOEC (lowest observed effect concentration). The MATC is also known as the chronic value.

[3] USEPA (2012).

[4] CCME (2014).

[5] BCMOE (2014a).

Table 2. Example checklist for determining the water classification of a National Wildlife Refuge.

Questions / Species Present on Refuge

Q1. Does the NWR provide critical habitat for one or more aquatic-obligate endangered species? Yes: _____ No: _____

Q2. If yes, list endangered species and habitat use by month.

	Month Species is Present											
Aquatic-Obligate Endangered Species	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**

Q3. Do any of the following sensitive taxa, or other taxa of concern, utilize aquatic habitats within the NWR? Yes: _____ No: _____

Q4. If yes, identify habitat use by month.

	Month Species is Present											
Sensitive Taxa or Taxa of Concern	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Freshwater mussels (Identify species)												
Sturgeon (Identify species)												
Salmonids (Identify species)												
Other (Identify species)												
Month-Specific Water Class:												

Overall Determination: _____

Table 3. Summary of selected water quality benchmarks for the protection of freshwater aquatic life.

Chemical	USEPA (2014a) AWQC		CCME (2014) WQG [1]		BCMOE (2014a) WQG		Units
	Chronic	Acute	Chronic	Acute	Chronic	Acute	
Conventionals							
Hardness	*No AWQC*	*No AWQC*	*No WQG*	*No WQG*	*No WQG*	*No WQG*	mg/L
pH	6.5 - 9	*No AWQC*	6.5 - 9.0	*No WQG*	6.5 - 9.0	*No WQG*	pH Scale
Alkalinity	20 [2]	*No AWQC*	*No WQG*	*No WQG*	*No WQG*	*No WQG*	mg/L
Temperature	*Species dependent* [3]		*Narrative statement* [4]		*Species/life stage dependent* [5]		°C
Total Suspended Solids (TSS)	*Narrative statement* [6]		*Based on background TSS* [7]		*Based on background TSS* [8]		mg/L
Dissolved Organic Carbon (DOC)	*No AWQC*	*No AWQC*	*No WQG*	*No WQG*	*Based on background DOC* [9]	*No WQG*	mg/L
Dissolved Oxygen (DO)	*Species/life stage dependent* [10]		*Species/life stage dependent* [11]	*No WQG*	8 [12]	5 [13]	mg/L
Nutrients							
Ammonia as TAN [14]	1.9 [15]	17 [15]	4.82 [16]	*No WQG*	1.22 [17]	19.2 [17]	mg/L
Nitrate as NO_3	*Varies by Ecoregion* [18]		13	550	13	145	mg/L
Nitrite as NO_2	*Varies by Ecoregion* [18]		197	*No WQG*	66	197	µg/L
Phosphorus (total)	*Varies by Ecoregion* [18]		*Narrative statement* [19]	*No WQG*	5 - 15	*No WQG*	µg/L
Major Ions							
Chloride	230	860	120	640	150	600	mg/L
Calcium	*No AWQC*	*No AWQC*	*No WQG*	*No WQG*	*No WQG*	*No WQG*	mg/L
Magnesium	*No AWQC*	*No AWQC*	*No WQG*	*No WQG*	*No WQG*	*No WQG*	mg/L
Potassium	*No AWQC*	*No AWQC*	*No WQG*	*No WQG*	*No WQG*	*No WQG*	mg/L
Sodium	*No AWQC*	*No AWQC*	*No WQG*	*No WQG*	*No WQG*	*No WQG*	mg/L
Sulfate [20]	*No AWQC*	*No AWQC*	*No WQG*	*No WQG*	218	*No WQG*	mg/L
Total Dissolved Solids (TDS)	*No AWQC*	*No AWQC*	*No WQG*	*No WQG*	*No WQG*	*No WQG*	mg/L
Metals (Based on the dissolved fraction; calculated for a hardness of 50 mg/L $CaCO_3$ when applicable)							
Aluminum	87	750	100	*No WQG*	50	100	µg/L
Arsenic	150	340	5	*No WQG*	5	*No WQG*	µg/L
Cadmium [20]	0.15	1.0	0.0892	1.04	0.018 [21]	*No WQG*	µg/L

Table 3. Summary of selected water quality benchmarks for the protection of freshwater aquatic life.

Chemical	USEPA (2014a) AWQC		CCME (2014) WQG [1]		BCMOE (2014a) WQG		Units
	Chronic	Acute	Chronic	Acute	Chronic	Acute	
Metals (Based on the dissolved fraction; calculated for a hardness of 50 mg/L $CaCO_3$ when applicable; cont.)							
Chromium (III) [20]	42	320	8.9	*No WQG*	8.9	*No WQG*	µg/L
Chromium (VI)	11	16	1	*No WQG*	1	*No WQG*	µg/L
Copper [20]	Use BLM [22]	Use BLM [22]	2	*No WQG*	2	6.7	µg/L
Lead [20]	1.2	30	1	*No WQG*	4.63	33.8	µg/L
Mercury (Inorganic)	0.77	1.4	0.026	*No WQG*	0.00125 - 0.02 [23]	*No WQG*	µg/L
Molybdenum	*No AWQC*	*No AWQC*	73	*No WQG*	1000	2000	µg/L
Nickel [20]	29	260	25	*No WQG*	25	*No WQG*	µg/L
Selenium	5.0 [24]	Equation [25]	1	*No WQG*	2	*No WQG*	µg/L
Silver [20]	*No AWQC*	0.98	0.1	*No WQG*	0.05	0.1	µg/L
Zinc [20]	66	65	30	*No WQG*	7.5	33	µg/L
PCBs							
Total PCBs	0.014	*No AWQC*	*No WQG*	*No WQG*	0.0001	*No WQG*	µg/L

Green cells indicate a working water quality guideline (Nagpal *et al.* 2006).

AWQC = ambient water quality criteria; BCMOE = British Columbia Ministry of Environment; CCME = Canadian Council of Ministers of the Environment; CMC = criterion maximum concentration; DO = dissolved oxygen; DOC = dissolved organic carbon; NWR = National Wildlife Refuge; PCBs = polychlorinated biphenyls; RSWQT = refuge-specific water quality target; TAN = total ammonia nitroge TDS = total dissolved solids; TSS = total suspended solids; USEPA = United States Environmental Protection Agency; WQG = water quality guideline.

[1] CCME WQGs for metals were developed for the total fraction, but are applied here to the dissolved fraction.

[2] This is a minimum value. Alkalinity cannot be lower than 20 mg/L except where alkalinity is naturally lower, in which case the criterion cannot be lower than 25% of the natural level (USEPA 2014a).

[3] See USEPA (1986) for a detailed description of the temperature criteria for freshwater aquatic life at the following link: http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/upload/2009_01_13_criteria_goldbook.pdf

[4] Thermal additions to receiving waters should be such that the maximum weekly average temperature is not exceeded. Thermal additions to receiving waters should be such that the short-term exposures to maximum temperatures are not exceeded. Exposures should not be so lengthy or frequent as to adversely affect the important species. For more information see CCME (2014) at: http://st-ts.ccme.ca/en/index.html?lang=en&factsheet=209

[5] The water quality guidelines vary according to the species and life stage present in the water body. See BCMOE (2014a) for details at: http://www.env.gov.bc.ca/wat/wq/BCguidelines/temptech/temperature.html

[6] Settleable and suspended solids should not reduce the depth of the compensation point for photosynthetic activity by more than 10 percent from the seasonally established norm for aquatic life (USEPA 1986).

Footnotes continued on next page…

Table 3. Summary of selected water quality benchmarks for the protection of freshwater aquatic life.

Chemical	USEPA (2014a) AWQC		CCME (2014) WQG [1]		BCMOE (2014a) WQG		Units
	Chronic	Acute	Chronic	Acute	Chronic	Acute	

[7] The WQG is based on background TSS concentration; see the explanation from CCME (2014) at the following link: http://st-ts.ccme.ca/en/index.html?lang=en&factsheet=218

[8] The WQG is based on background TSS concentration; see the explanation from BCMOE (2014a) at the following link: http://www.env.gov.bc.ca/wat/wq/BCguidelines/turbidity/turbidity.html

[9] The WQG is equal to the 30-day median ± 20% of the median background concentration (BCMOE 2014a).

[10] See Table 1 in the Dissolved Oxygen section of USEPA (1986) for the ambient water quality criteria for ambient dissolved oxygen concentration.

[11] Lowest acceptable dissolved oxygen concentration:
for warm water biota: early life stages = 6 mg/L
for warm water biota: other life stages = 5.5 mg/L
for cold water biota: early life stages = 9.5 mg/L
for cold water biota: other life stages = 6.5 mg/L (CCME 2014).

[12] This is the 30-day mean minimum value for all life stages other than buried embryo/alevin. Buried embryo/alevin life stages require a minimum of 11 mg/L oxygen in the water column and 8 mg/L oxygen in the interstitial water (BCMOE 2014a).

[13] This is the instantaneous minimum for all life stages other than buried embryo/alevin. Buried embryo/alevin life stages require a minimum of 9 mg/L oxygen in the water column and 6 mg/L oxygen in the interstitial water (BCMOE 2014a).

[14] The benchmarks for ammonia are pH and temperature dependent and are displayed at a pH of 7 and water temperature of 20°C. To calculate the benchmarks at a different pH and/or temperature, use the equation or table applicable to the benchmark of interest in its criteria document or on the website of the appropriate jurisdiction (i.e., USEPA [2013], BCMOE [2014a], CCME [2014]).

[15] AWQC at a temperature of 20°C and pH of 7. See USEPA (2013) for tables and equations to calculate the AWQC at other temperature and pH combinations.

[16] WQG at a temperature of 20°C and pH of 7. See the table at the following CCME (2014) link to determine the WQG at other temperature and pH combinations: http://st-ts.ccme.ca/en/index.html?lang=en&factsheet=5

[17] WQG at a temperature of 20°C and pH of 7. See Table 4 in the Overview Report under "Nitrogen - nitrate, nitrite, ammonia" at the following BCMOE (2014a) link to determine the chronic WQG at other temperature and pH combinations: http://www.env.gov.bc.ca/wat/wq/wq_guidelines.html

[18] USEPA (2014c) presents recommended criteria for nutrients (guidance on nutrient criteria that states and tribes may use as a starting point for developing their own water quality standards). This guidance varies by Ecoregion and can be accessed at the following link: http://www2.epa.gov/nutrient-policy-data/ecoregional-criteria-documents

[19] CCME (2014) provides trigger ranges for total phosphorus depending on the nutrient status of the water body. See the following link for details: http://st-ts.ccme.ca/en/index.html?lang=en&factsheet=167

[20] At least some benchmarks for this metal or ion are hardness dependent and are displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the benchmarks at a different hardness, go to the website of the appropriate jurisdiction (i.e., USEPA [2014a], CCME [2014], BCMOE [2014a]) or use the NWR Water Quality Target Tool.

[21] The BCMOE water quality guideline for cadmium is currently being updated; therefore, the water quality guideline that is presented here is outdated and will not be selected as a RSWQT.

[22] The USEPA (2014a) calculates the AWQC for copper using the biotic ligand model (BLM). See the following website for more details: http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/copper/index.cfm

[23] This WQG depends on the percentage of methylmercury (MeHg). When MeHg is 0.5% of total mercury (THg), the WQG = 0.02 µg/L. When MeHg is 1.0% of THg, the WQG = 0.01 µg/L. When MeHg is 8.0% of THg, the WQG = 0.00125 µg/L (BCMOE 2014a).

Footnotes continued on next page…

Table 3. Summary of selected water quality benchmarks for the protection of freshwater aquatic life.

Chemical	USEPA (2014a) AWQC		CCME (2014) WQG [1]		BCMOE (2014a) WQG		Units
	Chronic	Acute	Chronic	Acute	Chronic	Acute	

[24] EPA is in the process of updating this selenium criterion to reflect the latest scientific information. See the following website for more information: http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/selenium/index.cfm

[25] The CMC [acute AWQC] = 1/[(f1/CMC1) + (f2/CMC2)] where f1 and f2 are the fractions of total selenium that are treated as selenite and selenate, respectively, and CMC1 and CMC2 are 185.9 µg/L and 12.82 µg/L, respectively (USEPA 2014a). EPA is in the process of updating this criterion to reflect the latest scientific information. See the following website for more information: http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/selenium/index.cfm

Table 4. Recommended refuge-specific water quality targets for three classes of waters on National Wildlife Refuges.

Chemical	RSWQTs for Waters of Special Significance		RSWQTs for Sensitive Waters [1]		RSWQTs for Typical Waters [2]		Units
	Chronic	Acute	Chronic	Acute	Chronic	Acute	
Conventionals							
Hardness	Background approach	Background approach	Background approach	Background approach	Background approach	Background approach	mg/L
pH	Background approach	Background approach	6.5 - 9 [3]	Background approach	6.5 - 9	Background approach	pH Scale
Alkalinity	Background approach	Background approach	20 [4]	Background approach	20 [4]	Background approach	mg/L
Temperature	Background approach	Background approach	*Species dependent* [5]		*Species dependent* [5]		°C
Total Suspended Solids (TSS)	Background approach	Background approach	*Based on background TSS* [6, 7]		*Narrative statement* [8]		mg/L
Dissolved Organic Carbon (DOC)	Background approach	Background approach	*Based on background DOC* [9]	Background approach	*Based on background DOC* [9, 10]	Background approach	mg/L
Dissolved Oxygen (DO)	Background approach	Background approach	8 [11]	5 [12]	*Species/life stage dependent* [13]		mg/L
Nutrients							
Ammonia as Total Ammonia Nitrogen	Background	Background	0.42 [14]	7.2 [14]	1.9 [15]	17 [15]	mg/L
Nitrate as NO_3	Background approach	Background approach	13 [6]	145 [6]	*Varies by Ecoregion* [16]		mg/L
Nitrite as NO_2	Background approach	Background approach	66 [6]	197 [6]	*Varies by Ecoregion* [16]		µg/L
Phosphorus (total)	Background approach	Background approach	*Varies by Ecoregion* [16]		*Varies by Ecoregion* [16]		µg/L
Major Ions							
Chloride	Background approach	Background approach	120 [17]	600 [6]	230	860	mg/L
Calcium	Background approach	Background approach	Background approach	Background approach	Background approach	Background approach	mg/L

Table 4. Recommended refuge-specific water quality targets for three classes of waters on National Wildlife Refuges.

Chemical	RSWQTs for Waters of Special Significance		RSWQTs for Sensitive Waters [1]		RSWQTs for Typical Waters [2]		Units
	Chronic	Acute	Chronic	Acute	Chronic	Acute	
Major Ions (cont.)							
Magnesium	Background approach	Background approach	Background approach	Background approach	Background approach	Background approach	mg/L
Potassium	Background approach	Background approach	Background approach	Background approach	Background approach	Background approach	mg/L
Sodium	Background approach	Background approach	Background approach	Background approach	Background approach	Background approach	mg/L
Sulfate	Background approach	Background approach	218 [6, 18]	Background approach	218 [6, 10, 18]	Background approach	mg/L
Total Dissolved Solids (TDS)	Background approach	Background approach	Background approach	Background approach	Background approach	Background approach	mg/L
Metals (Based on the dissolved fraction; calculated for a hardness of 50 mg/L $CaCO_3$ when applicable)							
Aluminum	Background approach	Background approach	50 [6]	100 [6]	87	750	µg/L
Arsenic	Background approach	Background approach	5 [6, 17]	340 [19]	150	340	µg/L
Cadmium	Background approach	Background approach	0.09 [17, 20]	1.0 [19, 21]	0.15 [22]	1.0 [21]	µg/L
Chromium (III)	Background approach	Background approach	8.9 [17]	320 [19, 23]	42 [24]	320 [23]	µg/L
Chromium (VI)	Background approach	Background approach	1 [17]	16 [19]	11	16	µg/L
Copper	Background approach	Background approach	2 [6, 25]	6.7 [6, 26]	Use BLM [27]	Use BLM [27]	µg/L
Lead	Background approach	Background approach	1 [17, 28]	30 [19, 29]	1.2 [30]	30 [29]	µg/L
Mercury (Inorganic)	Background approach or site-specific bioaccumulation modeling	Background approach or site-specific bioaccumulation modeling	0.026 [17] or site-specific bioaccumulation modeling	1.4 [19] or site-specific bioaccumulation modeling	0.77	1.4	µg/L

Table 4. Recommended refuge-specific water quality targets for three classes of waters on National Wildlife Refuges.

Chemical	RSWQTs for Waters of Special Significance		RSWQTs for Sensitive Waters [1]		RSWQTs for Typical Waters [2]		Units
	Chronic	Acute	Chronic	Acute	Chronic	Acute	
Metals (Based on the dissolved fraction; calculated for a hardness of 50 mg/L $CaCO_3$ when applicable; cont.)							
Molybdenum	Background approach	Background approach	73 [17, 31]	2000 [6, 31]	73 [10, 17, 31]	2000 [6, 10, 31]	µg/L
Nickel	Background approach	Background approach	25 [17, 32]	260 [19, 33]	29 [34]	260 [33]	µg/L
Selenium	Background approach or site-specific bioaccumulation modeling	Background approach or site-specific bioaccumulation modeling	1 [17] or site-specific bioaccumulation modeling	Equation [19, 35, 36] or site-specific bioaccumulation modeling	5.0 [36]	Equation [35, 36]	µg/L
Silver	Background approach	Background approach	0.05 [6, 37]	0.1 [6, 38]	0.05 [6, 10, 37]	0.98 [39]	µg/L
Zinc	Background approach	Background approach	7.5 [6, 40]	33 [6, 41]	66 [42]	65 [43]	µg/L
PCBs							
Total PCBs	Background approach	Background approach	0.0001 [6]	No RSWQT [44]	0.014	No RSWQT [44]	µg/L

BCMOE = British Columbia Ministry of Environment; BLM = biotic ligand model; CCME = Canadian Council of Ministers of the Environment; CMC = criterion maximum concentration; DO = dissolved oxygen; DOC = dissolved organic carbon; NWR = National Wildlife Refuge; PCBs = polychlorinated biphenyls; RSWQT = refuge-specific water quality target; TDS = total dissolved solids; TSS = total suspended solids; EPA = Environmental Protection Agency; AWQC = ambient water quality criteria; WQG = water quality guideline; WQS = water quality standard.

[1] The lowest chronic value from those compiled in Table 3 was chosen for the chronic RSWQT and the lowest acute value from those compiled in Table 3 was chosen for the acute RSWQT.

[2] USEPA (2014a) AWQC are the RSWQTs for Typical Waters. If the NWR of interest is in a state with lower WQSs than the EPA AWQC, the state WQSs should be used instead.

[3] AWQC for USEPA (2014a), WQG for CCME (2014), and WQG for BCMOE (2014a) for the protection of aquatic life.

[4] This is a minimum value. Alkalinity cannot be lower than 20 mg/L except where alkalinity is naturally lower, in which case the criterion cannot be lower than 25% of the natural level (USEPA 2014a).

[5] See USEPA (1986) for a detailed description of the temperature criteria for freshwater aquatic life at the following link: http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/upload/2009_01_13_criteria_goldbook.pdf

[6] WQG for BCMOE (2014a) for the protection of aquatic life.

[7] The RSWQT is based on background TSS concentration; see the explanation from BCMOE (2014a) at the following link: http://www.env.gov.bc.ca/wat/wq/BCguidelines/turbidity/turbidity.html

Footnotes continued on next page…

Table 4. Recommended refuge-specific water quality targets for three classes of waters on National Wildlife Refuges.

Chemical	RSWQTs for Waters of Special Significance		RSWQTs for Sensitive Waters [1]		RSWQTs for Typical Waters [2]		Units
	Chronic	Acute	Chronic	Acute	Chronic	Acute	

[8] Settleable and suspended solids should not reduce the depth of the compensation point for photosynthetic activity by more than 10 percent from the seasonally established norm for aquatic life (USEPA 1986).

[9] The WQG is equal to the 30-day median ± 20% of the median background concentration (BCMOE 2014a).

[10] The RSWQT for Sensitive Waters is used here because USEPA (2014a) does not have AWQC for this chemical.

[11] This is the 30-day mean minimum value for all life stages other than buried embryo/alevin. Buried embryo/alevin life stages require a minimum of 11 mg/L oxygen in the water column and 8 mg/L oxygen in the interstitial water (BCMOE 2014a).

[12] This is the instantaneous minimum for all life stages other than buried embryo/alevin. Buried embryo/alevin life stages require a minimum of 9 mg/L oxygen in the water column and 6 mg/L oxygen in the interstitial water (BCMOE 2014a).

[13] See Table 1 in the Dissolved Oxygen section of USEPA (1986) for the ambient water quality criteria for ambient dissolved oxygen concentration.

[14] This is the RSWQT (developed *de novo*) at a temperature of 20°C and pH of 7. See Appendix 7 for the methods on how to apply this value when the pH and water temperature on the NWR are different.

[15] AWQC at a temperature of 20°C and pH of 7. See USEPA (2013) for tables and equations to calculate the AWQC at other temperature and pH combinations.

[16] USEPA (2014c) presents recommended criteria for nutrients (guidance on nutrient criteria that states and tribes may use as a starting point for developing their own water quality standards). This guidance varies by Ecoregion and can be accessed at the following link: http://www2.epa.gov/nutrient-policy-data/ecoregional-criteria-documents

[17] WQG for CCME (2014) for the protection of aquatic life.

[18] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. At a hardness of 0 - 30 mg/L $CaCO_3$, the RSWQT = 128 mg/L. At a hardness 31 - 75 mg/L $CaCO_3$, the RSWQT = 218 mg/L $CaCO_3$. At a hardness 76 - 180 mg/L $CaCO_3$, the RSWQT = 309 mg/L. At a hardness 181 - 250 mg/L $CaCO_3$, the RSWQT = 429 mg/L. At a hardness > 250 mg/L $CaCO_3$, the RSWQT must be determined based on site water toxicity testing.

[19] AWQC for USEPA (2014a) for the protection of aquatic life.

[20] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. At a hardness > 0 and < 17 mg/L $CaCO_3$, the RSWQT = 0.04 µg/L. At a hardness ≥ 17 and ≤ 280 mg/L $CaCO_3$, use this equation: RSWQT = $10^{\wedge[0.83 * \log(Hardness) - 2.46]}$. At a hardness > 280 mg/L $CaCO_3$, the RSWQT = 0.37 µg/L.

[21] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation:
RSWQT = $e^{[1.0166 * \ln(Hardness) - 3.924]} * [1.136672 - (\ln(Hardness)*0.041838)]$

[22] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation:
RSWQT = $e^{[0.7409 * \ln(Hardness) - 4.719]} * [1.101672 - (\ln(Hardness)*0.041838)]$

[23] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation: RSWQT = $e^{[0.8190 * \ln(Hardness) + 3.7256]} * 0.316$

[24] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation: RSWQT = $e^{[0.8190 * \ln(Hardness) + 0.6848]} * 0.86$

[25] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. For all values of hardness ≤ 50 mg/L $CaCO_3$, the RSWQT = 2 µg/L. To calculate the RSWQT at a hardness > 50 mg/L $CaCO_3$, use this equation: RSWQT = 0.04 * Hardness.

[26] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation: RSWQT = 0.094 * Hardness + 2.

Footnotes continued on next page…

Table 4. Recommended refuge-specific water quality targets for three classes of waters on National Wildlife Refuges.

Chemical	RSWQTs for Waters of Special Significance		RSWQTs for Sensitive Waters [1]		RSWQTs for Typical Waters [2]		Units
	Chronic	Acute	Chronic	Acute	Chronic	Acute	

[27] The USEPA (2014a) calculates the AWQC for copper using the biotic ligand model (BLM). See the following website for more details: http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/copper/index.cfm

[28] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. At a hardness ≤ 60 mg/L $CaCO_3$, the RSWQT = 1 µg/L. At a hardness > 60 and ≤ 180 mg/L $CaCO_3$, use this equation: RSWQT = $e^{[1.273 * \ln(Hardness) - 4.705]}$. At a hardness > 180 mg/L CaCO3, the RSWQT = 7 µg/L.

[29] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation: RSWQT = $e^{[1.273 * \ln(Hardness) - 1.46]} * [1.46203 - (\ln(Hardness)*0.145712)]$

[30] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation: RSWQT = $e^{[1.273 * \ln(Hardness) - 4.705]} * [1.46203 - (\ln(Hardness)*0.145712)]$

[31] This RSWQT is for the protection of aquatic life. If the goal for the NWR is the protection of wildlife, a more appropriate RSWQT would be 50 µg/L (from BCMOE 2014a).

[32] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. At a hardness > 0 and ≤ 60 mg/L $CaCO_3$, the RSWQT = 25 µg/L. At a hardness > 60 and ≤ 180 mg/L $CaCO_3$, use this equation: RSWQT = $e^{[0.76 * \ln(Hardness) + 1.06]}$. At a hardness > 180 mg/L $CaCO_3$, the RSWQT = 150 µg/L. If the hardness is unknown, the RSWQT = 25 µg/L.

[33] The RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation: RSWQT = $e^{[0.846 * \ln(Hardness) + 2.255]} * 0.998$

[34] The RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation: RSWQT = $e^{[0.846 * \ln(Hardness) + 0.0584]} * 0.997$

[35] The CMC [acute AWQC] = 1/[(f1/CMC1) + (f2/CMC2)] where f1 and f2 are the fractions of total selenium that are treated as selenite and selenate, respectively, and CMC1 and CMC2 are 185.9 µg/L and 12.82 µg/L, respectively (USEPA 2014a).

[36] EPA is in the process of updating this selenium criterion to reflect the latest scientific information. See the following website for more information: http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/selenium/index.cfm

[37] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. At a hardness of ≤ 100 mg/L $CaCO_3$, the RSWQT = 0.05 µg/L. At a hardness > 100 mg/L $CaCO_3$, the RSWQT = 1.5 µg/L.

[38] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. At a hardness of ≤ 100 mg/L $CaCO_3$, the RSWQT = 0.1 µg/L. At a hardness > 100 mg/L $CaCO_3$, the RSWQT = 3.0 µg/L.

[39] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation: RSWQT = $e^{[1.72 * \ln(Hardness) - 6.59]} * 0.85$

[40] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. For all values of hardness ≤ 90 mg/L $CaCO_3$, the RSWQT = 7.5 µg/L. To calculate the RSWQT at a hardness > 90 mg/L $CaCO_3$, use this equation: RSWQT = 0.75 * (Hardness - 90) + 7.5.

[41] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. For all values of hardness ≤ 90 mg/L $CaCO_3$, the RSWQT = 33 µg/L. To calculate the RSWQT at a hardness > 90 mg/L $CaCO_3$, use this equation: RSWQT = 0.75 * (Hardness - 90) + 33.

[42] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation: RSWQT = $e^{[0.8473 * \ln(Hardness) + 0.884]} * 0.986$

[43] RSWQT is hardness-dependent and is displayed at a hardness of 50 mg/L $CaCO_3$. To calculate the RSWQT at a different hardness, use this equation: RSWQT = $e^{[0.8473 * \ln(Hardness) + 0.884]} * 0.978$

[44] No RSWQT is recommended because USEPA (2014a), CCME (2014), and BCMOE (2014a) do not have acute AWQC or WQGs for PCBs. Direct exposure in water is a less significant exposure pathway for PCBs relative to dietary exposure (i.e., bioaccumulation).

Table 5. Recommended fish-tissue based refuge-specific water quality targets for selenium and mercury to protect aquatic life and aquatic-dependent wildlife.

Chemical of Potential Concern	Protection of Aquatic Life				Protection of Aquatic-Dependent Wildlife
	Dietary	Egg/Ovary	Whole-body	Muscle	Dietary
Selenium (mg/kg dry weight)					
USEPA[1]	N/A	15.2	8.1	11.8	N/A
BCMOE	4 [2]	11	4	4 [2]	N/A
Recommended Threshold	4 [2]	11	4	4 [2]	N/A
Mercury (mg/kg wet weight)					
BCMOE	N/A	N/A	N/A	N/A	0.033[3]
CCME	N/A	N/A	N/A	N/A	0.033[3]
Dillon *et al.* 2010	N/A	N/A	0.3[4] / 0.1[5]	N/A	N/A
Recommended Threshold	N/A	N/A	0.3[4] / 0.1[5]	N/A	0.033[3]

BCMOE = British Columbia Ministry of Environment; CCME = Canadian Council of Ministers of the Environment; N/A = not applicable; USEPA = United States Environmental Protection Agency.

[1] These are draft guidelines, currently under review (USEPA 2014a).

[2] Interim guidelines (BCMOE 2014a).

[3] Measured as methylmercury.

[4] Whole-body tissue concentration corresponding to 8.2% lethal equivalent effects in juvenile and adult fish (Dillon *et al.* 2010).

[5] Whole-body tissue concentration corresponding to 19.8% lethal equivalent effects in early life-stage fish (Dillon *et al.* 2010).

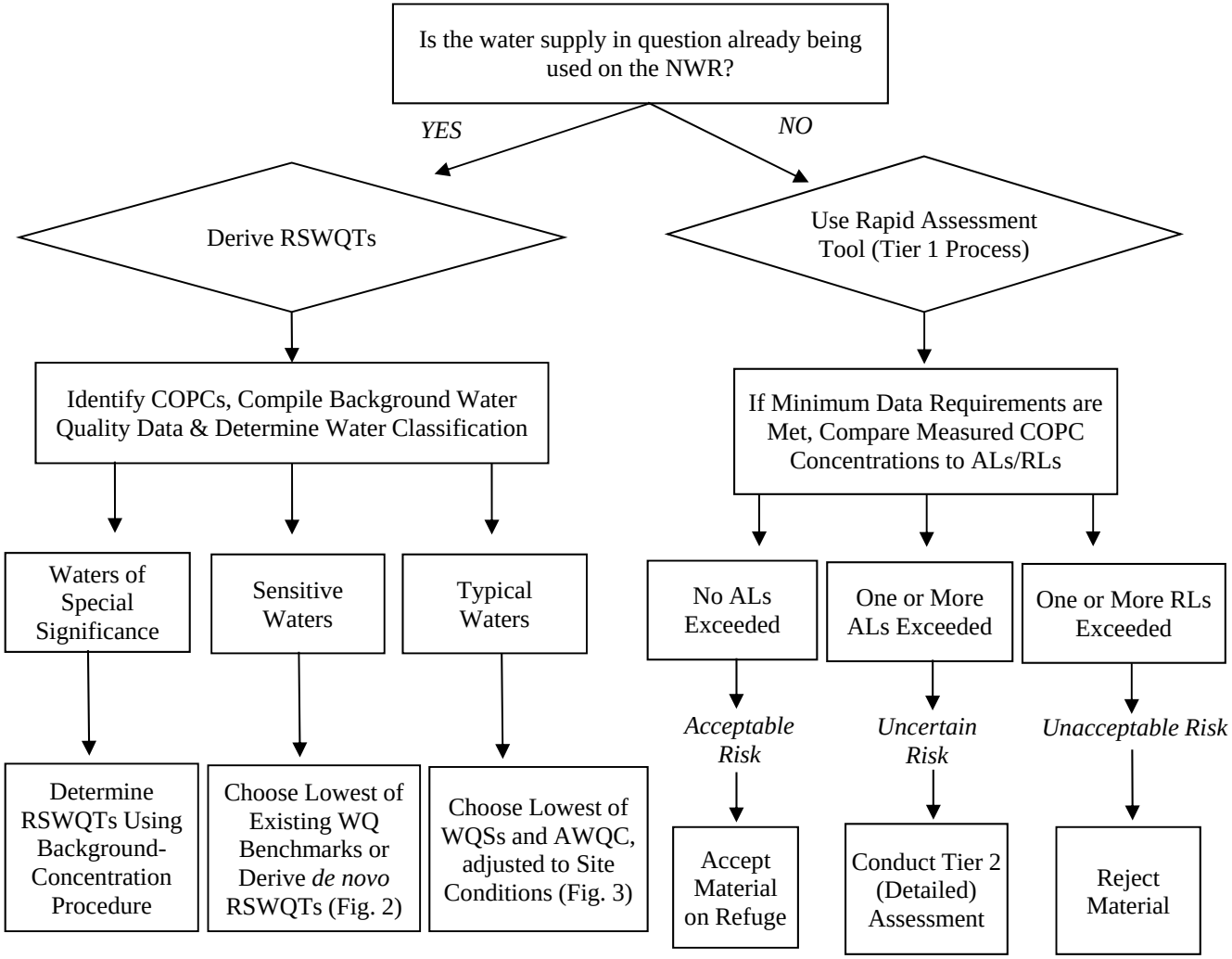
Table 6. Sources of variability in water quality conditions and recommended approaches to quantify their magnitude (MacDonald *et al.* 2009).

Source of Variability	Recommended Approach
Small scale spatial (m^3) [a]	▪ Replicate sampling to assess homogeneity over small distances (i.e., using a replicate sampler).
Depth [a]	▪ Depth integrated sampling and grab sampling at various water depths and compare the results using statistical methods. ▪ Profile across various water depths and compare the results using statistical methods.
Cross-sectional [a]	▪ Station evaluation to determine if water quality varies significantly along a cross-section of a river. ▪ Data collected along the transect are compared using statistical methods.
Longitudinal [a]	▪ Intensive water quality survey to collect water samples at numerous locations within a watershed. ▪ Data collected at the various stations are compared using statistical methods.
Diurnal [b]	▪ Intensive sampling at multiple times during a 24-hour period during station evaluations under various flow conditions (i.e., high, moderate, and low).
Seasonal [b]	▪ Frequent sampling during the course of a year, with intensive sampling conducted during freshet events. ▪ Use graphical and statistical techniques to evaluate seasonal variability.
Interannual [b]	▪ Long-term sampling at a fixed frequency at fixed stations. ▪ Use graphical and statistical techniques to evaluate long-term trends.
Regional and global influences [b]	▪ Long-term monitoring at a fixed frequency at fixed reference stations. ▪ Use graphical and statistical techniques to evaluate long-term trends.

Notes: [a] Location dependent
[b] Time dependent

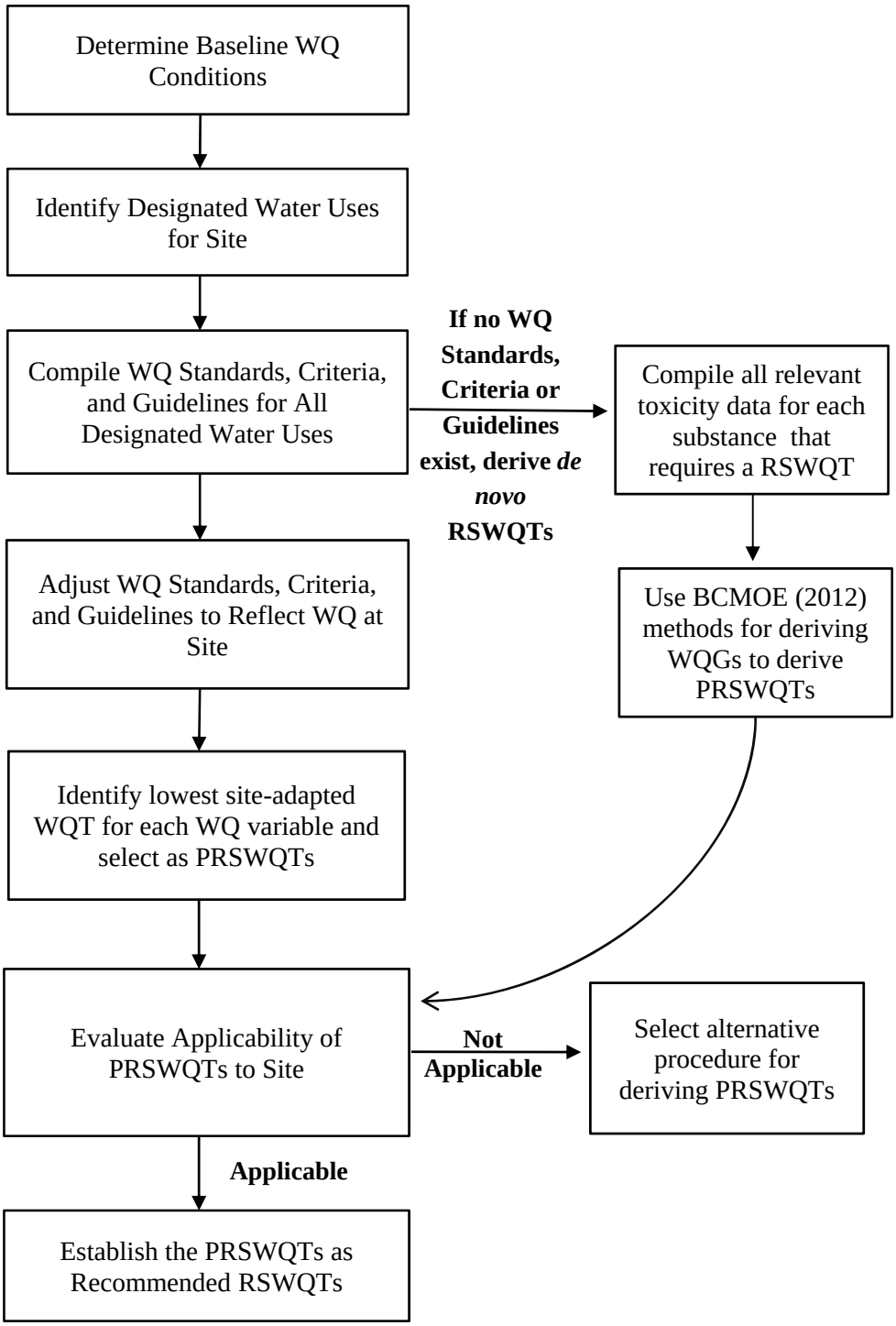
Figures

Figure 1. An overview of the decision framework for assessing potential risks to aquatic life and environmental quality on National Wildlife Refuges (NWRs; adapted from MacDonald *et al.* 2014).



ALs = acceptance levels; AWQC = ambient water quality criteria; COPC = chemical of potential concern; NWR = National Wildlife Refuge; RLs = rejection levels; RSWQTs = refuge-specific water quality targets; WQ = water quality; WQSs = water quality standards.

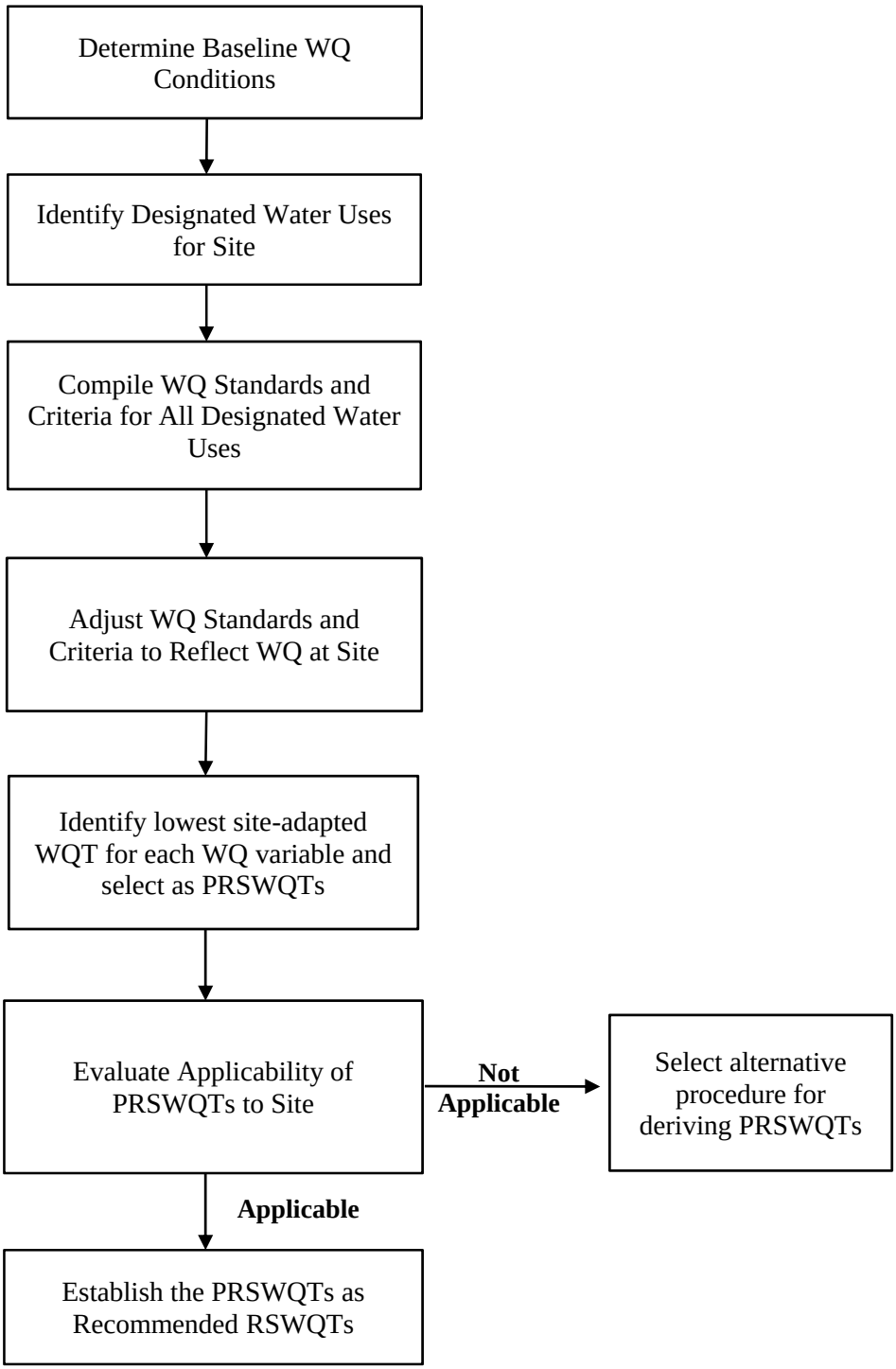
Figure 2. An overview of the process for deriving numerical refuge-specific water quality targets for aquatic life for Sensitive Waters (adapted from BCMOE 2013).



PRSWQT = preliminary refuge-specific water quality target; RSWQT = refuge-specific water quality target; WQ = water quality; WQG = water quality guideline; WQT = water quality target.

BCMOE (2012) = BCMOE (British Columbia Ministry of Environment). 2012. Derivation of water quality guidelines to protect aquatic life in British Columbia. Water Protection and Sustainability Branch, Environmental Sustainability and Strategic Policy Division, British Columbia Ministry of Environment. 34 p.

Figure 3. An overview of the process for deriving numerical refuge-specific water quality targets for aquatic life for Typical Waters (adapted from BCMOE 2013).



PRSWQT = preliminary refuge-specific water quality target; RSWQT = refuge-specific water quality target; WQ = water quality; WQT = water quality target.

Appendices

Appendix 1

Summary of the Compiled Aquatic Toxicity Data for Ammonia

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Table A1.1 Summary of compiled acute aquatic toxicity data for ammonia. A1-1

Table A1.2 Summary of compiled chronic aquatic toxicity data for ammonia. A1-42

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Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Data from USEPA (2013)[3]									
Amphibian									
Pseudacris crucifer	Spring peeper	NR	96-h	11.42	49.04	8	20	FT,U	Diamond *et al.* 1993
Pseudacris crucifer	Spring peeper	embryo	96-h	17.78	76.33	8	12	FT,U	Diamond *et al.* 1993
Pseudacris regilla	Pacific tree frog	embryo	96-h	41.19	33.36	6.7	22	R,M	Schuytema and Nebeker 1999a
Pseudacris regilla	Pacific tree frog	embryo	96-h	60.44	48.95	6.7	22	R,M	Schuytema and Nebeker 1999a
Pseudacris regilla	Pacific tree frog	embryo	96-h	103.1	83.53	6.7	22	R,M	Schuytema and Nebeker 1999a
Pseudacris regilla	Pacific tree frog	60 mg, Gosner Stage 26-27	96-h	116.4	160.2	7.3	22	R,M	Schuytema and Nebeker 1999b
Pseudacris regilla	Pacific tree frog	90 mg, Gosner Stage 26-27	96-h	136.6	188.1	7.3	22	R,M	Schuytema and Nebeker 1999b
Rana pipiens	Leopard frog	8 d	96-h	16.23	69.69	8	12	FT,M	Diamond *et al.* 1993
Rana pipiens	Leopard frog	embryo	96-h	31.04	133.3	8	20	FT,M	Diamond *et al.* 1993
Xenopus laevis	Clawed toad	embryo	96-h	32.37	39.55	7.2	24	R,M	Schuytema and Nebeker 1999a
Xenopus laevis	Clawed toad	embryo	96-h	38.59	40.91	7.2	22	R,M	Schuytema and Nebeker 1999a
Xenopus laevis	Clawed toad	embryo	96-h	60.71	74.17	7.2	24	R,M	Schuytema and Nebeker 1999a
Xenopus laevis	Clawed toad	17 mg, Gosner Stage 26-27	96-h	101.4	117.2	7.15	22	R,M	Schuytema and Nebeker 1999b
Xenopus laevis	Clawed toad	embryo	96-h	119.6	126.8	7.2	22	R,M	Schuytema and Nebeker 1999a

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Amphibian (cont.)									
Xenopus laevis	Clawed toad	21 mg, Gosner Stage 26-27	96-h	128.3	148.4	7.15	22	R,M	Schuytema and Nebeker 1999b
Xenopus laevis	Clawed toad	17 mg, Gosner Stage 26-27	96-h	135.9	157.2	7.15	22	R,M	Schuytema and Nebeker 1999b
Xenopus laevis	Clawed toad	embryo	96-h	37.3	367.4	8.43	25	R,M	Tietge *et al.* 2000
Xenopus laevis	Clawed toad	embryo	96-h	28.7	405.6	8.62	25	R,M	Tietge *et al.* 2000
Fish									
Acipenser brevirostrum	Shortnose sturgeon	fingerling	96-h	149.8	156.7	7.05	18	S,M	Fontenot *et al.* 1998
Campostoma anomalum	Central stoneroller	2.1 g	96-h	38.97	115.9	7.8	25.7	FT,M	Swigert and Spacie 1983
Catostomus commersonii	White sucker	110 mm	96-h	18.93	56.28	7.8	20.2	FT,M	Nimmo *et al.* 1989
Catostomus commersonii	White sucker	11.4 g	96-h	22.3	66.32	7.8	22.5	FT,M	Swigert and Spacie 1983
Catostomus commersonii	White sucker	110 mm	96-h	31.21	92.8	7.8	20.2	FT,M	Nimmo *et al.* 1989
Catostomus commersonii	White sucker	92 mm, 6.3 g	96-h	29.65	166.3	8.14	15.4	FT,M	Reinbold and Pescitelli 1982c
Catostomus commersonii	White sucker	92 mm, 6.3 g	96-h	30.28	176.6	8.16	15	FT,M	Reinbold and Pescitelli 1982c
Catostomus commersonii	White sucker	12.6 g	96-h	40.85	257.4	8.2	12.6	FT,M	West 1985; Arthur *et al.* 1987
Catostomus commersonii	White sucker	5.6 g	96-h	89.57	266.3	7.8	3.6	FT,M	West 1985; Arthur *et al.* 1987
Catostomus commersonii	White sucker	9.6 g	96-h	43.01	271	8.2	15.3	FT,M	West 1985; Arthur *et al.* 1987

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Catostomus commersonii	White sucker	5.2 g	96-h	60.86	316.1	8.1	11.3	FT,M	West 1985; Arthur *et al.* 1987
Catostomus platyrhynchus	Mountain sucker	45.3 g, 16.2 cm	96-h	47.59	117	7.69	13.2	FT,U	Thurston and Meyn 1984
Catostomus platyrhynchus	Mountain sucker	47.8 g, 15.9 cm	96-h	51.62	135.8	7.73	11.7	FT,U	Thurston and Meyn 1984
Catostomus platyrhynchus	Mountain sucker	63.3 g, 18.2 cm	96-h	66.91	159	7.67	12	FT,U	Thurston and Meyn 1984
Chasmistes brevirostris	Shortnose sucker	0.53-2.00 g	96-h	11.42	49.04	8	20	FT,M	Saiki *et al.* 1999
Chasmistes brevirostris	Shortnose sucker	NR	96-h	22.85	98.09	8	20	FT,M	Saiki *et al.* 1999
Cottus bairdii	Mottled sculpin	1.8 g, 5.4 cm	96-h	49.83	222.2	8.02	12.4	FT,M	Thurston and Russo 1981
Cyprinella lutrensis	Rainbow dace	NR	96-h	24.37	186.5	8.3	24	FT,M	Hazel *et al.* 1979
Cyprinella lutrensis	Rainbow dace	NR	96-h	6.502	206.1	9.1	24	FT,M	Hazel *et al.* 1979
Cyprinella spiloptera	Spotfin shiner	31-85 mm	96-h	18.52	72.39	7.95	26.5	FT,M	Rosage *et al.* 1979
Cyprinella spiloptera	Spotfin shiner	0.5 g	96-h	24.52	87.36	7.9	25.7	FT,M	Swigert and Spacie 1983
Cyprinella spiloptera	Spotfin shiner	41-78 mm	96-h	16.27	93.07	8.15	26.5	FT,M	Rosage *et al.* 1979
Cyprinella whipplei	Steelcolor shiner	0.5 g	96-h	22.72	80.94	7.9	25.7	FT,M	Swigert and Spacie 1983
Cyprinus carpio	Common carp	4-5 cm	96-h	45.05	70.78	7.4	28	R,M	Rao *et al.* 1975
Cyprinus carpio	Common carp	299 mg	96-h	48.97	126.6	7.72	28	R,M	Hasan and MacIntosh 1986

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Cyprinus carpio	Common carp	206 mg	96-h	51.78	133.9	7.72	28	R,M	Hasan and MacIntosh 1986
Deltistes luxatus	Lost River sucker	larvae	96-h	10.35	44.42	8	20	FT,M	Saiki *et al.* 1999
Deltistes luxatus	Lost River sucker	0.49-0.80 g	96-h	16.81	72.18	8	20	FT,M	Saiki *et al.* 1999
Etheostoma nigrum	Johnny darter	38 mm	96-h	6.937	43.72	8.2	6.2	FT,M	Nimmo *et al.* 1989
Etheostoma nigrum	Johnny darter	38 mm	96-h	11.47	59.57	8.1	5.8	FT,M	Nimmo *et al.* 1989
Etheostoma nigrum	Johnny darter	38 mm	96-h	15.63	67.08	8	20.1	FT,M	Nimmo *et al.* 1989
Etheostoma nigrum	Johnny darter	38 mm	96-h	13.46	69.93	8.1	5.8	FT,M	Nimmo *et al.* 1989
Etheostoma nigrum	Johnny darter	38 mm	96-h	28.9	103	7.9	20.6	FT,M	Nimmo *et al.* 1989
Etheostoma nigrum	Johnny darter	38 mm	96-h	24.61	105.7	8	20.1	FT,M	Nimmo *et al.* 1989
Etheostoma spectabile	Orangethroat darter	NR	96-h	7.65	71.12	8.4	21	FT,M	Hazel *et al.* 1979
Etheostoma spectabile	Orangethroat darter	NR	96-h	16.12	83.74	8.1	22	FT,M	Hazel *et al.* 1979
Gambusia affinis	Western mosquitofish	NR	96-h	14.64	165	8.5	23	S,U	Wallen *et al.* 1957
Gambusia affinis	Western mosquitofish	NR	96-h	42.53	182.6	8	24	S,U	Wallen *et al.* 1957
Gambusia affinis	Western mosquitofish	NR	96-h	34.54	217.7	8.2	19.5	S,U	Wallen *et al.* 1957
Gambusia affinis	Western mosquitofish	NR	96-h	129.6	352.9	7.75	19	S,U	Wallen *et al.* 1957

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Gasterosteus aculeatus	Threespine stickleback	juvenile-adult, 32-60 mm	96-h	78.7	142.8	7.5	23.3	S,M	Hazel *et al.* 1971
Gasterosteus aculeatus	Threespine stickleback	juvenile-adult, 32-60 mm	96-h	115.4	209.5	7.5	23.3	S,M	Hazel *et al.* 1971
Gasterosteus aculeatus	Threespine stickleback	juvenile-adult, 32-60 mm	96-h	198.1	216.5	7.1	23.3	S,M	Hazel *et al.* 1971
Gasterosteus aculeatus	Threespine stickleback	juvenile-adult, 32-60 mm	96-h	143.9	261.1	7.5	15	S,M	Hazel *et al.* 1971
Gasterosteus aculeatus	Threespine stickleback	juvenile-adult, 32-60 mm	96-h	203.8	264	7.25	23.3	S,M	Hazel *et al.* 1971
Gasterosteus aculeatus	Threespine stickleback	juvenile-adult, 32-60 mm	96-h	259	470	7.5	15	S,M	Hazel *et al.* 1971
Gasterosteus aculeatus	Threespine stickleback	juvenile-adult, 32-60 mm	96-h	577	667.4	7.15	15	S,M	Hazel *et al.* 1971
Hybognathus amarus	Rio Grande silvery minnow	3-5 d old	96-h	16.9	72.55	8	25	R,M	Buhl 2002
Ictalurus punctatus	Channel catfish	<110 d	96-h	15.09	64.77	8	20	FT,M	Diamond *et al.* 1993
Ictalurus punctatus	Channel catfish	0.5 g	96-h	32.85	97.67	7.8	25.7	FT,M	Swigert and Spacie 1983
Ictalurus punctatus	Channel catfish	NR	96-h	10.71	99.59	8.4	28	FT,M	Colt and Tchobanoglous 1978
Ictalurus punctatus	Channel catfish	3-11 mo	96-h	65.25	108.5	7.44	30	FT,M	DeGraeve *et al.* 1987
Ictalurus punctatus	Channel catfish	3-11 mo	96-h	72.15	121.7	7.45	20	FT,M	DeGraeve *et al.* 1987
Ictalurus punctatus	Channel catfish	NR	96-h	30.49	126.1	7.98	23.8	FT,M	Reinbold and Pescitelli 1982d
Ictalurus punctatus	Channel catfish	NR	96-h	33.1	127	7.94	23.8	FT,M	Reinbold and Pescitelli 1982d

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Ictalurus punctatus	Channel catfish	6.4 g	96-h	24.94	129.5	8.1	14.6	FT,M	West 1985; Arthur *et al.* 1987
Ictalurus punctatus	Channel catfish	3.5 g	96-h	44.71	132.9	7.8	19.6	FT,M	West 1985; Arthur *et al.* 1987
Ictalurus punctatus	Channel catfish	3-11 mo	96-h	85.69	136.5	7.41	25	FT,M	DeGraeve *et al.* 1987
Ictalurus punctatus	Channel catfish	NR	96-h	32.34	138.8	8	26	FT,M	West 1985
Ictalurus punctatus	Channel catfish	3-11 mo	96-h	89.41	140.5	7.4	25	FT,M	DeGraeve *et al.* 1987
Ictalurus punctatus	Channel catfish	3-11 mo	96-h	89.63	142.8	7.41	20	FT,M	DeGraeve *et al.* 1987
Ictalurus punctatus	Channel catfish	5.8 g	96-h	37.64	161.6	8	3.5	FT,M	West 1985; Arthur *et al.* 1987
Ictalurus punctatus	Channel catfish	7.1-12.7 g	96-h	32.33	164.8	8.09	22	FT,M	Roseboom and Richey 1977
Ictalurus punctatus	Channel catfish	3-11 mo	96-h	113.1	180.2	7.41	15	FT,M	DeGraeve *et al.* 1987
Ictalurus punctatus	Channel catfish	NR	96-h	40.83	212.1	8.1	17	FT,M	West 1985
Ictalurus punctatus	Channel catfish	3-11 mo	96-h	124.8	213.5	7.46	10	FT,M	DeGraeve *et al.* 1987
Ictalurus punctatus	Channel catfish	4.5-10.8 g	96-h	44.44	222.2	8.08	28	FT,M	Roseboom and Richey 1977
Ictalurus punctatus	Channel catfish	14.3 mm, 19.0 g	96-h	74.35	277.4	7.93	20	FT,M	Sparks 1975
Lepomis cyanellus	Green sunfish	NR	96-h	33.09	105.7	7.84	12.3	FT,M	Jude 1973
Lepomis cyanellus	Green sunfish	62.5 mg	96-h	55.79	144.3	7.72	22.4	FT,M	McCormick *et al.* 1984

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Lepomis cyanellus	Green sunfish	62.5 mg	96-h	9.24	148.6	8.69	22.4	FT,M	McCormick *et al.* 1984
Lepomis cyanellus	Green sunfish	62.5 mg	96-h	142.9	174.5	7.2	22.4	FT,M	McCormick *et al.* 1984
Lepomis cyanellus	Green sunfish	62.5 mg	96-h	254.5	197	6.61	22.4	FT,M	McCormick *et al.* 1984
Lepomis gibbosus	Pumpkinseed	4.13-9.22 g	96-h	9.11	25.69	7.77	12	FT,M	Jude 1973
Lepomis gibbosus	Pumpkinseed	NR	96-h	48.54	87.54	7.71	15.7	FT,M	Thurston 1981
Lepomis gibbosus	Pumpkinseed	NR	96-h	42.02	118.5	7.77	14.5	FT,M	Thurston 1981
Lepomis gibbosus	Pumpkinseed	NR	96-h	48.09	135.6	7.77	14	FT,M	Thurston 1981
Lepomis macrochirus	Bluegill sunfish	72 mg	96-h	8.846	43.38	8.07	22	FT,M	Roseboom and Richey 1977
Lepomis macrochirus	Bluegill sunfish	20.0-70.0 mm, young of year	96-h	0.7859	44.84	9.62	18.5	FT,M	Emery and Welch 1969
Lepomis macrochirus	Bluegill sunfish	217 mg	96-h	12.75	54.74	8	22	FT,M	Roseboom and Richey 1977
Lepomis macrochirus	Bluegill sunfish	28 mm, 0.250 g	96-h	12.55	73.19	8.16	4.5	FT,M	Reinbold and Pescitelli 1982b
Lepomis macrochirus	Bluegill sunfish	NR	96-h	5.509	75.01	8.6	24	FT,M	Hazel *et al.* 1979
Lepomis macrochirus	Bluegill sunfish	30 mm, 0.267 g	96-h	17.22	87.75	8.09	24.8	FT,M	Reinbold and Pescitelli 1982b
Lepomis macrochirus	Bluegill sunfish	20.0-70.0 mm, young of year	96-h	16.73	88.57	8.11	18.5	FT,M	Emery and Welch 1969
Lepomis macrochirus	Bluegill sunfish	20.0-70.0 mm, young of year	96-h	1.346	89.7	9.85	18.5	FT,M	Emery and Welch 1969

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Lepomis macrochirus	Bluegill sunfish	646 mg	96-h	24.08	90.66	7.93	22	FT,M	Roseboom and Richey 1977
Lepomis macrochirus	Bluegill sunfish	1.7 cm	96-h	21.56	92.54	8	20	FT,M	Diamond *et al.* 1993
Lepomis macrochirus	Bluegill sunfish	342 mg	96-h	14.81	93.31	8.2	28	FT,M	Roseboom and Richey 1977
Lepomis macrochirus	Bluegill sunfish	NR	96-h	44.03	93.31	7.6	21.7	FT,M	Smith *et al.* 1984
Lepomis macrochirus	Bluegill sunfish	0.38 g, 26.3 mm	96-h	19.39	100.7	8.1	22	FT,M	Mayes *et al.* 1986
Lepomis macrochirus	Bluegill sunfish	0.9 g	96-h	33.88	100.7	7.8	24.2	FT,M	Swigert and Spacie 1983
Lepomis macrochirus	Bluegill sunfish	NR	96-h	25.12	107.9	8	12	FT,M	Diamond *et al.* 1993
Lepomis macrochirus	Bluegill sunfish	1.2 g	96-h	37.52	111.6	7.8	26.6	FT,M	Swigert and Spacie 1983
Lepomis macrochirus	Bluegill sunfish	5.2 cm	96-h	33.06	117.8	7.9	24.25	FT,M	Lubinski *et al.* 1974
Lepomis macrochirus	Bluegill sunfish	0.9 g	96-h	58.69	124.4	7.6	26.5	FT,M	Swigert and Spacie 1983
Lepomis macrochirus	Bluegill sunfish	22 mm, 0.1106 g	96-h	23.37	126.2	8.12	25	FT,M	Reinbold and Pescitelli 1982b
Lepomis macrochirus	Bluegill sunfish	20.0-70.0 mm, young of year	96-h	3.755	135	9.19	18.5	FT,M	Emery and Welch 1969
Lepomis macrochirus	Bluegill sunfish	19 mm, 0.0781 g	96-h	14.64	136.1	8.4	4	FT,M	Reinbold and Pescitelli 1982b
Lepomis macrochirus	Bluegill sunfish	20.0-70.0 mm, young of year	96-h	6.581	193.8	9.05	18.5	FT,M	Emery and Welch 1969
Lepomis macrochirus	Bluegill sunfish	4.8 cm, 1.1 g	96-h	59.93	194.9	7.85	22.05	FT,M	Sparks 1975

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Lepomis macrochirus	Bluegill sunfish	20.0-70.0 mm, young of year	96-h	12.7	227.4	8.75	18.5	FT,M	Emery and Welch 1969
Lepomis macrochirus	Bluegill sunfish	20.0-70.0 mm, young of year	96-h	42.01	286.1	8.24	18.5	FT,M	Emery and Welch 1969
Micropterus dolomieu	Smallmouth bass	26-29 mm, 264-267 mg	96-h	39.3	105.2	7.74	22.3	FT,M	Broderius *et al.* 1985
Micropterus dolomieu	Smallmouth bass	26-29 mm, 264-267 mg	96-h	7.56	126	8.71	22.3	FT,M	Broderius *et al.* 1985
Micropterus dolomieu	Smallmouth bass	26-29 mm, 264-267 mg	96-h	123.4	144.3	7.16	22.3	FT,M	Broderius *et al.* 1985
Micropterus dolomieu	Smallmouth bass	26-29 mm, 264-267 mg	96-h	359.9	269.2	6.53	22.3	FT,M	Broderius *et al.* 1985
Micropterus salmoides	Largemouth bass	2.018-6.286 g	96-h	20.48	81.56	7.96	22	FT,M	Roseboom and Richey 1977
Micropterus salmoides	Largemouth bass	0.086-0.322 g	96-h	19.59	90.72	8.04	28	FT,M	Roseboom and Richey 1977
Micropterus treculii	Guadalupe bass	6.5 g	96-h	12.7	54.52	8	22	S,M	Tomasso and Carmichael 1986
Morone americana	White perch	76 mm	96-h	14.93	64.09	8	16	S,M	Stevenson 1977
Morone americana	White perch	76 mm	96-h	418.4	274.7	6	16	S,M	Stevenson 1977
Morone chrysops	White bass	4.4 g	96-h	132.4	144	7.09	19.7	S,M	Ashe *et al.* 1996
Morone saxatilis	Striped bass	126.6 g	96-h	12.86	98.43	8.3	21	S,M	Oppenborn and Goudie 1993
Morone saxatilis	Striped bass	20-93 mm	96-h	73.45	133.3	7.5	23.3	S,M	Hazel *et al.* 1971
Morone saxatilis	Striped bass	20-93 mm	96-h	92.17	144.8	7.4	23.3	S,M	Hazel *et al.* 1971

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Morone saxatilis	Striped bass	20-93 mm	96-h	48.03	180.8	7.93	23.3	S,M	Hazel *et al.* 1971
Morone saxatilis	Striped bass	20-93 mm	96-h	125.9	228.5	7.5	23.3	S,M	Hazel *et al.* 1971
Morone saxatilis	Striped bass	20-93 mm	96-h	182.3	330.7	7.5	15	S,M	Hazel *et al.* 1971
Morone saxatilis	Striped bass	20-93 mm	96-h	259.7	378.9	7.35	15	S,M	Hazel *et al.* 1971
Morone saxatilis	Striped bass	20-93 mm	96-h	165.7	524.6	7.84	15	S,M	Hazel *et al.* 1971
Morone saxatilis	Striped bass	20-93 mm	96-h	354.9	644	7.5	15	S,M	Hazel *et al.* 1971
Morone saxatilis x M. chrysops	Sunshine bass	larvae, 12 h	96-h	3.903	43.99	8.5	18.7	S,M	Harcke and Daniels 1999
Morone saxatilis x M. chrysops	Sunshine bass	42.7 g	96-h	56.55	56.55	7	25	S,M	Weirich *et al.* 1993
Morone saxatilis x M. chrysops	Sunshine bass	42.7 g	96-h	60.09	60.09	7	25	S,M	Weirich *et al.* 1993
Morone saxatilis x M. chrysops	Sunshine bass	367.2 g	96-h	8.147	62.37	8.3	21	S,M	Oppenborn and Goudie 1993
Morone saxatilis x M. chrysops	Sunshine bass	42.7 g	96-h	63.62	63.62	7	25	S,M	Weirich *et al.* 1993
Morone saxatilis x M. chrysops	Sunshine bass	42.7 g	96-h	64.51	64.51	7	25	S,M	Weirich *et al.* 1993
Morone saxatilis x M. chrysops	Sunshine bass	42.7 g	96-h	65.39	65.39	7	25	S,M	Weirich *et al.* 1993
Morone saxatilis x M. chrysops	Sunshine bass	42.7 g	96-h	79.53	79.53	7	25	S,M	Weirich *et al.* 1993
Morone saxatilis x M. chrysops	Sunshine bass	42.7 g	96-h	83.06	83.06	7	25	S,M	Weirich *et al.* 1993

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Morone saxatilis x M. chrysops	Sunshine bass	42.7 g	96-h	86.6	86.6	7	25	S,M	Weirich *et al.* 1993
Morone saxatilis x M. chrysops	Sunshine bass	42.7 g	96-h	95.43	95.43	7	25	S,M	Weirich *et al.* 1993
Morone saxatilis x M. chrysops	Sunshine bass	42.7 g	96-h	105.2	105.2	7	25	S,M	Weirich *et al.* 1993
Notemigonus crysoleucas	Golden shiner	8.7 g	96-h	34.73	63.02	7.5	24.5	FT,M	Swigert and Spacie 1983
Notropis topeka	Topeka shiner	adult, 29 mo	96-h	21.4	69.59	7.85	24.6	FT,M	Adelman *et al.* 2009
Notropis topeka	Topeka shiner	juvenile, 16 mo	96-h	18.7	88.27	8.05	25	FT,M	Adelman *et al.* 2009
Notropis topeka	Topeka shiner	juvenile, 15 mo	96-h	28.9	147.3	8.09	13.2	FT,M	Adelman *et al.* 2009
Oreochromis mossambicus	Mozambique tilapia	juvenile	96-h	151.5	185.2	7.2	28	R,U	Rani *et al.* 1998
Pimephales promelas	Fathead minnow	10 mm	96-h	7.322	46.15	8.2	6.2	FT,M	Nimmo *et al.* 1989
Pimephales promelas	Fathead minnow	10 mm	96-h	18.73	55.68	7.8	20.1	FT,M	Nimmo *et al.* 1989
Pimephales promelas	Fathead minnow	25 mm	96-h	11.56	72.86	8.2	6.2	FT,M	Nimmo *et al.* 1989
Pimephales promelas	Fathead minnow	25 mm	96-h	32.25	80.61	7.7	20.1	FT,M	Nimmo *et al.* 1989
Pimephales promelas	Fathead minnow	16 mm, 0.0315 g	96-h	19.55	87.16	8.02	23.9	FT,M	Reinbold and Pescitelli 1982b
Pimephales promelas	Fathead minnow	10 mm	96-h	32.12	95.49	7.8	19.8	FT,M	Nimmo *et al.* 1989
Pimephales promelas	Fathead minnow	21 mm, 0.0662 g	96-h	17.65	102.9	8.16	25.2	FT,M	Reinbold and Pescitelli 1982b

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Pimephales promelas	Fathead minnow	10 mm length	96-h	28.9	103	7.9	20.6	FT,M	Nimmo *et al.* 1989
Pimephales promelas	Fathead minnow	25 mm	96-h	19.94	103.6	8.1	5.8	FT,M	Nimmo *et al.* 1989
Pimephales promelas	Fathead minnow	4-5 mo	96-h	64.12	106.6	7.44	30	FT,M	DeGraeve *et al.* 1987
Pimephales promelas	Fathead minnow	25 mm	96-h	21.44	111.4	8.1	5.8	FT,M	Nimmo *et al.* 1989
Pimephales promelas	Fathead minnow	4-5 mo	96-h	66.94	112.9	7.45	20	FT,M	DeGraeve *et al.* 1987
Pimephales promelas	Fathead minnow	0.2 g	96-h	40.85	117.3	7.78	25.9	FT,M	Swigert and Spacie 1983
Pimephales promelas	Fathead minnow	4-5 mo	96-h	76.58	122	7.41	15	FT,M	DeGraeve *et al.* 1987
Pimephales promelas	Fathead minnow	4-5 mo	96-h	78.22	124.6	7.41	20	FT,M	DeGraeve *et al.* 1987
Pimephales promelas	Fathead minnow	0.5 g	96-h	42.65	126.8	7.8	25.6	FT,M	Swigert and Spacie 1983
Pimephales promelas	Fathead minnow	4-5 mo	96-h	81.81	128.5	7.4	25	FT,M	DeGraeve *et al.* 1987
Pimephales promelas	Fathead minnow	25 mm	96-h	24.89	129.3	8.1	19.6	FT,M	Nimmo *et al.* 1989
Pimephales promelas	Fathead minnow	0.13 g, 2.3 cm	96-h	58.4	132.1	7.64	13.6	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.42 g, 3.6 cm	96-h	58.2	136	7.66	13.4	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.42 g, 3.0 cm	96-h	50.28	139.3	7.76	19	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.26 g, 3.0 cm	96-h	58.8	139.7	7.67	13.9	FT,M	Thurston *et al.* 1983

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Pimephales promelas	Fathead minnow	2.2 g, 6.2 cm	96-h	52.2	139.7	7.74	12.8	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.28 g, 26.6 mm	96-h	25.16	141.2	8.14	22	FT,M	Mayes *et al.* 1986
Pimephales promelas	Fathead minnow	1.9 g, 5.2 cm	96-h	45.71	143.4	7.83	11.8	FT,M	Thurston *et al.* 1981c
Pimephales promelas	Fathead minnow	4-5 mo	96-h	91.4	145.6	7.41	25	FT,M	DeGraeve *et al.* 1987
Pimephales promelas	Fathead minnow	1.9 g, 5.2 cm	96-h	145.9	147.2	7.01	13.8	FT,M	Thurston *et al.* 1981c
Pimephales promelas	Fathead minnow	1.7 g	96-h	29.23	151.8	8.1	26.1	FT,M	West 1985; Arthur *et al.* 1987
Pimephales promelas	Fathead minnow	0.19 g, 2.6 cm	96-h	64.7	156.3	7.68	13.5	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	5.2 cm, 1.1 g	96-h	63.02	157.5	7.7	21.65	FT,M	Sparks 1975
Pimephales promelas	Fathead minnow	0.47 g, 3.2 cm	96-h	50.6	158.7	7.83	22	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.35 g, 3.1 cm	96-h	42.3	162.3	7.94	19.1	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	4-5 mo	96-h	97.27	166.4	7.46	6	FT,M	DeGraeve *et al.* 1987
Pimephales promelas	Fathead minnow	1.4 g, 4.9 cm	96-h	36.59	169.5	8.04	22.4	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	1.9 g, 5.2 cm	96-h	5.94	169.6	9.03	13.2	FT,M	Thurston *et al.* 1981c
Pimephales promelas	Fathead minnow	2.3 g, 6.3 cm	96-h	47.43	172.1	7.91	15.9	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	4-5 mo	96-h	101.7	174	7.46	10	FT,M	DeGraeve *et al.* 1987

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Pimephales promelas	Fathead minnow	1.4 g, 5.1 cm	96-h	50.9	174.8	7.88	21.7	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.09 g, 2.1 cm	96-h	50.2	175.6	7.89	13.1	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	1.7 g, 5.2 cm	96-h	55.43	177	7.84	21.7	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.5 g, 3.8 cm	96-h	49.3	178.9	7.91	18.9	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	2.1 g, 6.1 cm	96-h	66.73	184.9	7.76	13.1	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.09 g, 2.0 cm	96-h	51.55	187.1	7.91	16.3	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.8 g, 4.2 cm	96-h	66.7	188.1	7.77	14.3	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	1.9 g, 5.2 cm	96-h	260	192.9	6.51	13	FT,M	Thurston *et al.* 1981c
Pimephales promelas	Fathead minnow	1.9 g, 5.2 cm	96-h	62.72	193.3	7.82	12	FT,M	Thurston *et al.* 1981c
Pimephales promelas	Fathead minnow	15 mm, 0.0301 g	96-h	18.54	193.5	8.46	4.1	FT,M	Reinbold and Pescitelli 1982b
Pimephales promelas	Fathead minnow	0.47 g, 3.2 cm	96-h	58.91	198.7	7.87	15.8	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	1.4 g, 5.5 cm	96-h	89.85	199.9	7.63	13.2	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.22 g, 2.9 cm	96-h	42.6	205	8.06	22	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	1.0 g, 4.6 cm	96-h	72.71	205.1	7.77	14.1	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.22 g, 2.7 cm	96-h	47.6	216.3	8.03	22.1	FT,M	Thurston *et al.* 1983

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Pimephales promelas	Fathead minnow	19 mm, 0.0629 g	96-h	30.57	216.5	8.26	4.6	FT,M	Reinbold and Pescitelli 1982b
Pimephales promelas	Fathead minnow	1.9 g, 5.2 cm	96-h	18.88	216.9	8.51	13.5	FT,M	Thurston *et al.* 1981c
Pimephales promelas	Fathead minnow	1.4 g, 5.4 cm	96-h	91.8	221.8	7.68	12.9	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	NR	96-h	47.29	223.2	8.05	14	FT,M	DeGraeve *et al.* 1980
Pimephales promelas	Fathead minnow	1.4 g, 5.0 cm	96-h	44.8	224	8.08	21.4	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	1.6 g	96-h	52.22	224.2	8	17.1	FT,M	West 1985; Arthur *et al.* 1987
Pimephales promelas	Fathead minnow	1.4 g, 5.0 cm	96-h	47.39	276.4	8.16	21.4	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	1.8 g	96-h	56.07	291.3	8.1	12.1	FT,M	West 1985; Arthur *et al.* 1987
Pimephales promelas	Fathead minnow	1.5 g, 5.6 cm	96-h	107.5	298	7.76	12.9	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.31 g, 3.1 cm	96-h	66.48	313.8	8.05	13.6	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	0.31 g, 3.0 cm	96-h	74.65	352.4	8.05	13	FT,M	Thurston *et al.* 1983
Pimephales promelas	Fathead minnow	1.9 g	96-h	229.7	818.4	7.9	3.4	FT,M	West 1985; Arthur *et al.* 1987
Poecilia reticulata	Guppy	0.13 g, 2.03 cm	96-h	5.929	10.76	7.5	27.55	S,U	Kumar and Krishnamoorthi 1983
Poecilia reticulata	Guppy	8.25 (6.3-11.0) mm	96-h	75.65	127.6	7.45	25	S,U	Rubin and Elmaraghy 1976
Poecilia reticulata	Guppy	8.7 (6.8-10.6) mm	96-h	82.95	139.9	7.45	25	S,U	Rubin and Elmaraghy 1976

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Poecilia reticulata	Guppy	8.0 mm	96-h	129.4	161.8	7.22	25	S,U	Rubin and Elmaraghy 1976
Sander vitreus	Walleye	13.4 g	96-h	6.123	46.87	8.3	19	FT,M	West 1985; Arthur *et al.* 1987
Sander vitreus	Walleye	3.0 g, 65.6 mm	96-h	21.49	103.4	8.06	21.5	FT,M	Mayes *et al.* 1986
Sander vitreus	Walleye	22.6 g	96-h	48.37	172.3	7.9	3.7	FT,M	West 1985; Arthur *et al.* 1987
Sander vitreus	Walleye	19.4 g	96-h	89.93	224.8	7.7	11.1	FT,M	West 1985; Arthur *et al.* 1987
Fish - Salmonid									
Oncorhynchus aguabonita	Golden trout	0.09 g, 24 cm	96-h	23.3	112.1	8.06	13.2	FT,M	Thurston and Russo 1981
Oncorhynchus clarkii	Cutthroat trout	3.6 g	96-h	17.3	43.24	7.7	10	FT,M	Thurston *et al.* 1981a
Oncorhynchus clarkii	Cutthroat trout	4.1 g	96-h	19.3	48.24	7.7	10	FT,M	Thurston *et al.* 1981a
Oncorhynchus clarkii	Cutthroat trout	4.1 g	96-h	26.3	65.73	7.7	10	FT,M	Thurston *et al.* 1981a
Oncorhynchus clarkii	Cutthroat trout	3.6 g	96-h	29.1	72.73	7.7	10	FT,M	Thurston *et al.* 1981a
Oncorhynchus clarkii	Cutthroat trout	3.4 g	96-h	32.57	93.49	7.78	12.2	FT,M	Thurston *et al.* 1978
Oncorhynchus clarkii	Cutthroat trout	3.3 g	96-h	36.55	108.7	7.8	12.4	FT,M	Thurston *et al.* 1978
Oncorhynchus clarkii	Cutthroat trout	1.0 g	96-h	37.75	112.2	7.8	12.8	FT,M	Thurston *et al.* 1978
Oncorhynchus clarkii	Cutthroat trout	1.0 g	96-h	43.72	132.3	7.81	13.1	FT,M	Thurston *et al.* 1978

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish - Salmonid (cont.)									
Oncorhynchus gorbuscha	Pink salmon	late alevins	96-h	230.5	164.6	6.4	4.3	S,M	Rice and Bailey 1980
Oncorhynchus gorbuscha	Pink salmon	fry	96-h	277.7	198.3	6.4	4.3	S,M	Rice and Bailey 1980
Oncorhynchus kisutch	Coho salmon	6 g	96-h	11.59	60.2	8.1	17.2	FT,M	Buckley 1978
Oncorhynchus kisutch	Coho salmon	NR	96-h	82.02	82.02	7	15	FT,M	Wilson 1974; Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	Coho salmon	NR	96-h	84.43	84.43	7	15	FT,M	Wilson 1974; Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	Coho salmon	NR	96-h	50.65	91.9	7.5	15	FT,M	Wilson 1974; Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	Coho salmon	NR	96-h	21.63	92.84	8	15	FT,M	Wilson 1974; Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	Coho salmon	NR	96-h	22	94.44	8	15	FT,M	Wilson 1974; Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	Coho salmon	NR	96-h	52.76	95.73	7.5	15	FT,M	Wilson 1974; Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	Coho salmon	NR	96-h	9.093	102.5	8.5	15	FT,M	Wilson 1974; Robinson-Wilson and Seim 1975
Oncorhynchus mykiss	Rainbow trout	230 g	96-h	10.5	27.15	7.72	8.2	FT,M	Thurston *et al.* 1981a
Oncorhynchus mykiss	Rainbow trout	40.0 g; swimming fish	96-h	32.38	31.56	6.97	16.6	FT,M	Wicks *et al.* 2002
Oncorhynchus mykiss	Rainbow trout	0.12 g, 2.4 cm	96-h	11.07	38.02	7.88	12.8	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	2080 g	96-h	17	40.4	7.67	7.7	FT,M	Thurston *et al.* 1981a
Oncorhynchus mykiss	Rainbow trout	1122 g, 45.6 cm	96-h	17.75	43.62	7.69	10.4	FT,M	Thurston and Russo 1983

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish - Salmonid (cont.)									
Oncorhynchus mykiss	Rainbow trout	8.0 g, 8.9 cm	96-h	24.2	43.91	7.5	14.5	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	1698 g, 50.9 cm	96-h	19.46	44.73	7.65	9.8	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	2596 g, 57.0 cm	96-h	20.53	44.93	7.62	7.9	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	0.08 g, 2.0 cm	96-h	12.68	46.01	7.91	13.1	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	2596 g	96-h	21.6	47.27	7.62	7.9	FT,M	Thurston *et al.* 1981a
Oncorhynchus mykiss	Rainbow trout	1140 g, 46.4 cm	96-h	20.18	49.59	7.69	10.7	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	28.0 g, 13.1 cm	96-h	23.8	50.43	7.6	13	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	244 g	96-h	19.8	51.2	7.72	8.1	FT,M	Thurston *et al.* 1981a
Oncorhynchus mykiss	Rainbow trout	293 g	96-h	20.7	52.62	7.71	8.5	FT,M	Thurston *et al.* 1981a
Oncorhynchus mykiss	Rainbow trout	24.5 g, 12.7 cm	96-h	25.14	53.27	7.6	12.9	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	6.3 g, 8.1 cm	96-h	32.49	54	7.44	12.8	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	22.4 g	96-h	15.23	54.24	7.9	16.2	FT,M	West 1985; Arthur *et al.* 1987
Oncorhynchus mykiss	Rainbow trout	0.14 g, 2.6 cm	96-h	15.91	54.64	7.88	12.9	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	0.15 g, 2.7 cm	96-h	16.81	56.69	7.87	12.9	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	29.6 g, 13.3 cm	96-h	25.65	57.06	7.63	12.9	FT,M	Thurston and Russo 1983

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish - Salmonid (cont.)									
Oncorhynchus mykiss	Rainbow trout	1496 g, 48.5 cm	96-h	25.82	58.38	7.64	9.8	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	230 g	96-h	22.3	59.69	7.74	8.3	FT,M	Thurston *et al.* 1981a
Oncorhynchus mykiss	Rainbow trout	513 g, 35.9 cm	96-h	25.95	60.65	7.66	9.8	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	380 g, 32.4 cm	96-h	22.44	62.19	7.76	10	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	15.1 g, 10.7 cm	96-h	28.62	62.64	7.62	14.4	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	152 g, 23.4 cm	96-h	25.62	62.96	7.69	10.7	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	18 g	96-h	19.3	63.91	7.86	9.6	FT,M	Thurston *et al.* 1981a
Oncorhynchus mykiss	Rainbow trout	0.18 g, 2.9 cm	96-h	18.99	64.04	7.87	12.9	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	0.23 g, 3.2 cm	96-h	19.08	64.34	7.87	13.1	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	stage 8	96-h	40.99	64.4	7.4	14.4	FT,M	Calamari *et al.* 1977
Oncorhynchus mykiss	Rainbow trout	14.8 g, 10.5 cm	96-h	27.3	64.87	7.67	14	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	22.8 g, 12.3 cm	96-h	28.64	65.84	7.65	13.2	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	22.6 g, 12.3 cm	96-h	28.27	66.07	7.66	13.6	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	18.9 g, 11.6 cm	96-h	29.28	66.21	7.64	13.1	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	12.3 g, 10.2 cm	96-h	29.02	66.71	7.65	14.3	FT,M	Thurston and Russo 1983

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish - Salmonid (cont.)									
Oncorhynchus mykiss	Rainbow trout	0.23 g, 3.2 cm	96-h	19.43	66.73	7.88	13.4	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	7.0 g, 8.8 cm	96-h	20.02	67.51	7.87	12.2	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	23.6 g, 13.2 cm	96-h	27.51	67.6	7.69	13.4	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	29.8 g, 13.1 cm	96-h	32.62	68.03	7.59	12.7	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	0.33 g, 3.6 cm	96-h	20.7	68.55	7.86	13	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	248 g, 25.2 cm	96-h	25.76	68.95	7.74	10.4	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	0.06 g, 1.7 cm	96-h	19.44	69.26	7.9	13.4	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	9.5 g, 9.4 cm	96-h	2.51	69.5	9.01	14.5	FT,M	Thurston *et al.* 1981c
Oncorhynchus mykiss	Rainbow trout	11.2 g, 10.0 cm	96-h	23.65	70.32	7.8	9.7	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	0.18 g, 2.9 cm	96-h	21.15	71.32	7.87	13	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	0.06 g, 1.7 cm	96-h	28.54	71.33	7.7	13.9	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	9.5 g, 9.4 cm	96-h	20.03	71.36	7.9	12.7	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	558 g, 37.0 cm	96-h	31.85	72.02	7.64	10	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	247 g	96-h	28	74.94	7.74	8.1	FT,M	Thurston *et al.* 1981a
Oncorhynchus mykiss	Rainbow trout	0.06 g, 1.7 cm	96-h	20.99	76.17	7.91	13	FT,M	Thurston and Russo 1983

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish - Salmonid (cont.)									
Oncorhynchus mykiss	Rainbow trout	4.3 g, 7.1 cm	96-h	30.22	76.83	7.71	11.5	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	0.15 g, 2.7 cm	96-h	19.75	77.19	7.95	12.5	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	6.7 g, 8.6 cm	96-h	24.54	78.38	7.84	12.2	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	0.33 g, 3.6 cm	96-h	23.71	78.52	7.86	13.4	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	26.0 g, 13.0 cm	96-h	33.97	79.39	7.66	12.8	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	9.5 g, 9.4 cm	96-h	3.95	80.02	8.82	13.9	FT,M	Thurston *et al.* 1981c
Oncorhynchus mykiss	Rainbow trout	38.0 g, 14.4 cm	96-h	33.15	80.11	7.68	13	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	7.9 g, 9.2 cm	96-h	22.65	80.69	7.9	11.9	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	9.5 g, 9.4 cm	96-h	94.05	80.83	6.8	14.1	FT,M	Thurston *et al.* 1981c
Oncorhynchus mykiss	Rainbow trout	4.0 g, 7.0 cm	96-h	32.02	81.4	7.71	11.4	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	25.8 g, 13.6 cm	96-h	31.53	85.87	7.75	11.8	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	4.6 g, 7.3 cm	96-h	32.09	87.39	7.75	12.7	FT,M	Thurston *et al.* 1981b
Oncorhynchus mykiss	Rainbow trout	42.0 g, 16.0 cm	96-h	31.81	89.71	7.77	13.6	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	7.1 g, 8.4 cm	96-h	25.36	92.03	7.91	19	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	8.6 g, 8.9 cm	96-h	23.21	92.42	7.96	19.2	FT,M	Thurston and Russo 1983

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish - Salmonid (cont.)									
Oncorhynchus mykiss	Rainbow trout	8.1 g, 9.3 cm	96-h	33.94	92.43	7.75	12.3	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	1.8 g, 5.8 cm	96-h	17.34	93.61	8.12	13.6	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	1.7 g, 5.9 cm	96-h	18.14	94.23	8.1	13.9	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	0.47 g, 4.0 cm	96-h	28.77	95.27	7.86	12.7	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	10.1 g, 9.8 cm	96-h	26.44	95.95	7.91	19.1	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	10.9 g	96-h	38.52	96.27	7.7	3.6	FT,M	West 1985; Arthur *et al.* 1987
Oncorhynchus mykiss	Rainbow trout	0.47 g, 4.0 cm	96-h	29.77	96.81	7.85	12.5	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	3.3 g	96-h	12.75	97.57	8.3	18.7	FT,M	West 1985; Arthur *et al.* 1987
Oncorhynchus mykiss	Rainbow trout	52.1 g, 15.5 cm	96-h	28.6	98.22	7.88	10	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	5.7 g, 8.0 cm	96-h	36.97	100.7	7.75	12.5	FT,M	Thurston *et al.* 1981b
Oncorhynchus mykiss	Rainbow trout	1.7 g, 5.8 cm	96-h	26.49	101.6	7.94	12.8	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	9.5 g, 9.4 cm	96-h	74.2	102.2	7.3	14	FT,M	Thurston *et al.* 1981c
Oncorhynchus mykiss	Rainbow trout	2.5 g, 6.0 cm	96-h	31.55	102.6	7.85	13.1	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	9.0 g, 9.3 cm	96-h	32.3	103.2	7.84	12.9	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	8.0 g, 9.5 cm	96-h	33.67	103.7	7.82	13.2	FT,M	Thurston and Russo 1983

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish - Salmonid (cont.)									
Oncorhynchus mykiss	Rainbow trout	9.5 g, 9.4 cm	96-h	13.85	104	8.29	14.1	FT,M	Thurston *et al.* 1981c
Oncorhynchus mykiss	Rainbow trout	21 g	96-h	31.6	104.6	7.86	9.7	FT,M	Thurston *et al.* 1981a
Oncorhynchus mykiss	Rainbow trout	4.6 g, 7.4 cm	96-h	33.55	105.2	7.83	13.5	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	1.8 g, 5.7 cm	96-h	33.09	105.7	7.84	13.8	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	2.6 g, 6.2 cm	96-h	31.8	107.2	7.87	12.1	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	10.3 g	96-h	30.15	107.4	7.9	11.3	FT,M	West 1985; Arthur *et al.* 1987
Oncorhynchus mykiss	Rainbow trout	NR	96-h	22.9	108.1	8.05	14	FT,M	DeGraeve *et al.* 1980
Oncorhynchus mykiss	Rainbow trout	5.0 g, 7.6 cm	96-h	39.08	108.3	7.76	12.5	FT,M	Thurston *et al.* 1981b
Oncorhynchus mykiss	Rainbow trout	0.61 g, 4.3 cm	96-h	33.59	109.2	7.85	13.1	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	1.02 g, 4.9 cm	96-h	33.99	110.5	7.85	12.3	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	9.4 g, 9.6 cm	96-h	34.17	111.1	7.85	16.1	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	2.1 g, 6.2 cm	96-h	27.02	111.7	7.98	12.5	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	119 mm, 20.6 g	96-h	15.4	113.4	8.28	12.8	FT,M	Reinbold and Pescitelli 1982b
Oncorhynchus mykiss	Rainbow trout	52 mm, 1.47 g	96-h	10.09	113.7	8.5	14.9	FT,M	Reinbold and Pescitelli 1982b
Oncorhynchus mykiss	Rainbow trout	4.0 g, 7.2 cm	96-h	36.49	114.5	7.83	12.8	FT,M	Thurston *et al.* 1981b

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish - Salmonid (cont.)									
Oncorhynchus mykiss	Rainbow trout	0.36 g, 3.4 cm	96-h	23.05	115.2	8.08	12.8	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	1.7 g, 5.8 cm	96-h	34.95	115.7	7.86	14.1	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	11.1 g, 9.9 cm	96-h	34.32	115.7	7.87	13	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	42 mm, 0.61 g	96-h	11.86	116.8	8.43	3	FT,M	Reinbold and Pescitelli 1982b
Oncorhynchus mykiss	Rainbow trout	9.5 g, 9.4 cm	96-h	157.4	116.8	6.51	14.1	FT,M	Thurston *et al.* 1981c
Oncorhynchus mykiss	Rainbow trout	48.6 g, 15.2 cm	96-h	35.31	116.9	7.86	10.2	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	5.7 g, 8.0 cm	96-h	40.88	119.4	7.79	12.9	FT,M	Thurston *et al.* 1981b
Oncorhynchus mykiss	Rainbow trout	1.7 g, 5.7 cm	96-h	41.97	122.6	7.79	12.4	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	4.3 g, 7.1 cm	96-h	38.69	123.6	7.84	13	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	5.7 g, 8.4 cm	96-h	42.02	124.9	7.8	13.3	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	9.7 g, 9.7 cm	96-h	35.75	127.4	7.9	13	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	1.8 g, 5.9 cm	96-h	36.73	128.5	7.89	12.4	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	9.3 g, 9.0 cm	96-h	37.41	133.3	7.9	13	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	45 mm, 0.86 g	96-h	23.39	136.4	8.16	14.2	FT,M	Reinbold and Pescitelli 1982b
Oncorhynchus mykiss	Rainbow trout	53 mm, 1.48 g	96-h	35.14	137.3	7.95	10	FT,M	Broderius and Smith Jr. 1979

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish - Salmonid (cont.)									
Oncorhynchus mykiss	Rainbow trout	14.0 g	96-h	55.15	137.8	7.7	9.8	FT,M	West 1985; Arthur *et al.* 1987
Oncorhynchus mykiss	Rainbow trout	2.3 g, 6.1 cm	96-h	47.87	142.3	7.8	12.4	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	115 mm, 18.1 g	96-h	17.32	143.3	8.34	5	FT,M	Reinbold and Pescitelli 1982b
Oncorhynchus mykiss	Rainbow trout	2.1 g, 6.2 cm	96-h	39.25	150.6	7.94	12.5	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	1.01 g, 4.6 cm	96-h	33.64	161.8	8.06	13.2	FT,M	Thurston and Russo 1983
Oncorhynchus mykiss	Rainbow trout	40.0 g; resting fish	96-h	207	201.7	6.97	16.6	FT,M	Wicks *et al.* 2002
Oncorhynchus mykiss	Rainbow trout	44 mm, 0.76 g	96-h	15.27	207.9	8.6	3.3	FT,M	Reinbold and Pescitelli 1982b
Oncorhynchus mykiss	Rainbow trout	juvenile	96-h	174	212.6	7.2	10	FT,M	Wicks and Randall 2002
Oncorhynchus tshawytscha	Chinook salmon	14.4 g, 11.9 cm	96-h	18.47	62.29	7.87	13.5	FT,U	Thurston and Meyn 1984
Oncorhynchus tshawytscha	Chinook salmon	18.1 g, 12.7 cm	96-h	24.74	79.02	7.84	12.3	FT,U	Thurston and Meyn 1984
Oncorhynchus tshawytscha	Chinook salmon	15.3 g, 12.1 cm	96-h	27.23	83.9	7.82	12.2	FT,U	Thurston and Meyn 1984
Oncorhynchus tshawytscha	Chinook salmon	1.0-7 g	96-h	28.03	111.6	7.96	7	S,M	Servizi and Gordon 1990
Prosopium williamsoni	Mountain whitefish	177 g, 27.0 cm	96-h	11.3	27.31	7.68	12.1	FT,U	Thurston and Meyn 1984
Prosopium williamsoni	Mountain whitefish	63.0 g, 20.4 cm	96-h	21.2	63.04	7.8	12.3	FT,U	Thurston and Meyn 1984
Prosopium williamsoni	Mountain whitefish	56.9 g, 19.1 cm	96-h	25.47	81.35	7.84	12.4	FT,U	Thurston and Meyn 1984

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish - Salmonid (cont.)									
Salmo salar	Atlantic salmon	1.5 g	96-h	35.74	60.26	7.45	8.5	S,M	Soderberg and Meade 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	123	87.86	6.4	1.8	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	133.9	95.64	6.4	1.8	S,M	Knoph 1992
Salmo salar	Atlantic salmon	1.5 g	96-h	60.29	101.7	7.45	8.5	S,M	Soderberg and Meade 1992
Salmo salar	Atlantic salmon	36 g	96-h	70.62	119.1	7.45	8.5	S,M	Soderberg and Meade 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	171.3	124.4	6.45	7.4	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	214.4	155.7	6.45	7.4	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	230.6	167.4	6.45	12.5	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	248.3	180.3	6.45	12.5	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	297.2	195.1	6	2.1	S,M	Knoph 1992
Salmo salar	Atlantic salmon	36 g	96-h	118.2	199.3	7.45	8.5	S,M	Soderberg and Meade 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	341.1	223.9	6	2.1	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	356.1	235.4	6.05	17.1	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	373	246.6	6.05	17.1	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	400	264.4	6.05	2.5	S,M	Knoph 1992

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish - Salmonid (cont.)									
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	403.5	266.7	6.05	12.5	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	451.5	298.5	6.05	12.5	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	491.7	325	6.05	2.5	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	581.5	381.7	6	7.3	S,M	Knoph 1992
Salmo salar	Atlantic salmon	4.8-9.2 cm	96-h	587.6	385.7	6	7.3	S,M	Knoph 1992
Salmo trutta	Brown trout	1.20 g, 5.4 cm	96-h	29.58	96.2	7.85	13.2	FT,U	Thurston and Meyn 1984
Salmo trutta	Brown trout	0.91 g, 4.9 cm	96-h	33.3	102.6	7.82	14.2	FT,U	Thurston and Meyn 1984
Salmo trutta	Brown trout	1.17 g, 5.3 cm	96-h	32.46	107.5	7.86	13.8	FT,U	Thurston and Meyn 1984
Salvelinus fontinalis	Brook trout	3.12 g, 7.2 cm	96-h	45.21	149.7	7.86	13.6	FT,U	Thurston and Meyn 1984
Salvelinus fontinalis	Brook trout	3.40 g, 7.4 cm	96-h	52.03	163.2	7.83	13.8	FT,U	Thurston and Meyn 1984
Salvelinus namaycush	Lake trout, siscowet	8 g	96-h	83.11	140.1	7.45	8.5	S,M	Soderberg and Meade 1992
Salvelinus namaycush	Lake trout, siscowet	0.9 g	96-h	90.43	152.5	7.45	8.5	S,M	Soderberg and Meade 1992
Salvelinus namaycush	Lake trout, siscowet	8 g	96-h	96.25	162.3	7.45	8.5	S,M	Soderberg and Meade 1992
Salvelinus namaycush	Lake trout, siscowet	0.9 g	96-h	110.2	185.9	7.45	8.5	S,M	Soderberg and Meade 1992

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - ALS insect									
Callibaetis skokianus	Mayfly	NR	96-h	263.5	307.2	7.7	10.8	FT,M	Arthur *et al.* 1987
Callibaetis skokianus	Mayfly	NR	96-h	211.7	432.7	7.9	13.3	FT,M	West 1985; Arthur *et al.* 1987
Callibaetis sp.	Mayfly	middle to late instar	96-h	107.8	166.7	7.81	11.9	FT,M	Thurston *et al.* 1984
Chironomus riparius	Midge	10 d old, 2-3 instar	96-h	357.7	1029	7.7	21.7	R,M	Monda *et al.* 1995
Chironomus tentans	Midge	2nd instar	96-h	50.5	397	8.1	25	FT,M	Schubauer-Berigan *et al.* 1995
Chironomus tentans	Midge	2nd instar	96-h	368	411.7	6.5	25	FT,M	Schubauer-Berigan *et al.* 1995
Chironomus tentans	Midge	2nd instar	96-h	371	415.1	6.5	25	FT,M	Schubauer-Berigan *et al.* 1995
Chironomus tentans	Midge	2nd instar	96-h	78.1	614	8.1	25	FT,M	Schubauer-Berigan *et al.* 1995
Drunella grandis	Mayfly	middle to late instar	96-h	195.6	355.6	7.84	13.2	FT,M	Thurston *et al.* 1984
Drunella grandis	Mayfly	middle to late instar	96-h	259.1	455.5	7.84	12.8	FT,M	Thurston *et al.* 1984
Drunella grandis	Mayfly	middle to late instar	96-h	319	534.5	7.85	12	FT,M	Thurston *et al.* 1984
Enallagma sp.	Damselfly	8-10 mm	96-h	93.1	164	7.9	11.5	FT,M	Williams *et al.* 1986
Erythromma najas	Insect	8th-10th instar	96-h	589	1618	7.5	25	R,U	Beketov 2002
Erythromma najas	Insect	8th-10th instar	96-h	49.2	2361	9.1	25	R,U	Beketov 2002
Erythromma najas	Insect	8th-10th instar	96-h	168	4163	8.7	25	R,U	Beketov 2002

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - ALS insect (cont.)									
Pachydiplax longipennis	Dragonfly	<233 d old	96-h	76.92	170.1	8	12	FT,M	Diamond *et al.* 1993
Pachydiplax longipennis	Dragonfly	<140 d old	96-h	74.37	319.2	8	20	FT,M	Diamond *et al.* 1993
Philarctus quaeris	Caddisfly	NR	96-h	561.7	958.4	7.8	13.3	FT,M	West 1985; Arthur *et al.* 1987
Philarctus quaeris	Caddisfly	NR	96-h	296.5	1032	7.8	21.9	FT,M	Arthur *et al.* 1987
Skwala americana	Little golden stonefly	middle to late instar	96-h	109.3	186.7	7.81	13.1	FT,M	Thurston *et al.* 1984
Skwala americana	Little golden stonefly	middle to late instar	96-h	119.6	198.3	7.76	13.8	FT,M	Thurston *et al.* 1984
Stenelmis sexlineata	Beetle	NR	96-h	29.7	735.9	8.7	25	FT,M	Hazel *et al.* 1979
Invertebrate - Amphipod									
Crangonyx pseudogracilis	Amphipod	NR	96-h	25.1	161.7	8	24.9	FT,M	West 1985; Arthur *et al.* 1987
Crangonyx pseudogracilis	Amphipod	NR	96-h	199.5	227.3	8	4	FT,M	West 1985; Arthur *et al.* 1987
Crangonyx pseudogracilis	Amphipod	NR	96-h	115.3	284.1	8	13.3	FT,M	West 1985; Arthur *et al.* 1987
Crangonyx pseudogracilis	Amphipod	NR	96-h	81.6	287.9	8.2	13	FT,M	West 1985; Arthur *et al.* 1987
Crangonyx pseudogracilis	Amphipod	NR	96-h	216	481.7	8	12.1	FT,M	West 1985; Arthur *et al.* 1987
Crangonyx sp.	Amphipod	8-42 d	96-h	19.83	85.13	8	20	FT,M	Diamond *et al.* 1993
Crangonyx sp.	Amphipod	13 d	96-h	79.23	175.3	8	12	FT,M	Diamond *et al.* 1993

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - Amphipod (cont.)									
Hyalella azteca	Amphipod	7-14 d old	96-h	105	114.6	6.43	25	R,M	Ankley *et al.* 1995
Hyalella azteca	Amphipod	7-14 d old	96-h	64	135.1	7.31	25	R,M	Ankley *et al.* 1995
Hyalella azteca	Amphipod	7-14 d old	96-h	39.8	461.2	8.3	25	R,M	Ankley *et al.* 1995
Invertebrate - Cladoceran									
Ceriodaphnia acanthina	Water flea	NR	48-h	104.8	154.3	7.06	24	FT,M	Mount 1982
Ceriodaphnia dubia	Water flea	NR	48-h	16.65	35.72	8.2	7	R,M	Nimmo *et al.* 1989
Ceriodaphnia dubia	Water flea		48-h	14.52	94.35	8	25	S,M	Scheller 1997
Ceriodaphnia dubia	Water flea	NR	48-h	48.59	97.89	7.4	23	R,NR	Manning *et al.* 1996
Ceriodaphnia dubia	Water flea	NR	48-h	15.6	114.5	8.08	24.75	S,M	Andersen and Buckley 1998
Ceriodaphnia dubia	Water flea	NR	48-h	7.412	117.1	8.4	26.4	R,M	Cowgill and Milazzo 1991
Ceriodaphnia dubia	Water flea	NR	48-h	28.65	119.5	7.85	23	S,M	Sarda 1994
Ceriodaphnia dubia	Water flea	NR	48-h	28.77	120	7.85	23	S,M	Sarda 1994
Ceriodaphnia dubia	Water flea	<24 hr	48-h	47.05	129.2	7.5	25	S,M	Bailey *et al.* 2001
Ceriodaphnia dubia	Water flea	<24 hr	48-h	21.26	141.1	8.02	24.8	S,M	Andersen and Buckley 1998
Ceriodaphnia dubia	Water flea	NR	48-h	33.98	152.9	7.8	25	R,M	Nimmo *et al.* 1989

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - Cladoceran (cont.)									
Ceriodaphnia dubia	Water flea	<24 hr	48-h	56.84	156.1	7.5	25	S,M	Bailey *et al.* 2001
Ceriodaphnia dubia	Water flea	<24 hr	48-h	24.77	170.5	8.16	22	S,M	Black 2001
Ceriodaphnia dubia	Water flea	<24 hr	48-h	28.06	334.5	8.4	23	S,M	Black 2001
Ceriodaphnia dubia	Water flea	<24 hr	48-h	32.63	389	8.4	23	S,M	Black 2001
Chydorus sphaericus	Water flea	<24 hr	96-h	37.88	162.6	8	20	S,M	Dekker *et al.* 2006
Daphnia magna	Water flea	NR	48-h	9.463	37.66	7.92	21	S,M	Gulyas and Fleit 1990
Daphnia magna	Water flea	NR	48-h	42.31	69.88	7.4	20.6	S,M	Russo *et al.* 1985
Daphnia magna	Water flea	NR	48-h	43.52	80.98	7.5	20.3	S,M	Russo *et al.* 1985
Daphnia magna	Water flea	NR	48-h	48.32	89.74	7.51	20.1	S,M	Russo *et al.* 1985
Daphnia magna	Water flea	NR	48-h	55.41	106.1	7.53	20.1	S,M	Russo *et al.* 1985
Daphnia magna	Water flea	NR	48-h	20.71	197.5	8.2	25	S,M	Parkhurst *et al.* 1979, 1981
Daphnia magna	Water flea	NR	48-h	38.7	226.1	8.04	22.8	S,M	Russo *et al.* 1985
Daphnia magna	Water flea	NR	48-h	41.51	227.9	8.09	20.9	S,M	Russo *et al.* 1985
Daphnia magna	Water flea	NR	48-h	51.3	236.7	7.95	22	S,M	Russo *et al.* 1985
Daphnia magna	Water flea	NR	48-h	51.09	242.4	8.07	19.6	S,M	Russo *et al.* 1985

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - Cladoceran (cont.)									
Daphnia magna	Water flea	NR	48-h	37.44	252.8	8.15	22	S,M	Russo *et al.* 1985
Daphnia magna	Water flea	NR	48-h	26.34	296.9	8.5	20	S,M	Gersich and Hopkins 1986
Daphnia magna	Water flea	NR	48-h	51.92	419.1	8.34	19.7	R,U	Reinbold and Pescitelli 1982a
Daphnia pulicaria	Water flea	NR	48-h	34.5	99.03	8.05	14	FT,M	DeGraeve *et al.* 1980
Simocephalus vetulus	Water flea	adult	48-h	21.36	114.7	8.1	20.4	FT,M	Arthur *et al.* 1987
Simocephalus vetulus	Water flea	NR	48-h	83.51	122.9	7.06	24	FT,M	Mount 1982
Simocephalus vetulus	Water flea	NR	48-h	83.51	157	7.25	24.5	FT,M	Mount 1982
Simocephalus vetulus	Water flea	adult	48-h	31.58	188.5	8.3	17	FT,M	West 1985; Arthur *et al.* 1987
Invertebrate - Clam									
Musculium transversum	Long fingernailclam	NR	96-h	38.18	71.74	8.2	5.4	FT,M	West 1985; Arthur *et al.* 1987
Musculium transversum	Long fingernailclam	NR	96-h	6.429	91.24	8.6	20.5	FT,M	West 1985; Arthur *et al.* 1987
Musculium transversum	Long fingernailclam	NR	96-h	32.83	109	8.1	14.6	FT,M	West 1985; Arthur *et al.* 1987
Invertebrate - Decapod									
Orconectes immunis	Crayfish	NR	96-h	488.1	1367	7.9	17.1	FT,M	Arthur *et al.* 1987
Orconectes immunis	Crayfish	adult	96-h	999.4	1757	8.2	4.6	FT,M	West 1985; Arthur *et al.* 1987

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - Decapod (cont.)									
Orconectes nais	Crayfish	2.78 cm	96-h	23.15	303.8	8.3	26.5	FT,M	Evans 1979
Procambarus clarkii	Red swamp crayfish	2.1 cm	96-h	26.08	112	8	20	FT,M	Diamond et al. 1993
Procambarus clarkii	Red swamp crayfish	<2.5 cm	96-h	76.92	170.1	8	12	FT,M	Diamond *et al.* 1993
Invertebrate - Isopod									
Asellus aquaticus	Isopod	adult	96-h	1	246.6	7.05	24	FT,M	Dehedin *et al.* 2013
Asellus aquaticus	Isopod	adult	96-h	1	246.6	7.05	24	FT,M	Dehedin *et al.* 2013
Asellus aquaticus	Isopod	adult	96-h	1.25	276.6	7.05	12	FT,M	Dehedin *et al.* 2013
Asellus aquaticus	Isopod	adult	96-h	1.4	323.9	7.05	18	FT,M	Dehedin *et al.* 2013
Asellus aquaticus	Isopod	adult	96-h	1.7	376.1	7.05	12	FT,M	Dehedin *et al.* 2013
Asellus aquaticus	Isopod	adult	96-h	1.95	451.1	7.05	18	FT,M	Dehedin *et al.* 2013
Asellus aquaticus	Isopod	adult	96-h	2	493.1	7.05	24	FT,M	Dehedin *et al.* 2013
Asellus aquaticus	Isopod	adult	96-h	2.6	575.2	7.05	12	FT,M	Dehedin *et al.* 2013
Asellus aquaticus	Isopod	adult	96-h	2.61	603.8	7.05	18	FT,M	Dehedin *et al.* 2013
Caecidotea racovitzai	Aquatic sowbug	NR	96-h	176	272.2	7.81	11.9	FT,M	Thurston *et al.* 1983
Caecidotea racovitzai	Aquatic sowbug	adult	96-h	357.8	407.7	8	4	FT,M	West 1985; Arthur *et al.* 1987

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - Isopod (cont.)									
Caecidotea racovitzai	Aquatic sowbug	NR	96-h	148.8	522.3	7.8	22	FT,M	Arthur *et al.* 1987
Invertebrate - Mussel									
Actinonaias ligamentina	Mucket	glochidia	24-h	5.073	38.84	8.3	20	S,M	Wang *et al.* 2007a [4]
Actinonaias ligamentina	Mucket	glochidia	24-h	8.9	68.13	8.3	20	S,M	Wang *et al.* 2007a [4]
Actinonaias ligamentina	Mucket	glochidia	24-h	8.099	75.29	8.4	20	S,M	Wang *et al.* 2007a [4]
Actinonaias ligamentina	Mucket	glochidia	24-h	6.141	83.61	8.6	20	S,M	Wang *et al.* 2007a [4]
Actinonaias pectorosa	Pheasantshell	juvenile	96-h	14.06	75.8	7.9	25	S,M	Keller 2000
Actinonaias pectorosa	Pheasantshell	juvenile	96-h	14.08	83.3	7.95	25	S,M	Keller 2000
Alasmidonta heterodon	Dwarf wedgemussel	glochidia	24-h	> 14.24	> 109	8.3	20	S,M	Wang *et al.* 2007a [4]
Epioblasma capsaeformis	Oyster mussel	glochidia	6-h	5	17.81	8.5	20	R,M	Wang *et al.* 2007a [4]
Epioblasma capsaeformis	Oyster mussel	glochidia	6-h	3.4	31.61	8.5	20	R,M	Wang *et al.* 2007a [4]
Epioblasma capsaeformis	Oyster mussel	< 5-d old juvenile	96-h	4.76	53.63	8.5	20	R,M	Wang *et al.* 2007a [5]
Fusconaia masoni	Atlantic pigtoe	glochidia	6-h	15.9	47.4	7.6	24.9	S,M	Black 2001
Lampsilis abrupta	Pink mucket	2 mo old juvenile	96-h	2.8	26.03	8.4	20	FT,M	Wang *et al.* 2007b
Lampsilis cardium	Plain pocketbook	1-2 d old juvenile	96-h	38.9	47.19	7.1	21.2	FT,M	Newton and Bartsch 2007

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - Mussel (cont.)									
Lampsilis cardium	Plain pocketbook	1-2 d old juvenile	96-h	23.1	54.07	7.6	21.2	FT,M	Newton and Bartsch 2007
Lampsilis fasciola	Wavy-rayed lampmussel	2-5 d old juvenile	96-h	14.9	25.31	7.83	12.6	R,M	Mummert *et al.* 2003
Lampsilis fasciola	Wavy-rayed lampmussel	glochidia	24-h	5.518	51.3	8.4	20	S,M	Wang *et al.* 2007a [4]
Lampsilis fasciola	Wavy-rayed lampmussel	glochidia	24-h	7.743	59.28	8.3	20	S,M	Wang *et al.* 2007a [4]
Lampsilis fasciola	Wavy-rayed lampmussel	< 5-d old juvenile	96-h	6.179	69.63	8.5	20	R,M	Wang *et al.* 2007a [5]
Lampsilis higginsii	Higgin's eye	1-2 d old juvenile	96-h	31.7	38.46	7.1	21.2	FT,M	Newton and Bartsch 2007
Lampsilis higginsii	Higgin's eye	1-2 d old juvenile	96-h	19.5	45.64	7.6	21.2	FT,M	Newton and Bartsch 2007
Lampsilis rafinesqueana	Neosho mucket	glochidia	24-h	7.387	56.55	8.3	20	S,M	Wang *et al.* 2007a [4]
Lampsilis rafinesqueana	Neosho mucket	< 5-d old juvenile	96-h	9.185	70.31	8.3	20	R,M	Wang *et al.* 2007a [5]
Lampsilis rafinesqueana	Neosho mucket	< 5-d old juvenile	96-h	9.269	86.17	8.4	20	R,M	Wang *et al.* 2007a [5]
Lampsilis siliquoidea	Fatmucket	7 d old juvenile	96-h	11	24.3	7.6	20.5	FT,M	Wang *et al.* 2008
Lampsilis siliquoidea	Fatmucket	7 d old juvenile	96-h	0.96	27.51	9	20.6	FT,M	Wang *et al.* 2008
Lampsilis siliquoidea	Fatmucket	7 d old juvenile	96-h	5.2	28.39	8.1	20.6	FT,M	Wang *et al.* 2008
Lampsilis siliquoidea	Fatmucket	2 mo old juvenile	96-h	4.6	28.99	8.2	20	FT,M	Wang *et al.* 2007b
Lampsilis siliquoidea	Fatmucket	7 d old juvenile	96-h	3.4	40.27	8.5	20.6	FT,M	Wang *et al.* 2008

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - Mussel (cont.)									
Lampsilis siliquoidea	Fatmucket	glochidia	24-h	6.497	49.74	8.3	20	S,M	Wang *et al.* 2007a [4]
Lampsilis siliquoidea	Fatmucket	7 d old juvenile	96-h	11	54.37	8.1	19.4	FT,M	Wang *et al.* 2008
Lampsilis siliquoidea	Fatmucket	7 d old juvenile	96-h	88	65.59	6.6	19.6	FT,M	Wang *et al.* 2008
Lampsilis siliquoidea	Fatmucket	glochidia	24-h	8.772	66.77	8.3	20	S,M	Wang *et al.* 2007a [4]
Lampsilis siliquoidea	Fatmucket	3 mo old juvenile	96-h	8.8	74.25	8.35	20	FT,M	Miao *et al.* 2010a [6]
Lampsilis siliquoidea	Fatmucket	glochidia	24-h	13.35	84.14	8.2	20	S,M	Wang *et al.* 2007a [4]
Lampsilis siliquoidea	Fatmucket	glochidia	24-h	9.79	91.01	8.4	20	S,M	Wang *et al.* 2007a [4]
Lampsilis siliquoidea	Fatmucket	glochidia	24-h	11.57	107.6	8.4	20	S,M	Wang *et al.* 2007a [4]
Lampsilis siliquoidea	Fatmucket	glochidia	24-h	> 14.24	> 160.5 [7]	8.5	20	S,M	Wang *et al.* 2007a [4]
Lasmigona subviridis	Green floater	<2 d old juvenile	96-h	3.969	21.84	7.92	24.8	R,M	Black 2001
Lasmigona subviridis	Green floater	<2 d old juvenile	96-h	6.613	24.24	7.73	24	R,M	Black 2001
Lasmigona subviridis	Green floater	<2 d old juvenile	96-h	6.613	24.24	7.73	24	R,M	Black 2001
Potamilus ohiensis	Pink papershell	glochidia	24-h	> 14.24	> 109	8.3	20	S,M	Wang *et al.* 2007a [4]
Pyganodon grandis	Giant floater mussel	adult	96-h	25.13	69.02	7.5	25	S,M	Scheller 1997
Pyganodon grandis	Giant floater mussel	adult	96-h	18.84	72.49	7.71	25	S,M	Scheller 1997

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - Mussel (cont.)									
Utterbackia imbecillis	Pondshell mussel	<2 d old juvenile	96-h	2.734	17.91	8	25.1	R,M	Black 2001
Utterbackia imbecillis	Pondshell mussel	juvenile	96-h	8.235	40.87	7.9	24	S,M	Keller 2000
Utterbackia imbecillis	Pondshell mussel	juvenile	96-h	3.269	41.75	8.35	25	S,M	Keller 2000
Utterbackia imbecillis	Pondshell mussel	<2 d old juvenile	96-h	5.254	46.38	8.16	25	R,M	Black 2001
Utterbackia imbecillis	Pondshell mussel	glochidia	24-h	7.395	49.9	8.02	25	S,M	Black 2001
Utterbackia imbecillis	Pondshell mussel	juvenile	96-h	9.355	50.45	7.9	25	S,M	Keller 2000
Utterbackia imbecillis	Pondshell mussel	<2 d old juvenile	96-h	5.781	52.03	8.17	25	R,M	Black 2001
Utterbackia imbecillis	Pondshell mussel	8 d old juvenile	96-h	14.29	59.19	7.8	24	R,M	Wade *et al.* 1992
Utterbackia imbecillis	Pondshell mussel	<2 d old juvenile	96-h	8.845	100.5	8.29	25	R,M	Black 2001
Venustaconcha ellipsiformis	Ellipse	glochidia	24-h	4.55	23.12	8.1	20	S,M	Wang *et al.* 2007a [4]
Villosa iris	Rainbow mussel	< 24-h old glochidia	24-h	3.29	12.62	7.94	20	S,M	Scheller 1997
Villosa iris	Rainbow mussel	2-5 d old juvenile	96-h	20.6	15.17	7.29	12.6	R,M	Mummert *et al.* 2003
Villosa iris	Rainbow mussel	<1 h old glochidia	24-h	3.57	21.89	8.1	22	R,M	Goudreau *et al.* 1993
Villosa iris	Rainbow mussel	2 mo old juvenile	96-h	2.505	23.29	8.4	20	R,M	Wang *et al.* 2007a [5]
Villosa iris	Rainbow mussel	<1 h old glochidia	24-h	4.278	26.23	8.1	22	R,M	Goudreau *et al.* 1993

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - Mussel (cont.)									
Villosa iris	Rainbow mussel	< 5-d old juvenile	96-h	5.261	27.33	8.1	20	R,M	Wang *et al.* 2007a [5]
Villosa iris	Rainbow mussel	<3 d old juvenile	96-h	7.07	64.87	8.18	25	S,M	Scheller 1997
Villosa iris	Rainbow mussel	2 mo old juvenile	96-h	8.935	68.4	8.3	20	R,M	Wang *et al.* 2007a [5]
Villosa iris	Rainbow mussel	5 d old juvenile	96-h	7.81	71.66	8.18	25	S,M	Scheller 1997
Villosa iris	Rainbow mussel	glochidia	24-h	10.68	99.28	8.4	20	S,M	Wang *et al.* 2007a [4]
Invertebrate - Snail									
Fluminicola sp.	Pebblesnail	1.8 mm	96-h	> 8.801	> 62.15 [7]	8.25	20.2	FT,M	Besser 2011
Lymnaea stagnalis	Great pond snail	25-30 mm	96-h	50.33	88.62	7.9	11.5	FT,M	Williams *et al.* 1986
Physa gyrina	Pouch snail	NR	96-h	114.9	131	8	4	FT,M	West 1985; Arthur *et al.* 1987
Physa gyrina	Pouch snail	NR	96-h	62.39	153.7	8	13.3	FT,M	West 1985; Arthur *et al.* 1987
Physa gyrina	Pouch snail	NR	96-h	85.13	161.3	8.2	5.5	FT,M	West 1985; Arthur *et al.* 1987
Physa gyrina	Pouch snail	NR	96-h	26.33	169.7	8	24.9	FT,M	West 1985; Arthur *et al.* 1987
Physa gyrina	Pouch snail	NR	96-h	50.25	174.4	8.2	12.8	FT,M	West 1985; Arthur *et al.* 1987
Physa gyrina	Pouch snail	NR	96-h	76.29	205.9	8.1	12.1	FT,M	West 1985; Arthur *et al.* 1987
Planorbella trivolvis	Marsh ramshorn snail	NR	96-h	47.73	200.7	7.9	22	FT,M	Arthur *et al.* 1987

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - Snail (cont.)									
Planorbella trivolvis	Marsh ramshorn snail	NR	96-h	63.73	223	8.2	12.9	FT,M	Arthur *et al.* 1987
Pleurocera uncialis	Pagoda hornsnail	adult	96-h	11.18	68.54	8.1	22	R,M	Goudreau *et al.* 1993
Invertebrate - Worm									
Dendrocoelum lacteum	Flatworm	NR	96-h	22.37	119.5	8.2	18	S,U	Stammer 1953
Limnodrilus hoffmeisteri	Tubificid worm	30-40 mm	96-h	96.62	170.2	7.9	11.5	FT,M	Williams *et al.* 1986
Lumbriculus variegatus	Oligochaete worm	adult	96-h	100	111.9	6.5	25	FT,M	Schubauer-Berigan *et al.* 1995
Lumbriculus variegatus	Oligochaete worm	adult	96-h	200	223.8	6.5	25	FT,M	Schubauer-Berigan *et al.* 1995
Lumbriculus variegatus	Oligochaete worm	adult	96-h	34	267.3	8.1	25	FT,M	Schubauer-Berigan *et al.* 1995
Lumbriculus variegatus	Oligochaete worm	adult	96-h	43.5	342	8.1	25	FT,M	Schubauer-Berigan *et al.* 1995
Tubifex tubifex	Tubificid worm	NR	96-h	66.67	216.5	8.2	12	S,U	Stammer 1953
Additional Data[8]									
Fish									
Ictalurus punctatus	Channel catfish	larvae, 1 d	96-h	13.03	82.1	8.2	23.8	R,M	Bader and Grizzle 1992
Ictalurus punctatus	Channel catfish	juvenile, 7 d	96-h	17.22	108.5	8.2	23.9	R,M	Bader and Grizzle 1992

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Fish (cont.)									
Lepomis cyanellus	Green sunfish	larvae, 9 d swim up fry	96-h	8.43	62.07	8.28	26.2	FT,U	Reinbold and Pescitelli 1982a
Pimephales promelas	Fathead minnow	NR	96-h	5.389	23.13	8	20	R,M	Diamond *et al.* 1993
Pimephales promelas	Fathead minnow	NR	96-h	6.1	26.19	8	20	R,M	Diamond *et al.* 1993
Pimephales promelas	Fathead minnow	4-6 d old	96-h	14.4	63	8.01	25	R,M	Buhl 2002
Sander vitreus	Walleye	NR	96-h	17.43	87.13	8.08	18.2	FT,U	Reinbold and Pescitelli 1982a
Fish - Salmonid									
Oncorhynchus mykiss	Rainbow trout	1.7-1.9 cm	96-h	20.03	31.47	7.4	14.5	FT,U	Calamari *et al.* 1981
Oncorhynchus mykiss	Rainbow trout	NR	96-h	46.31	72.77	7.4	14.5	FT,U	Calamari *et al.* 1981
Oncorhynchus mykiss	Rainbow trout	8-10 cm	96-h	55.07	86.53	7.4	14.5	FT,U	Calamari *et al.* 1981
Oncorhynchus mykiss	Rainbow trout	129 mm	96-h	207.5	207.5	7	15	FT,U	Blahm 1978
Oncorhynchus mykiss	Rainbow trout	129 mm	96-h	70	300.5	8	15	FT,U	Blahm 1978
Invertebrate - Mussel									
Lampsilis abrupta	Pink mucket	2 mo old juvenile	96-h	1.921	14.71	8.3	20	R,M	Wang *et al.* 2007a [5]
Lampsilis siliquoidea	Fatmucket	2 mo old juvenile	96-h	4.092	21.26	8.1	20	R,M	Wang *et al.* 2007a [5]
Lampsilis siliquoidea	Fatmucket	Juvenile (3 months old)	96-h	6.2	**53.33**	8.36	20	FT	Miao *et al.* 2010b

Table A1.1. Summary of compiled acute aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Concentration [1] (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
				Original Effect	Normalized Effect [2]				
Invertebrate - Mussel (cont.)									
Lampsilis siliquoidea	Fatmucket	< 5-d old juvenile	96-h	8.35	94.09	8.5	20	R,M	Wang *et al.* 2007a [5]
					94.09				
Invertebrate - Snail									
Fluminicola sp.	Pebblesnail	8-13 weeks	96-h	6.02	**49.81**	8.34	20	FT	Besser *et al.* 2013
Fluminicola sp.	Pebblesnail	< 6 months (Small)	96-h	11.4	**74.68**	8.22	20	FT	Besser *et al.* 2013
Fluminicola sp.	Pebblesnail	< 6 months (Large)	96-h	13.2	**86.48**	8.22	20	FT	Besser *et al.* 2013
Invertebrate - Worm									
Lumbriculus variegatus	Oligochaete worm	10-25 mm	96-h	13.66	56.88	8.2	15	R,M	Hickey and Vickers 1994

ALS = aquatic life stage; AWQC = ambient water quality criteria; d = day; EC = effective concentration; FT = flow-through; h = hour; LC = lethal concentration; M = measured; mo = month; NR = not reported; R = renewal; S = static; TAN = total ammonia nitrogen; U = unmeasured; USEPA = United States Environmental Protection Agency.

[1] All acute toxicity data presented are LC_{50} or EC_{50} values for mortality.

[2] Effect value normalized to pH 7 (all species) and to 20°C (invertebrates only).

[3] Data from USEPA (2013) used in the calculation of SMAVs for the AWQC for ammonia. Values were used in the recalculation of SMAVs for this report except where noted.

[4] The EC_{50}s reported in this study were based on nominal concentrations; EC_{50}s based on measured concentrations were estimated from the reported EC_{50}s by multiplying by the average (0.890) of the percent nominal concentrations of measured concentrations from ammonia measurements made on exposure day 0 and estimated for day 1 of the study.

[5] The EC_{50}s reported in this study were based on nominal concentrations; EC_{50}s based on measured concentrations were estimated from the reported EC_{50}s by multiplying by the average (0.835) of the percent nominal concentrations of measured concentrations from ammonia measurements made on exposure days 0 and 4 of the study.

[6] LC_{50} was calculated after 24-h exposure to clean water to make sure mussels were actually dead.

[7] This value was not used in the recalculation of SMAVs because it is a "greater than" value and there are measured values for this species.

[8] Additional data not used in the derivation of the aquatic life ambient water quality criteria for ammonia (USEPA 2013). Bolded values were used in the recalculation of the SMAV.

Table A1.2. Summary of compiled chronic aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
						Original Effect	Normalized Effect [1]				
Data from USEPA (2013)[2]											
Fish											
Catostomus commersonii	White sucker	ELS (3-d old embryo)	30-d	EC_{20}	Biomass	> 2.9	> 11.62	8.32	18.6	NR	Reinbold and Pescitelli 1982a
Cyprinus carpio	Common carp	ELS (fertilized)	28-d	EC_{20}	Weight	8.36	16.53	7.85	23	NR	Mallet and Sims 1994
Esox lucius	Northern pike	ELS (fertilized)	52-d	EC_{20}	Biomass	13.44	20.38	7.62	8.7	NR	Harrahy *et al.* 2004
Ictalurus punctatus	Channel catfish	ELS	30-d	EC_{20}	Biomass	11.5	20.35	7.76	26.9	NR	Swigert and Spacie 1983
Ictalurus punctatus	Channel catfish	Juvenile	30-d	EC_{20}	Survival	5.02	21.15	8.35	27.9	NR	Colt and Tchobanoglous 1978
Ictalurus punctatus	Channel catfish	ELS	30-d	EC_{20}	Weight	12.2	22.66	7.8	25.8	NR	Reinbold and Pescitelli 1982a
Lepomis cyanellus	Green sunfish	ELS	30-d	EC_{20}	Biomass	5.61	11.85	7.9	22	NR	McCormick *et al.* 1984
Lepomis cyanellus	Green sunfish	ELS	30-d	EC_{20}	Survival	5.84	18.06	8.16	25.4	NR	Reinbold and Pescitelli 1982a
Lepomis macrochirus	Bluegill sunfish	ELS	30-d	EC_{20}	Biomass	1.85	3.273	7.76	22.5	NR	Smith *et al.* 1984
Micropterus dolomieu	Smallmouth bass	ELS	32-d	EC_{20}	Biomass	9.61	8.65	6.6	22.3	NR	Broderius *et al.* 1985
Micropterus dolomieu	Smallmouth bass	ELS	32-d	EC_{20}	Biomass	8.62	9.726	7.25	22.3	NR	Broderius *et al.* 1985
Micropterus dolomieu	Smallmouth bass	ELS	32-d	EC_{20}	Biomass	1.54	11.31	8.68	22.3	NR	Broderius *et al.* 1985
Micropterus dolomieu	Smallmouth bass	ELS	32-d	EC_{20}	Biomass	8.18	15.77	7.83	22.3	NR	Broderius *et al.* 1985
Pimephales promelas	Fathead minnow	Life cycle	NR	EC_{20}	Hatchability	1.97	4.784	8	24.2	NR	Thurston *et al.* 1986

Table A1.2. Summary of compiled chronic aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
						Original Effect	Normalized Effect [1]				
Fish (cont.)											
Pimephales promelas	Fathead minnow	ELS	30-d	EC_{20}	Biomass	3.73	7.101	7.82	25.1	NR	Swigert and Spacie 1983
Pimephales promelas	Fathead minnow	ELS (embryo-larvae)	28-d	EC_{20}	Survival	5.12	12.43	8	24.8	NR	Mayes *et al.* 1986
Pimephales promelas	Fathead minnow	ELS (embryo-larvae)	32-d	EC_{20}	Biomass	7.457	16.87	7.95	25.5	NR	Adelman *et al.* 2009
Fish - Salmonid											
Oncorhynchus clarkii henshawi	Lahontan cutthroat trout	ELS (fertilized)	103-d	EC_{20}	Survival	17.89	25.83	7.57	13.7	NR	Koch *et al.* 1980
Oncorhynchus mykiss	Rainbow trout	ELS	72-d	EC_{20}	Survival	2.6	3.246	7.4	14.5	NR	Calamari *et al.* 1977, 1981
Oncorhynchus mykiss	Rainbow trout	ELS (fertilized)	73-d	EC_{20}	Survival	< 2.55	< 3.515 [3]	7.52	14.9	NR	Solbe and Shurben 1989
Oncorhynchus mykiss	Rainbow trout	Life cycle	5-year	EC_{20}	NR	> 6.71	> 11.08 [3]	7.7	7.5-10.5	NR	Thurston *et al.* 1984b
Oncorhynchus mykiss	Rainbow trout	ELS	90-d	EC_{20}	Survival	8.919	15.6	7.75	11.4	NR	Brinkman *et al.* 2009
Oncorhynchus nerka	Sockeye salmon	Embryos	62-d	EC_{20}	Hatchability	< 2.13	< 10.09	8.42	10	NR	Rankin 1979
Invertebrate - ALS insect											
Pteronarcella badia	Stonefly	Juvenile	24-d	EC_{20}	Survival	21.66	26.27	7.81	13.2	NR	Thurston *et al.* 1984b
Pteronarcella badia	Stonefly	Juvenile	30-d	EC_{20}	Survival	133.8	207	8.04	12.1	NR	Thurston *et al.* 1984b
Invertebrate - Amphipod											
Hyalella azteca	Amphipod	Partial life cycle	28-d	EC_{20}	Biomass	8.207	29.17	8.04	25	NR	Borgmann 1994

Table A1.2. Summary of compiled chronic aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
						Original Effect	Normalized Effect [1]				
Invertebrate - Cladoceran											
Ceriodaphnia acanthina	Water flea	Life cycle	7-d	EC_{20}	Reproduction	44.9	64.1	7.15	24.5	NR	Mount 1982
Ceriodaphnia dubia	Water flea	Life cycle	7-d	EC_{20}	Reproduction	15.2	38.96	7.8	25	NR	Nimmo *et al.* 1989
Ceriodaphnia dubia	Water flea	Life cycle	7-d	EC_{20}	Reproduction	5.8	52.15	8.57	26	NR	Willingham 1987
Daphnia magna	Water flea	Life cycle	21-d	EC_{20}	Reproduction	7.37	36.27	8.45	19.8	NR	Gerisch *et al.* 1985
Daphnia magna	Water flea	Life cycle	21-d	EC_{20}	Reproduction	21.7	47.4	7.92	20.1	NR	Reinbold and Pescitelli 1982a
Invertebrate - Clam											
Musculium transversum	Long fingernailclam	Juvenile	42-d	EC_{20}	Survival	1.23	2.565	7.8	21.8	NR	Sparks and Sandusky 1981
Musculium transversum	Long fingernailclam	Juvenile	42-d	EC_{20}	Survival	5.82	22.21	8.15	23.5	NR	Anderson et al. 1978
Invertebrate - Mussel											
Lampsilis fasciola	Wavy-rayed lampmussel	2 month old juveniles	28-d	EC_{20}	Survival	0.4272	1.408	8.2	20	NR	Wang *et al.* 2007b
Lampsilis siliquoidea	Fatmucket	2 month old juveniles	28-d	EC_{20}	Survival	0.8988	3.211	8.25	20	NR	Wang *et al.* 2011a
Villosa iris	Rainbow mussel	2 month old juveniles	28-d	EC_{20}	Survival	1.063	3.501	8.2	20	NR	Wang *et al.* 2007b
Invertebrate - Snail											
Fluminicola sp.	Pebblesnail	1.81 mm juvenile	28-d	EC_{20}	Change in length	2.281	7.828	8.22	20.1	NR	Besser 2011

Table A1.2. Summary of compiled chronic aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
						Original Effect	Normalized Effect [1]				
Additional Data [4]											
Invertebrate - Mussel											
Lampsilis fasciola	Wavy-rayed lampmussel	2 month old juveniles	28-d	IC_{25}	Survival	0.39	**1.285**	8.2	20	FT	Wang *et al.* 2007c
Lampsilis fasciola	Wavy-rayed lampmussel	2 month old juveniles	28-d	IC_{25}	Length (mm)	0.57	1.879	8.2	20	FT	Wang *et al.* 2007c
Lampsilis fasciola	Wavy-rayed lampmussel	2 month old juveniles	28-d	MATC	Survival	0.67	2.208	8.2	20	FT	Wang *et al.* 2007c
Lampsilis fasciola	Wavy-rayed lampmussel	2 month old juveniles	28-d	MATC	Length (mm)	0.67	2.208	8.2	20	FT	Wang *et al.* 2007c
Lampsilis siliquoidea	Fatmucket	2 month old juveniles	28-d	IC_{25}	Survival	0.32	**1.055**	8.2	20	FT	Wang *et al.* 2007c
Lampsilis siliquoidea	Fatmucket	2 month old juveniles	28-d	MATC	Survival	0.37	1.219	8.2	20	FT	Wang *et al.* 2007c
Lampsilis siliquoidea	Fatmucket	2 month old juveniles	28-d	MATC	Length (mm)	0.37	1.219	8.2	20	FT	Wang *et al.* 2007c
Lampsilis siliquoidea	Fatmucket	2 month old juveniles	28-d	MATC	Biomass	0.36	1.307	8.26	20	FT	Wang *et al.* 2011b
Lampsilis siliquoidea	Fatmucket	2 month old juveniles	28-d	MATC	Survival	0.36	**1.307**	8.26	20	FT	Wang *et al.* 2011b
Lampsilis siliquoidea	Fatmucket	2 month old juveniles	28-d	MATC	Length	0.36	1.307	8.26	20	FT	Wang *et al.* 2011b
Lampsilis siliquoidea	Fatmucket	2 month old juveniles	28-d	MATC	Dry weight	0.36	1.307	8.26	20	FT	Wang *et al.* 2011b
Lampsilis siliquoidea	Fatmucket	2 month old juveniles	28-d	IC_{25}	Length (mm)	0.44	1.45	8.2	20	FT	Wang *et al.* 2007c
Lampsilis siliquoidea	Fatmucket	2 month old juveniles	28-d	EC_{20}	Survival	0.63	2.288	8.26	20	FT	Wang *et al.* 2011b
Villosa iris	Rainbow mussel	2 month old juveniles	28-d	MATC	Length (mm)	< 0.4	< 1.318	8.2	20	FT	Wang *et al.* 2007c

Table A1.2. Summary of compiled chronic aquatic toxicity data for ammonia.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (mg TAN/L)		pH	Temp (°C)	Test Type	Reference
						Original Effect	Normalized Effect [1]				
Invertebrate - Mussel (cont.)											
Villosa iris	Rainbow mussel	2 month old juveniles	28-d	IC_{25}	Length (mm)	0.73	**2.406**	8.2	20	FT	Wang *et al.* 2007c
Villosa iris	Rainbow mussel	2 month old juveniles	28-d	IC_{25}	Survival	1	3.296	8.2	20	FT	Wang *et al.* 2007c
Villosa iris	Rainbow mussel	2 month old juveniles	28-d	MATC	Survival	1.16	3.823	8.2	20	FT	Wang *et al.* 2007c
Fluminicola sp.	Pebblesnail	8-13 weeks	14-d	EC_{20}	Survival	1.59	**6.589**	8.34	20	FT	Besser *et al. 2*013
Fluminicola sp.	Pebblesnail	< 6 months (Large)	28-d	EC_{20}	Survival	2.58	**8.781**	8.22	20	FT	Besser *et al. 2*013

ALS = aquatic life stage; AWQC = ambient water quality criteria; d = day; EC = effective concentration; ELS = early life stage; FT = flow-through; IC = inhibition concentration; MATC = maximum acceptable toxicant concentration; NR = not reported; TAN = total ammonia nitrogen; USEPA = United States Environmental Protection Agency.

[1] Effect value normalized to pH 7 (all species) and to 20°C (invertebrates only).

[2] Data from USEPA (2013) used in the calculation of SMCVs for the AWQC for ammonia. When an EC_{20} was not provided in a study, the USEPA's statistical Toxicity Relationship Analysis Program (TRAP) was used to estimate the EC_{20}. Values were used in the recalculation of SMCVs for this report except where noted.

[3] This value was not used in the recalculation of SMCVs because it is a "greater than" or "less than" value and there are measured values for this species.

[4] Additional data not used in the derivation of the aquatic life AWQC for ammonia (USEPA 2013). Bolded values were used in the recalculation of the SMCV.

List of References

Adelman, I.R., L.I. Kusilek, J. Koehle and J. Hess. 2009. Acute and chronic toxicity of ammonia, nitrite and nitrate to the endangered Topeka shiner *(Notropis topeka*) and fathead minnows (*Pimephales promelas*). Environmental Toxicology and Chemistry 28(10): 2216-2223. (As cited in USEPA 2013).

Andersen, H. and J. Buckley. 1998. Acute toxicity of ammonia to *Ceriodaphnia dubia* and a procedure to improve control survival. Bulletin of Environmental Contamination and Toxicology 61(1): 116-122. (As cited in USEPA 2013).

Anderson, K.B., R.E. Sparks and A.A. Paparo. 1978. Rapid assessment of water quality, using the fingernail clam, *Musculium transversum*. WRC Research Report No. 133. University of Illinois, Water Resources Center, Urbana, IL. (As cited in USEPA 2013).

Ankley, G.T., M.K. Schubauer-Berigan and P.D. Monson. 1995. Influence of pH and hardness on toxicity of ammonia to the amphipod *Hyalella azteca.* Canadian Journal of Fisheries and Aquatic Sciences 52(10): 2078-2083. (As cited in USEPA 2013).

Arthur, J.W., C.W. West, K.N. Allen and S.F. Hedtke. 1987. Seasonal toxicity of ammonia to five fish and nine invertebrates species. Bulletin of Environmental Contamination and Toxicology 38(2): 324-331. (As cited in USEPA 2013).

Ashe, D., J.R. Tomasso, A.G. Eversole and T.I.J. Smith. 1996. Toxicity of ammonia to fingerling white bass: Effect of selected environments on uptake dynamics. Progressive Fish Culturist 58(4): 277-280. (As cited in USEPA 2013).

Bader, J.A. and J.M. Grizzle. 1992. Effects of ammonia on growth and survival of recently hatched channel catfish. Journal of Aquatic Animal Health 4(1): 17-23. (As cited in USEPA 2013).

Bailey, H.C., J.R. Elphick, R. Krassoi and A. Lovell. 2001. Joint acute toxicity of diazinon and ammonia to *Ceriodaphnia dubia.* Environmental Toxicology and Chemistry 20: 2877-2882. (As cited in USEPA 2013).

Beketov, M.A. 2002. Ammonia toxicity to larvae of *Erythromma najas* (Hansemann), *Lestes sponsa* (Hansemann) and *Sympetrum flaveolum* (Linnaeus) (Zygoptera: Coenagrionidae, Lestidae; Anisoptera: Libellulidae). Odonatologica 31(3): 297-304. (As cited in USEPA 2013).

Besser, J.M. 2011. U.S. Geological Survey, Columbia Environmental Research Center, Columbia, MO. (Memorandum to L.F. Huff, U.S. Environmental Protection Agency, Office of Water, Health and Ecological Criteria Division, Washington, DC. February 23. Report: Besser, J.M, C.G. Ingersoll, N. Wang and D.R. Mount. 2010. Chronic toxicity of ammonia to pebblesnails (*Fluminicola* sp.). CERC project number 8335C2F. (As cited in USEPA 2013).

Besser, J., R. Warbritton, and C. Ingersoll. 2013. Data summary for project, "Development of methods for propagation of ESA-listed and surrogate species of freshwater snails for use in toxicity testing." Draft. Columbia Environmental Research Center, U.S. Geological Survey, Columbia, Missouri.

Black, M.C. 2001. Water quality standards for North Carolina's endangered mussels. Final Report. Department of Health Science, University of Georgia, Athens, Georgia. (As cited in USEPA 2013).

Blahm, T.H. 1978. Toxicity of chemical fire retardants to juvenile coho salmon and rainbow trout. Ph.D. Thesis, University of Idaho, Moscow, ID. Available from: Dissertation Abstracts International B Sciences and Engineering 39(9):4115. (As cited in USEPA 2013).

Borgmann, U. 1994. Chronic toxicity of ammonia to the amphipod *Hyalella azteca;* importance of ammonium ion and water hardness. Environmental Pollution 86(3):329-335. (As cited in USEPA 2013).

Brinkman, S.C., J.D. Woodling, A.M. Vajda and D.O. Norris. 2009. Chronic toxicity of ammonia to early life stage rainbow trout. Transactions of the American Fisheries Society 138:433-440. (As cited in USEPA 2013).

Broderius, S.J. and L.L. Smith, Jr. 1979. Lethal and sublethal effects of binary mixtures of cyanide and hexavalent chromium, zinc, or ammonia to the fathead minnow (*Pimephales promelas*) and rainbow trout (*Salmo gairdneri*). Journal of the Fisheries Research Board of Canada 36(2):164-172. (As cited in USEPA 2013).

Broderius, S., R. Drummond, J. Fiandt and C. Russom. 1985. Toxicity of ammonia to early life stages of the smallmouth bass at four pH values. Environmental Toxicology and Chemistry 4(1):87-96. (As cited in USEPA 2013).

Buckley, J.A. 1978. Acute toxicity of un-ionized ammonia to fingerling coho salmon. Progressive Fish Culturist 40(1):30-32. (As cited in USEPA 2013).

Buhl, K.J. 2002. The relative toxicity of waterborne inorganic contaminants to the Rio Grande silvery minnow (*Hybognathus amarus*) and fathead minnow (*Pimephales promelas*) in a water quality simulating that in the Rio Grande, Albuquerque, NM. Final Report to the U.S. Fish and Wildlife Service, New Mexico Ecological Services Field Office, Albuquerque, New Mexico. (As cited in USEPA 2013).

Calamari, D., R. Marchetti and G. Vailati. 1977. Effect of prolonged treatments with ammonia on stages of development of *Salmo gairdneri*. Nuovi Annali d'Igiene e Microbiologia 28(5):333-345. (As cited in USEPA 2013).

Calamari, D., R. Marchetti and G. Vailati. 1981. Effects of long-term exposure to ammonia on the developmental stages of rainbow trout (*Salmo gairdneri*). Rapports et procès-verbaux des réunions / Conseil permanent international pour l'exploration de la mer 178:81-86. (As cited in USEPA 2013).

Colt, J. and G. Tchobanoglous. 1978. Chronic exposure of channel catfish, *Ictalurus punctatus*, to ammonia: Effects on growth and survival. Aquaculture 15:353-372. (As cited in USEPA 2013).

Cowgill, U.M. and D.P. Milazzo. 1991. The response of the three brood *Ceriodaphnia* test to fifteen formulations and pure compounds in common use. Archives of Environmental Contamination and Toxicology 21(1):35-40. (As cited in USEPA 2013).

DeGraeve, G.M., R.L. Overcast and H.L. Bergman. 1980. Toxicity of underground coal gasification condenser water and selected constituents to aquatic biota. Archives of Environmental Contamination and Toxicology 9(5):543-555. (As cited in USEPA 2013).

DeGraeve, G.M., W.D. Palmer, E.L. Moore, J.J. Coyle and P.L. Markham. 1987. The effect of temperature on the acute and chronic toxicity of un-ionized ammonia to fathead minnows and channel catfish. Battelle, Columbus, Ohio. (As cited in USEPA 2013).

Dehedin, A., C. Piscart and P. Marmonier. 2013. Seasonal variations of the effect of temperature on lethal and sublethal toxicities of ammonia for three common freshwater shredders. Chemosphere 90(3):1016-1022. (As cited in USEPA 2013).

Dekker, T., G.D. Greve, T.L. Ter Laak, M.E. Boivin, B. Veuger, G. Gortzak, S. Dumfries, S.M.G. Lucker, M.H.S. Kraak, W. Admiraal and H.G. van der Geest. 2006. Development and application of a sediment toxicity test using the benthic cladoceran *Chydorus sphaericus*. Environmental Pollution 140:231-238. (As cited in USEPA 2013).

Diamond, J.M., D.G. Mackler, W.J. Rasnake and D. Gruber. 1993. Derivation of site-specific ammonia criteria for an effluent-dominated headwater stream. Environmental Toxicology and Chemistry 12(4): 649-658. (As cited in USEPA 2013).

Emery, R.M. and E.B. Welch. 1969. The toxicity of alkaline solutions of ammonia to juvenile bluegill sunfish (*Lepomis macrochirus* Raf.). Tennessee Valley Authority, Division of Health and Safety, Chattanooga, Tennessee. (As cited in USEPA 2013).

Evans, J.W. 1979. The construction and use of a continuous-flow bioassay apparatus to determine a preliminary un-ionized ammonia 96-hour LC_{50} for the crayfish. M.S. Thesis, University of Kansas, Lawrence, Kansas. (As cited in USEPA 2013).

Fontenot, Q.C., J.J. Isely and J.R. Tomasso. 1998. Acute toxicity of ammonia and nitrite to shortnose sturgeon fingerlings. Progressive Fish Culturist 60:315-318. (As cited in USEPA 2013).

Gersich, F.M. and D.L. Hopkins. 1986. Site-specific acute and chronic toxicity of ammonia to *Daphnia magna* Straus. Environmental Toxicology and Chemistry 5(5):443-447. (As cited in USEPA 2013).

Gersich, F.M., D.L. Hopkins, S.L. Applegath, C.G. Mendoza and D.P. Milazzo. 1985. The sensitivity of chronic end points used in *Daphnia magna* Straus life-cycle tests. In: Aquatic toxicology and hazard assessment: Eighth Symposium, Fort Mitchell, KY., USA, Apr. 15-17, 1984. Bahner, R.C. and D.J. Hansen (Ed.). ASTM STP 891. American Society for Testing and Materials. Philadelphia, Pennsylvania. pp. 245-252. (As cited in USEPA 2013).

Goudreau, S.E., R.J. Neves and R.J. Sheehan. 1993. Effects of wastewater treatment plant effluents on freshwater mollusks in the upper Clinch River, Virginia, USA. Hydrobiologia 252(3):211-230. (As cited in USEPA 2013).

Gulyas, P. and E. Fleit. 1990. Evaluation of ammonia toxicity on *Daphnia magna* and some fish species. Aquacultura Hungarica 6:171-183. (As cited in USEPA 2013).

Harcke, J.E. and H.V. Daniels. 1999. Acute toxicity of ammonia and nitrite to different life stages of reciprocal cross hybrid striped bass eggs and larvae. Aquaculture 30: 496-500. (As cited in USEPA 2013).

Harrahy, E.A., M. Barman, S. Geis, J. Hemming, D. Karner and A. Mager. 2004. Effects of ammonia on the early life stages of northern pike (*Esox lucius*). Bulletin of Environmental Contamination and Toxicology 72:1290-1296. (As cited in USEPA 2013).

Hasan, M.R. and D.J. Macintosh. 1986. Acute toxicity of ammonia to common carp fry. Aquaculture 54(1-2):97-107. (As cited in USEPA 2013).

Hazel, C.R., W. Thomsen and S.J. Meith. 1971. Sensitivity of striped bass and stickleback to ammonia in relation to temperature and salinity. California Fish and Game 57(3):138-153. (As cited in USEPA 2013).

Hazel, R.H., C.E. Burkhead and D.G. Huggins. 1979. The development of water quality criteria for ammonia and total residual chlorine for the protection of aquatic life in two Johnson County, Kansas streams. Project completion report for period July 1977 to September 1979. Kansas Water Resources Research Institute, University of Kansas, KS. (As cited in USEPA 2013).

Hickey, C.W. and M.L. Vickers. 1994. Toxicity of ammonia to nine native New Zealand freshwater invertebrate species. Archives of Environmental Contamination and Toxicology 26(3):292-298. (As cited in USEPA 2013).

Jude, D.J. 1973. Sublethal effects of ammonia and cadmium on growth of green sunfish (*Lepomis cyanellus*). Ph.D. Thesis, Michigan Department of Fish and Wildlife, Michigan State University, East Lansing, Michigan. (As cited in USEPA 2013).

Keller, A.E. 2000. Memorandum to Rob Pepin. Subject: Water quality and toxicity data for unpublished unionid mussels tests. (As cited in USEPA 2013).

Knoph, M.B. 1992. Acute toxicity of ammonia to Atlantic salmon (*Salmo salar*) parr. Comparative Biochemistry and Physiology Part C: Comparative Pharmacology 101(2):275-282. (As cited in USEPA 2013).

Koch, D.L., E.L. Lider and S.C. Vigg. 1980. Evaluation of the combined effects of ammonia, nitrite and nitrate on the egg incubation, hatching and fry development of Lahontan cutthroat trout (*Salmo clarki henshawi*). University of Nevada, Desert Research Institute, Reno, Nevada. (As cited in USEPA 2013).

Kumar, N.J. and K.P. Krishnamoorthi. 1983. Evaluation of toxicity of ammoniacal fertilizer effluents. Environmental Pollution Series A 30(1):77-86. (As cited in USEPA 2013).

Lubinski, K.S., R.E. Sparks and L.A. Jahn. 1974. The development of toxicity indices for assessing the quality of the Illinois River. WRC Research Report No. 96, University of Illinois, Water Resources Center, Urbana, Illinois. (As cited in USEPA 2013).

Mallet, M.J. and I. Sims. 1994. Effects of ammonia on the early life stages of carp (*Cyprinus carpio*) and roach (*Rutilus rutilus*). *In:* Sublethal and chronic effects of pollutants on freshwater fish. Muller, R. and R. Lloyd (Eds.), Fishing News Books, London. pp. 211-228. (As cited in USEPA 2013).

Manning, T.M., S.P. Wilson and J.C. Chapman. 1996. Toxicity of chlorine and other chlorinated compounds to some Australian aquatic organisms. Bulletin of Environmental Contamination and Toxicology 56(6):971-976. (As cited in USEPA 2013).

Mayes, M.A., H.C. Alexander, D.L. Hopkins and P.B. Latvaitis. 1986. Acute and chronic toxicity of ammonia to freshwater fish: A site-specific study. Environmental Toxicology and Chemistry 5(5):437-442. (As cited in USEPA 2013).

McCormick, J.H., S.J. Broderius and J.T. Findt. 1984. Toxicity of ammonia to early life stages of the green sunfish *Lepomis cyanellus* (with erratum). Environmental Pollution Series A 36:147-163. (As cited in USEPA 2013).

Miao, J., M.C. Barnhart, E.L. Brunson, D.K. Hardesty, C.G. Ingersoll and N. Wang. 2010a. An evaluation of the influence of substrate on the response of juvenile freshwater mussels (fatmucket, *Lampsilis siliquoidea*) in acute water exposure to ammonia. Environmental Toxicology and Chemistry 29(9):2112-2116. (As cited in USEPA 2013).

Miao, J., M.C. Barnhart, E.L. Brunson, D.K. Hardesty, C.G. Ingersoll and N. Wang. 2010b. An evaluation of the influence of substrate on the response of juvenile freshwater mussels (fatmucket, *Lampsilis siliquoidea*) in acute water exposure to ammonia. Environmental Toxicology and Chemistry 29(9):2112-2116.

Monda, D.P., D.L. Galat, S.E. Finger and M.S. Kaiser. 1995. Acute toxicity of ammonia (NH_3-N) in sewage effluent to *Chironomus riparius*: II. Using a generalized linear model. Archives of Environmental Contamination and Toxicology 28(3):385-390. (As cited in USEPA 2013).

Mount, D.I. 1982. Ammonia toxicity tests with *Ceriodaphnia acanthina* and *Simocephalus vetulus*. Letter to R.C. Russo, U.S. Environmental Protection Agency, Duluth, Minnesota. U.S. EPA, Duluth, MN. (As cited in USEPA 2013).

Mummert, A.K., R.J. Neves, T.J. Newcomb and D.S. Cherry. 2003. Sensitivity of juvenile freshwater mussels (*Lampsilis fasciola*, *Villosa iris*) to total and un-ionized ammonia. Environmental Toxicology and Chemistry 22:2545-2553. (As cited in USEPA 2013).

Newton, T.J. and M.R. Bartsch. 2007. Lethal and sublethal effects of ammonia to juvenile *Lampsilis mussels* (Unionidae) in sediment and water-only exposures. Environmental Toxicology and Chemistry 26(10):2057. (As cited in USEPA 2013).

Nimmo, D.W.R., D. Link, L.P. Parrish, G.J. Rodriguez, W. Wuerthele and P.H. Davies. 1989. Comparison of on-site and laboratory toxicity tests: Derivation of site-specific criteria for un-ionized ammonia in a Colorado transitional stream. Environmental Toxicology and Chemistry 8(12):1177-1189. (As cited in USEPA 2013).

Oppenborn, J.B. and C.A. Goudie. 1993. Acute and sublethal effects of ammonia on striped bass and hybrid striped bass. Journal of the World Aquaculture Society 24(1):90-101. (As cited in USEPA 2013).

Parkhurst, B.R., A.S. Bradshaw, J.L. Forte and G.P. Wright. 1979. An evaluation of the acute toxicity to aquatic biota of a coal conversion effluent and its major components. Bulletin of Environmental Contamination and Toxicology 23(3):349-356. (As cited in USEPA 2013).

Parkhurst, B.R., J.S. Meyer, G.M. DeGraeve and H.L. Bergman. 1981. Reevaluation of the toxicity of coal conversion process waters. Bulletin of Environmental Contamination and Toxicology 26(1):9-15. (As cited in USEPA 2013).

Rani, E.F., M. Elumalal and M.P. Balasubramanian. 1998. Toxic and sublethal effects of ammonium chloride on a freshwater fish *Oreochromis mossambicus*. Water Air and Soil Pollution 104:1-8. (As cited in USEPA 2013).

Rankin, D.P. 1979. The influence of un-ionized ammonia on the long-term survival of sockeye salmon eggs. Fisheries and Marine Service Technical Report No. 912. Pacific Biological Station, Nanaimo, B.C., Canada. (As cited in USEPA 2013).

Rao, T.S., M.S. Rao and S.B.S.K. Prasad. 1975. Median tolerance limits of some chemicals to the fresh water fish *Cyprinus carpio*. Indian Journal of Environmental Health 17(2):140-146. (As cited in USEPA 2013).

Reinbold, K.A. and S.M. Pescitelli. 1982a. Effects of exposure to ammonia on sensitive life stages of aquatic organisms. Project Report, Contract No. 68-01-5832. Illinois Natural History Survey, Champaign, Illinois. (As cited in USEPA 2013).

Reinbold, K.A. and S.M. Pescitelli. 1982b. Effects of cold temperature on toxicity of ammonia to rainbow trout, bluegills and fathead minnows. Project Report, Contract No. 68-01-5832. Illinois Natural History Survey, Champaign, Illinois. (As cited in USEPA 2013).

Reinbold, K.A. and S.M. Pescitelli. 1982c. Acute toxicity of ammonia to the white sucker. Final report, Contract No. 2W-3946 NAEX. Illinois Natural History Survey, Champaign, Illinois. (As cited in USEPA 2013).

Reinbold, K.A. and S.M. Pescitelli. 1982d. Acute toxicity of ammonia to channel catfish. Final report, Contract No. J 2482 NAEX. Illinois Natural History Survey, Champaign, Illinois. (As cited in USEPA 2013).

Rice, S.D. and J.E. Bailey. 1980. Survival, size and emergence of pink salmon, *Oncorhynchus gorbuscha*, alevins after short and long-term exposures to ammonia. U.S. National Marine Fisheries Service Fishery Bulletin 78(3):641-648. (As cited in USEPA 2013).

Robinson-Wilson, E.F. and W.K. Seim. 1975. The lethal and sublethal effects of a zirconium process effluent on juvenile salmonids. Water Research Bulletin 11(5):975-986. (As cited in USEPA 2013).

Rosage, T.F., R.M. Schutsky and K.M. Rapp. 1979. Toxicity of un-ionized ammonia to the spotfin shiner (*Notropis spilopterus*). Proceedings of the Pennsylvania Academy of Science 53:39-42. (As cited in USEPA 2013).

Roseboom, D.P. and D.L. Richey. 1977. Acute toxicity of residual chlorine and ammonia to some native Illinois fishes. Report of Investigations 85. U.S. NTIS PB-170871. Office of Water Research and Technology, Washington, District of Columbia. (As cited in USEPA 2013).

Rubin, A.J. and M.A. Elmaraghy. 1976. Studies on the toxicity of ammonia, nitrate and their mixtures to the common guppy. Water Resource Center Report No.490. U.S. NTIS PB-255721 Ohio State University, Columbus, Ohio. (As cited in USEPA 2013).

Russo, R.C., A. Pilli and E.L. Meyn. 1985. Memorandum to N.A. Jaworski. 4 March 1985. (As cited in USEPA 2013).

Saiki, M.K., D.P. Monda and B.L. Bellerud. 1999. Lethal levels of selected water quality variables to larval and juvenile Lost River and shortnose suckers. Environmental Pollution 105(1):37-44. (As cited in USEPA 2013).

Sarda, N. 1994. Spatial and temporal heterogeneity in sediments with respect to pore water ammonia and toxicity of ammonia to *Ceriodaphnia dubia* and *Hyalella azteca.* M.S. Thesis. Wright State University, Dayton, Ohio. (As cited in USEPA 2013).

Scheller, J.L. 1997. The effect of dieoffs of Asian clams (*Corbicula fluminea*) on native freshwater mussels (unionidae). Virginia Polytechnic Institute and State University, Blacksburg, Virginia. (As cited in USEPA 2013).

Schubauer-Berigan, M.K., P.D. Monson, C.W. West and G.T. Ankley. 1995. Influence of pH on the toxicity of ammonia to *Chironomus tentans* and *Lumbriculus variegatus.* Environmental Toxicology and Chemistry 14:713-717. (As cited in USEPA 2013).

Schuytema, G.S. and A.V. Nebeker. 1999a. Comparative effects of ammonium and nitrate compounds on Pacific treefrog and African clawed frog embryos. Archives of Environmental Contamination and Toxicology 36:200-206. (As cited in USEPA 2013).

Schuytema, G.S. and A.V. Nebeker. 1999b. Comparative toxicity of ammonium and nitrate compounds to Pacific treefrog and African clawed frog tadpoles. Environmental Toxicology and Chemistry 18(10):2251-2257. (As cited in USEPA 2013).

Servizi, J. and R. Gordon. 1990. Acute lethal toxicity of ammonia and suspended sediment mixtures to Chinook salmon (*Oncorhynchus tshawytscha*). Bulletin of Environmental Contamination and Toxicology 44(4):650-656. (As cited in USEPA 2013).

Smith, W.E., T.H. Roush and J.T. Fiandt. 1984. Toxicity of ammonia to early life stages of bluegill (*Lepomis macrochirus*). Internal Report 600/X-84-175. Environmental Research Laboratory-Duluth, U.S. Environmental Protection Agency, Duluth, Minnesota. (As cited in USEPA 2013).

Soderberg, R.W. and J.W. Meade. 1992. Effects of sodium and calcium on acute toxicity of un-ionized ammonia to Atlantic salmon and lake trout. Journal of Applied Aquaculture 1(4):82-92. (As cited in USEPA 2013).

Solbe, J.F.D. and D.G. Shurben. 1989. Toxicity of ammonia to early life stages of rainbow trout (*Salmo gairdneri*). Water Research 23(1):127-129. (As cited in USEPA 2013).

Sparks, R.E. 1975. The acute, lethal effects of ammonia on channel catfish (*Ictalurus punctatus*), bluegills (*Lepomis macrochirus*) and fathead minnows (*Pimephales promelas*). Report to Illinois, Project No. 20.060. Institute for Environmental Quality, Chicago, Illinois. (As cited in USEPA 2013).

Sparks, R.E. and M.J. Sandusky. 1981. Identification of factors responsible for decreased production of fish food organisms in the Illinois and Mississippi Rivers. Final Report Project No. 3-291-R. Illinois Natural History Survey, River Research Laboratory, Havana, Illinois. (As cited in USEPA 2013).

Stammer, H.A. 1953. The effect of hydrogen sulfide and ammonia on characteristic animal forms in the saprobiotic system (Der einfly von schwefelwasserstoff und ammoniak auf tierische leitformen des sparobiensystems). Vom Wasser 20:34-71. (As cited in USEPA 2013).

Stevenson, T.J. 1977. The effects of ammonia, pH and salinity on the white perch, *Morone americana*. Ph.D. Thesis. University of Rhode Island, Kingston, RI. Available from: Dissertation Abstracts International B Sciences and Engineering 39(1):35 (Author Communication Used). (As cited in USEPA 2013).

Swigert, J.P. and A. Spacie. 1983. Survival and growth of warmwater fishes exposed to ammonia under low-flow conditions. Technical Report 157. Purdue University, Water Resource Research Center, West Lafayette, Indiana. (As cited in USEPA 2013).

Thurston, R.V. 1981. Memorandum to R.C. Russo. November 16, 1981. (As cited in USEPA 2013).

Thurston, R.V. and E.L. Meyn. 1984. Acute toxicity of ammonia to five fish species from the northwest United States. Technical Report No.84-4. Fisheries Bioassay Laboratory, Montana State University, Bozeman, Montana. (As cited in USEPA 2013).

Thurston, R.V. and R.C. Russo. 1981. Acute toxicity of ammonia to golden trout (*Salmo aguabonita*) and mottled sculpin (*Cottus bairdi*). Technical Report No. 81-1. Fisheries Bioassay Laboratory, Montana State University, Bozeman, Montana. (As cited in USEPA 2013).

Thurston, R.V. and R.C. Russo. 1983. Acute toxicity of ammonia to rainbow trout. Transactions of the American Fisheries Society 112:696-704. (As cited in USEPA 2013).

Thurston, R.V., R.C. Russo and C.E. Smith. 1978. Acute toxicity of ammonia and nitrite to cutthroat trout fry. Transactions of the American Fisheries Society 107(2):361-368. (As cited in USEPA 2013).

Thurston, R.V., C. Chakoumakos and R.C. Russo. 1981a. Effect of fluctuating exposures on the acute toxicity of ammonia to rainbow trout (*Salmo gairdneri*) and cutthroat trout (*S. clarki*). Water Research 15(7):911-917. (As cited in USEPA 2013).

Thurston, R.V., G.R. Phillips, R.C. Russo and S.M. Hinkins. 1981b. Increased toxicity of ammonia to rainbow trout (*Salmo gairdneri*) resulting from reduced concentrations of dissolved oxygen. Canadian Journal of Fisheries and Aquatic Sciences 38(8):983-988. (As cited in USEPA 2013).

Thurston, R.V., R.C. Russo and G.A. Vinogradov. 1981c. Ammonia toxicity to fishes: Effect of pH on the toxicity of the un-ionized ammonia species. Environmental Science and Technology 15(7):837-840. (As cited in USEPA 2013).

Thurston, R.V., R.C. Russo and G.R. Phillips. 1983. Acute toxicity of ammonia to fathead minnows. Transactions of the American Fisheries Society 112(5):705-711. (As cited in USEPA 2013).

Thurston, R.V., R.J. Luedtke and R.C. Russo. 1984. Toxicity of ammonia to freshwater insects of three families. Technical Report No. 84-2. Fisheries Bioassay Laboratory, Montana State University, Bozeman, Montana. (As cited in USEPA 2013).

Thurston, R.V., R.C. Russo, E.L. Meyn, R.K. Zajdel and C.E. Smith. 1986. Chronic toxicity of ammonia to fathead minnows. Transactions of the American Fisheries Society 115(2):196-207. (As cited in USEPA 2013).

Tietge, J.E., G.T. Ankley, D.L. DeFoe, G.W. Holcombe and K.M. Jensen. 2000. Effects of water quality on development of *Xenopus laevis*: A frog embryo teratogenesis assay--*Xenopus* assessment of surface water associated with malformations in native anurans. Environmental Toxicology and Chemistry 19(8):2114-2121. (As cited in USEPA 2013).

Tomasso, J. and G. Carmichael. 1986. Acute toxicity of ammonia, nitrite, and nitrate to the Guadalupe bass, *Micropterus treculi*. Bulletin of Environmental Contamination and Toxicology 36(6):866-870. (As cited in USEPA 2013).

USEPA (United States Environmental Protection Agency). 2013. Aquatic life ambient water quality criteria for ammonia - freshwater 2013. EPA-822-R-13-001. Office of Water, Office of Science and Technology. Washington, District of Columbia.

Wade, D., J. Posey and D.J. Simbeck. 1992. Definitive evaluation of Wheeler Reservoir sediments toxicity using juvenile freshwater mussels *(Andodonta imbecillis* Say). TVA/WR-92/25. Tennessee Valley Authority, Water Resources Division, Tennessee. (As cited in USEPA 2013).

Wallen, I.E., W.C. Greer and R. Lasater. 1957. Toxicity to *Gambusia affinis* of certain pure chemicals in turbid waters. Sewage and Industrial Wastes 29:695-711. (As cited in USEPA 2013).

Wang, N., C.G. Ingersoll , D.K. Hardesty, C.D. Ivey, J.L. Kunz, T.W. May, F.J. Dwyer, A.D. Roberts, T. Augspurger, C.M. Kane, R.J. Neves and M.C. Barnhart. 2007a. Contaminant sensitivity of freshwater mussels: Acute toxicity of copper, ammonia, and chlorine to glochidia and juveniles of freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10):2036-2047. (As cited in USEPA 2013).

Wang, N., C.G. Ingersoll, D.K. Hardesty, I.E. Greer, D.J. Hardesty, C.D. Ivey, J.L. Kunz, W.G. Brumbaugh, F.J. Dwyer, A.D. Roberts, J.T. Augspurger, C.M. Kane, R.J. Neves and M.C. Barnhart. 2007b. Contaminant sensitivity of freshwater mussels: Chronic toxicity of copper and ammonia to juvenile freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10):2048-2056. (As cited in USEPA 2013).

Wang, N., C.G. Ingersoll, D.K. Hardesty, I.E. Greer, D.J. Hardesty, C.D. Ivey, J.L. Kunz, W.G. Brumbaugh, F.J. Dwyer, A.D. Roberts, J.T. Augspurger, C.M. Kane, R.J. Neves and M.C. Barnhart. 2007c. Contaminant sensitivity of freshwater mussels: Chronic toxicity of copper and ammonia to juvenile freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10):2048-2056.

Wang, N., R.J. Erickson, C.G. Ingersoll, C.D. Ivey, E.L. Brunson, T. Augspurger and M.C. Barnhart. 2008. Influence of pH on the acute toxicity of ammonia to juvenile freshwater mussels (fatmucket, *Lampsilis siliquoidea*). Environmental Toxicology and Chemistry 27:1141-1146. (As cited in USEPA 2013).

Wang, N. R.A. Consbrock, C.G. Ingersoll, and M.C. Barnhart. 2011a. Evaluation of influence of sediment on the sensitivity of unionid mussel (*Lampsilis siliquoidea*) to ammonia in 28-day water exposures. Environmental Toxicology and Chemistry 30(10):2270-2276. (As cited in USEPA 2013).

Wang, N. R.A. Consbrock, C.G. Ingersoll, and M.C. Barnhart. 2011b. Evaluation of influence of sediment on the sensitivity of unionid mussel (*Lampsilis siliquoidea*) to ammonia in 28-day water exposures. Environmental Toxicology and Chemistry 30(10):2270-2276.

Weirich, C.R., J.R. Tomasso and T.I.J. Smith. 1993. Toxicity of ammonia and nitrite to sunshine bass in selected environments. Journal of Aquatic Animal Health 5(1):64-72. (As cited in USEPA 2013).

West, C.W. 1985. Acute toxicity of ammonia to 14 freshwater species. Internal Report. U.S. Environmental Protection Agency, Environmental Research Laboratory, Duluth, Minnesota. (As cited in USEPA 2013).

Wicks, B.J. and D.J. Randall. 2002. The effect of feeding and fasting on ammonia toxicity in juvenile rainbow trout, *Oncorhynchus mykiss*. Aquatic Toxicology 59(1-2):71-82. (As cited in USEPA 2013).

Wicks, B.J., R. Joensen, Q. Tang and D.J. Randall. 2002. Swimming and ammonia toxicity in salmonids: The effect of sub-lethal ammonia exposure on the swimming performance of coho salmon and the acute toxicity of ammonia in swimming and resting rainbow trout. Aquatic Toxicology 59(1-2):55-69. (As cited in USEPA 2013).

Williams, K.A., D.W.J. Green and D. Pascoe. 1986. Studies on the acute toxicity of pollutants to freshwater macroinvertebrates. 3. Ammonia. Archiv für Hydrobiologie 106(1):61-70. (As cited in USEPA 2013).

Willingham, T. 1987. Acute and short-term chronic ammonia toxicity to fathead minnows (*Pimephales promelas*) and *Ceriodaphnia dubia* using laboratory dilution water and Lake Mead dilution water. U.S. Environmental Protection Agency, Denver, Colorado. (As cited in USEPA 2013).

Wilson, E.F. 1974. The lethal and sub-lethal effects of a zirconium process effluent on juvenile salmonids. Ph.D. thesis. Oregon State University, Corvallis, Oregon. (As cited in USEPA 2013).

Appendix 2

Summary of the Compiled Aquatic Toxicity Data for Cadmium

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Table A2.1 Summary of compiled acute aquatic toxicity data for cadmium. A2-1

Table A2.2 Summary of compiled chronic aquatic toxicity data for cadmium. A2-20

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Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Data from USEPA (2001)[2]										
Amphibian										
Ambystoma gracile	Salamander	3 months (larvae)	NR	FT,M	NR	LC_{50}/EC_{50}	468.4	521.4	45	Nebeker *et al.* 1995a
Xenopus laevis	Clawed toad	NR	NR	R,U	NR	LC_{50}/EC_{50}	3597	1529	116	Sunderman *et al.* 1991
Fish										
Carassius auratus	Goldfish	8.8 g	NR	FT,M	NR	LC_{50}/EC_{50}	748	844	44.4	Phipps and Holcombe 1985
Catostomus commersonii	White sucker	NR	NR	FT,M	NR	LC_{50}/EC_{50}	1110	3136	18	Duncan and Klaverkamp 1983
Cyprinus carpio	Common carp	Fingerling	NR	S,U	NR	LC_{50}/EC_{50}	17100	8452	100	Suresh *et al.* 1993
Cyprinus carpio	Common carp	Fry	NR	S,U	NR	LC_{50}/EC_{50}	4300	2125	100	Suresh *et al.* 1993
Gambusia affinis	Western mosquitofish	NR	NR	FT,M	NR	LC_{50}/EC_{50}	900	4157	11.1	Giesy *et al.* 1977
Gambusia affinis	Western mosquitofish	NR	NR	FT,M	NR	LC_{50}/EC_{50}	2200	10161	11.1	Giesy *et al.* 1977
Gasterosteus aculeatus	Threespine stickleback	NR	NR	R,M	NR	LC_{50}/EC_{50}	23000	10613	107	Pascoe and Mattey 1977
Gasterosteus aculeatus	Threespine stickleback	NR	NR	S,U	NR	LC_{50}/EC_{50}	6500	2787	115	Pascoe and Cram 1977
Gila elegans	Bonytail	Juvenile	NR	S,U	NR	LC_{50}/EC_{50}	168	41.25	199	Buhl 1997
Gila elegans	Bonytail	Larva	NR	S,U	NR	LC_{50}/EC_{50}	148	36.34	199	Buhl 1997
Ictalurus punctatus	Channel catfish	7.4 g	NR	FT,M	NR	LC_{50}/EC_{50}	4480	5055	44.4	Phipps and Holcombe 1985

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish (cont.)										
Jordanella floridae	Flagfish	NR	NR	FT,M	NR	LC_{50}/EC_{50}	2500	2847	44	Spehar 1976a,b
Lepomis cyanellus	Green sunfish	NR	NR	FT,M	NR	LC_{50}/EC_{50}	20500	2965	335	Jude 1973
Lepomis macrochirus	Bluegill sunfish	NR	NR	FT,M	NR	LC_{50}/EC_{50}	21100	4978	207	Eaton 1980
Lepomis macrochirus	Bluegill sunfish	1.0 g	NR	FT,M	NR	LC_{50}/EC_{50}	6470	7300	44.4	Phipps and Holcombe 1985
Morone saxatilis	Striped bass	63 d	NR	S,U	NR	LC_{50}/EC_{50}	10	1.704	285	Palawski *et al.* 1985
Morone saxatilis	Striped bass	63 d	NR	S,U	NR	LC_{50}/EC_{50}	4	5.019	40	Palawski *et al.* 1985
Notropis lutrensis	Red shiner	0.8-2.0 g	NR	S,M	NR	LC_{50}/EC_{50}	6620	3837	85.5	Carrier and Beitinger 1988
Oreochromis mossambicus	Mozambique tilapia	NR	NR	R,U	NR	LC_{50}/EC_{50}	6000	10663	28.4	Gaikwad 1989
Pimephales promelas	Fathead minnow	< 24 hr	NR	S,M	NR	LC_{50}/EC_{50}	60	10.05	290	Schubauer-Berigan *et al.* 1993
Pimephales promelas	Fathead minnow	< 24 hr	NR	S,M	NR	LC_{50}/EC_{50}	65	10.88	290	Schubauer-Berigan *et al.* 1993
Pimephales promelas	Fathead minnow	< 24 hr	NR	S,M	NR	LC_{50}/EC_{50}	73	12.22	290	Schubauer-Berigan *et al.* 1993
Pimephales promelas	Fathead minnow	< 24 hr	NR	S,U	NR	LC_{50}/EC_{50}	210	174.5	60	Rifici *et al.* 1996
Pimephales promelas	Fathead minnow	1-2 d	NR	S,U	NR	LC_{50}/EC_{50}	180	149.5	60	Rifici *et al.* 1996
Pimephales promelas	Fathead minnow	30 d	NR	FT,M	NR	LC_{50}/EC_{50}	13.2	15.03	44	Spehar and Fiandt 1986
Pimephales promelas	Fathead minnow	Fry	NR	S,M	NR	LC_{50}/EC_{50}	19.3	24.85	39	Spehar 1982

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish (cont.)										
Pimephales promelas	Fathead minnow	Fry	NR	S,M	NR	LC_{50}/EC_{50}	21.5	26.97	40	Spehar 1982
Pimephales promelas	Fathead minnow	Fry	NR	S,M	NR	LC_{50}/EC_{50}	29	33.02	44	Spehar 1982
Pimephales promelas	Fathead minnow	Fry	NR	S,M	NR	LC_{50}/EC_{50}	42.4	47.19	45	Spehar 1982
Pimephales promelas	Fathead minnow	Fry	NR	S,M	NR	LC_{50}/EC_{50}	54.2	57.72	47	Spehar 1982
Pimephales promelas	Fathead minnow	Fry	NR	S,M	NR	LC_{50}/EC_{50}	11.7	12.2	48	Spehar 1982
Poecilia reticulata	Guppy	NR	NR	S,U	NR	LC_{50}/EC_{50}	1270	3224	20	Pickering and Henderson 1966
Poecilia reticulata	Guppy	3-4 wk	NR	R,M	NR	LC_{50}/EC_{50}	3800	1787	105	Canton and Slooff 1982
Poecilia reticulata	Guppy	3-4 wk	NR	R,M	NR	LC_{50}/EC_{50}	11100	2591	209.2	Canton and Slooff 1982
Ptychocheilus lucius	Colorado squawfish	Juvenile	NR	S,U	NR	LC_{50}/EC_{50}	108	26.52	199	Buhl 1997
Ptychocheilus lucius	Colorado squawfish	Larva	NR	S,U	NR	LC_{50}/EC_{50}	78	19.15	199	Buhl 1997
Ptychocheilus oregonensis	Northern pikeminnow	Juvenile	NR	FT,M	NR	LC_{50}/EC_{50}	1092	2209	25	Andros and Garton 1980
Ptychocheilus oregonensis	Northern pikeminnow	Juvenile	NR	FT,M	NR	LC_{50}/EC_{50}	1104	2234	25	Andros and Garton 1980
Xyrauchen texanus	Razorback sucker	Juvenile	NR	S,U	NR	LC_{50}/EC_{50}	160	39.29	199	Buhl 1997
Xyrauchen texanus	Razorback sucker	Larva	NR	S,U	NR	LC_{50}/EC_{50}	139	34.13	199	Buhl 1997

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid										
Oncorhynchus kisutch	Coho salmon	Parr	NR	FT,M	NR	LC_{50}/EC_{50}	2.7	6.221	22	Chapman 1975
Oncorhynchus mykiss	Rainbow trout	NR	NR	FT,M	NR	LC_{50}/EC_{50}	1.75	2.845	31	Davies 1976
Oncorhynchus mykiss	Rainbow trout	1130 mg	NR	FT,M	NR	LC_{50}/EC_{50}	0.38	0.6344	30.2	Stratus Consulting 1999
Oncorhynchus mykiss	Rainbow trout	1150 mg	NR	FT,M	NR	LC_{50}/EC_{50}	0.51	0.8105	31.7	Stratus Consulting 1999
Oncorhynchus mykiss	Rainbow trout	263 mg	NR	FT,M	NR	LC_{50}/EC_{50}	0.71	1.166	30.7	Stratus Consulting 1999
Oncorhynchus mykiss	Rainbow trout	289 mg	NR	FT,M	NR	LC_{50}/EC_{50}	2.85	1.581	89.3	Stratus Consulting 1999
Oncorhynchus mykiss	Rainbow trout	299 mg	NR	FT,M	NR	LC_{50}/EC_{50}	1.29	2.168	30	Stratus Consulting 1999
Oncorhynchus mykiss	Rainbow trout	659 mg	NR	FT,M	NR	LC_{50}/EC_{50}	0.47	0.8092	29.3	Stratus Consulting 1999
Oncorhynchus mykiss	Rainbow trout	8.8 g	NR	FT,M	NR	LC_{50}/EC_{50}	3	3.385	44.4	Phipps and Holcombe 1985
Oncorhynchus mykiss	Rainbow trout	Fry	NR	FT,M	NR	LC_{50}/EC_{50}	< 0.5	< 2.795 [3]	9.2	Cusimano *et al.* 1986a
Oncorhynchus mykiss	Rainbow trout	Parr	NR	FT,M	NR	LC_{50}/EC_{50}	1	2.202	23	Chapman 1978a
Oncorhynchus mykiss	Rainbow trout	Smolt	NR	FT,M	NR	LC_{50}/EC_{50}	> 2.9	> 6.386 [3]	23	Chapman 1975
Oncorhynchus mykiss	Rainbow trout	Smolt	NR	FT,M	NR	LC_{50}/EC_{50}	4.1	9.029	23	Chapman 1975
Oncorhynchus mykiss	Rainbow trout	Swim-up	NR	FT,M	NR	LC_{50}/EC_{50}	1.3	2.863	23	Chapman 1975, 1978a
Oncorhynchus tshawytscha	Chinook salmon	Juvenile	NR	FT,M	NR	LC_{50}/EC_{50}	1.1	2.657	21	Finlayson and Verrue 1982

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid (cont.)										
Oncorhynchus tshawytscha	Chinook salmon	Juvenile	NR	FT,M	NR	LC_{50}/EC_{50}	1.41	2.853	25	Chapman 1982a
Oncorhynchus tshawytscha	Chinook salmon	Parr	NR	FT,M	NR	LC_{50}/EC_{50}	3.5	7.707	23	Chapman 1975, 1978a
Oncorhynchus tshawytscha	Chinook salmon	Smolt	NR	FT,M	NR	LC_{50}/EC_{50}	> 2.9	> 6.386 [3]	23	Chapman 1975, 1978a
Oncorhynchus tshawytscha	Chinook salmon	Swim-up	NR	FT,M	NR	LC_{50}/EC_{50}	1.8	3.964	23	Chapman 1975, 1978a
Salmo trutta	Brown trout	NR	NR	S,M	NR	LC_{50}/EC_{50}	1.4	1.613	53.5	Spehar and Carlson 1984a,b
Salvelinus confluentus	Bull trout	200 mg	NR	FT,M	NR	LC_{50}/EC_{50}	0.99	1.705	29.3	Stratus Consulting 1999
Salvelinus confluentus	Bull trout	218 mg	NR	FT,M	NR	LC_{50}/EC_{50}	0.9	1.503	30.2	Stratus Consulting 1999
Salvelinus confluentus	Bull trout	221 mg	NR	FT,M	NR	LC_{50}/EC_{50}	1	1.589	31.7	Stratus Consulting 1999
Salvelinus confluentus	Bull trout	72.7 mg	NR	FT,M	NR	LC_{50}/EC_{50}	6.06	3.361	89.3	Stratus Consulting 1999
Salvelinus confluentus	Bull trout	76.1 mg	NR	FT,M	NR	LC_{50}/EC_{50}	0.91	1.494	30.7	Stratus Consulting 1999
Salvelinus confluentus	Bull trout	84.2 mg	NR	FT,M	NR	LC_{50}/EC_{50}	2.89	4.858	30	Stratus Consulting 1999
Salvelinus fontinalis	Brook trout	NR	NR	S	NR	LC_{50}/EC_{50}	< 1.5	< 1.791 [4]	42	Carroll *et al.* 1979
Invertebrate - ALS insect										
Chironomus riparius	Midge	10-12 mm	NR	FT,M	NR	LC_{50}/EC_{50}	300000	96880	152	Williams *et al.* 1985
Ephemerella grandis	Mayfly	NR	NR	S,U	NR	LC_{50}/EC_{50}	2000	2278	44	Warnick and Bell 1969

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Amphipod										
Crangonyx pseudogracilis	Amphipod	4 mm	NR	R,U	NR	LC_{50}/EC_{50}	1700	1700	50	Martin and Holdieh 1986
Gammarus pseudolimnaeus	Amphipod	NR	NR	S,M	NR	LC_{50}/EC_{50}	68.3	78.69	43.5	Spehar and Carlson 1984a,b
Invertebrate - Bryozoan										
Lophopodella carteri	Bryozoan	NR	NR	S,U	NR	LC_{50}/EC_{50}	150	35.74	205	Pardue and Wood 1980
Pectinatella magnifica	Bryozoan	NR	NR	S,U	NR	LC_{50}/EC_{50}	700	166.8	205	Pardue and Wood 1980
Plumatella emarginata	Bryozoan	NR	NR	S,U	NR	LC_{50}/EC_{50}	1090	259.7	205	Pardue and Wood 1980
Invertebrate - Cladoceran										
Alona affinis	Water flea	NR	NR	S,U	NR	LC_{50}/EC_{50}	546	247.2	109	Ghosh *et al.* 1990
Ceriodaphnia dubia	Water flea	< 24 hr	NR	R,M	NR	LC_{50}/EC_{50}	54.5	33.8	80	Diamond et al. 1997
Ceriodaphnia dubia	Water flea	< 24 hr	NR	S,U	NR	LC_{50}/EC_{50}	54	29.71	90	Bitton *et al.* 1996
Ceriodaphnia dubia	Water flea	< 24 hr	NR	S,U	NR	LC_{50}/EC_{50}	55.9	30.75	90	Lee *et al.* 1997
Ceriodaphnia reticulata	Water flea	< 24 hr	NR	S,U	NR	LC_{50}/EC_{50}	184	37.35	240	Elnabarawy *et al.* 1986a
Ceriodaphnia reticulata	Water flea	< 6 hr	NR	S,U	NR	LC_{50}/EC_{50}	110	45.17	120	Hall *et al.* 1986
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	3.6	1.038	170	Baird *et al.* 1991
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	4.5	1.297	170	Baird *et al.* 1991

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Cladoceran (cont.)										
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	9	2.594	170	Baird *et al.* 1991
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	9	2.594	170	Baird *et al.* 1991
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	27.1	7.81	170	Baird *et al.* 1991
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	115.9	33.4	170	Baird *et al.* 1991
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	23.6	6.454	179	Barata *et al.* 1998
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	233	63.72	179	Barata *et al.* 1998
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	30.1	32.69	46.1	Barata *et al.* 1998
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	112	121.6	46.1	Barata *et al.* 1998
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	23.4	12.77	90.7	Barata *et al.* 1998
Daphnia magna	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	106	57.86	90.7	Barata *et al.* 1998
Daphnia magna	Water flea	NR	NR	S,U	NR	LC_{50}/EC_{50}	20	8.213	120	Hall et al. 1986
Daphnia magna	Water flea	NR	NR	S,U	NR	LC_{50}/EC_{50}	40	16.43	120	Hall et al. 1986
Daphnia magna	Water flea	NR	NR	S,U	NR	LC_{50}/EC_{50}	280	54.52	250	Crisinel et al. 1994
Daphnia magna	Water flea	NR	NR	S,U	NR	LC_{50}/EC_{50}	65	72.35	45	Biesinger and Christensen 1972
Daphnia magna	Water flea	< 24 hr	NR	FT,M	NR	LC_{50}/EC_{50}	58	21.96	130	Attar and Maly 1982

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Cladoceran (cont.)										
Daphnia magna	Water flea	< 24 hr	NR	R,M	NR	LC_{50}/EC_{50}	30	14.11	105	Canton and Slooff 1982
Daphnia magna	Water flea	< 24 hr	NR	R,M	NR	LC_{50}/EC_{50}	30	7.002	209.2	Canton and Slooff 1982
Daphnia magna	Water flea	< 24 hr	NR	S,M	NR	LC_{50}/EC_{50}	33	15.67	104	Chapman *et al.* Manuscript
Daphnia magna	Water flea	< 24 hr	NR	S,M	NR	LC_{50}/EC_{50}	34	15.99	105	Chapman *et al.* Manuscript
Daphnia magna	Water flea	< 24 hr	NR	S,M	NR	LC_{50}/EC_{50}	24.5	7.061	170	Stuhlbacher *et al.* 1992
Daphnia magna	Water flea	< 24 hr	NR	S,M	NR	LC_{50}/EC_{50}	129.4	37.29	170	Stuhlbacher *et al.* 1992
Daphnia magna	Water flea	< 24 hr	NR	S,M	NR	LC_{50}/EC_{50}	63	15.63	197	Chapman *et al.* Manuscript
Daphnia magna	Water flea	< 24 hr	NR	S,M	NR	LC_{50}/EC_{50}	49	11.45	209	Chapman *et al.* Manuscript
Daphnia magna	Water flea	< 24 hr	NR	S,M	NR	LC_{50}/EC_{50}	9.9	9.703	51	Chapman *et al.* Manuscript
Daphnia magna	Water flea	< 24 hr	NR	S,U	NR	LC_{50}/EC_{50}	9.5	2.738	170	Guilhermino *et al.* 1996
Daphnia magna	Water flea	< 24 hr	NR	S,U	NR	LC_{50}/EC_{50}	178	36.13	240	Elnabarawy *et al.* 1986a
Daphnia pulex	Water flea	NR	NR	S,U	NR	LC_{50}/EC_{50}	47	41.14	57	Bertram and Hart 1979
Daphnia pulex	Water flea	NR	NR	S,U	NR	LC_{50}/EC_{50}	66	38.48	85	Roux *et al.* 1993
Daphnia pulex	Water flea	NR	NR	S,U	NR	LC_{50}/EC_{50}	70	40.82	85	Roux *et al.* 1993
Daphnia pulex	Water flea	NR	NR	S,U	NR	LC_{50}/EC_{50}	99	57.72	85	Roux *et al.* 1993

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Cladoceran (cont.)										
Daphnia pulex	Water flea	< 24 hr	NR	S,M	NR	LC_{50}/EC_{50}	70.1	65.44	53.5	Stackhouse and Benson 1988
Daphnia pulex	Water flea	< 24 hr	NR	S,U	NR	LC_{50}/EC_{50}	80	32.85	120	Hall *et al.* 1986
Daphnia pulex	Water flea	< 24 hr	NR	S,U	NR	LC_{50}/EC_{50}	100	41.07	120	Hall *et al.* 1986
Daphnia pulex	Water flea	< 24 hr	NR	S,U	NR	LC_{50}/EC_{50}	319	64.75	240	Elnabarawy *et al.* 1986a
Moina macrocopa	Water flea	NR	NR	S,U	NR	LC_{50}/EC_{50}	71.25	43.09	82	Hatakeyama and Yasuno 1981
Simocephalus serrulatus	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	7	32.33	11.1	Giesy *et al.* 1977
Simocephalus serrulatus	Water flea	NR	NR	S,M	NR	LC_{50}/EC_{50}	24.5	28.23	43.5	Spehar and Carlson 1984a,b
Invertebrate - Copepod										
Cyclops varicans	Copepod	NR	NR	S,U	NR	LC_{50}/EC_{50}	493	223.2	109	Ghosh *et al.* 1990
Invertebrate - Decapod										
Orconectes immunis	Crayfish	1.8 g	NR	FT,M	NR	LC_{50}/EC_{50}	> 10200	> 11509 [4]	44.4	Phipps and Holcombe 1985
Orconectes virilis	Crayfish	NR	NR	FT,M	NR	LC_{50}/EC_{50}	6100	11859	26	Mirenda 1986a
Procambarus clarkii	Red swamp crayfish	Juvenile	NR	S,M	NR	LC_{50}/EC_{50}	1040	1748	30	Naqvi and Howell 1993
Invertebrate - Isopod										
Asellus bicrenata	Isopod	NR	NR	FT,M	NR	LC_{50}/EC_{50}	2129	472.1	220	Bosnak and Morgan 1981

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Isopod (cont.)										
Lirceus alabamae	Isopod	NR	NR	FT,M	NR	LC_{50}/EC_{50}	150	48.44	152	Bosnak and Morgan 1981
Invertebrate - Mussel										
Actinonaias pectorosa	Mussel	Juvenile	NR	S,M	NR	LC_{50}/EC_{50}	46.4	28.06	82	Keller Unpublished
Actinonaias pectorosa	Mussel	Juvenile	NR	S,M	NR	LC_{50}/EC_{50}	69	40.72	84	Keller Unpublished
Lampsilis straminea claibornensis	Mussel	Juvenile	NR	S,M	NR	LC_{50}/EC_{50}	38	47.68	40	Keller Unpublished
Lampsilis teres	Mussel	NR	NR	S,M	NR	LC_{50}/EC_{50}	11	13.8	40	Keller Unpublished
Lampsilis teres	Mussel	Juvenile	NR	S,M	NR	LC_{50}/EC_{50}	33	41.4	40	Keller Unpublished
Utterbackia imbecillis	Pondshell mussel	NR	NR	S,M	NR	LC_{50}/EC_{50}	111.8	61.51	90	Keller Unpublished
Utterbackia imbecillis	Pondshell mussel	NR	NR	S,M	NR	LC_{50}/EC_{50}	114.7	63.1	90	Keller Unpublished
Utterbackia imbecillis	Pondshell mussel	Juvenile	NR	S,M	NR	LC_{50}/EC_{50}	9	11.59	39	Keller and Zam 1991
Utterbackia imbecillis	Pondshell mussel	Juvenile	NR	S,M	NR	LC_{50}/EC_{50}	93.0	53.59	86	Keller Unpublished
Utterbackia imbecillis	Pondshell mussel	Juvenile	NR	S,M	NR	LC_{50}/EC_{50}	81.9	44.06	92	Keller Unpublished
Utterbackia imbecillis	Pondshell mussel	Juvenile	NR	S,M	NR	LC_{50}/EC_{50}	107	58.87	90	Keller and Zam 1991
Villosa vibex	Mussel	NR	NR	S,M	NR	LC_{50}/EC_{50}	125	32.88	186	Keller Unpublished
Villosa vibex	Mussel	NR	NR	S,M	NR	LC_{50}/EC_{50}	30	37.64	40	Keller Unpublished

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Snail										
Aplexa hypnorum	Snail	NR	NR	FT,M	NR	LC_{50}/EC_{50}	93	102.8	45.3	Holcombe *et al.* 1984
Aplexa hypnorum	Snail	Adult	NR	FT,M	NR	LC_{50}/EC_{50}	93	104.9	44.4	Phipps and Holcombe 1985
Physa gyrina	Pouch snail	Immature	NR	S,M	NR	LC_{50}/EC_{50}	410	100.2	200	Wier and Walter 1976
Invertebrate - Worm										
Branchiura sowerbyi	Tubificid worm	NR	NR	S,M	NR	LC_{50}/EC_{50}	240	2350	5.3	Chapman *et al.* 1982
Dendrocoelum lacteum	Flatworm	NR	NR	R,M	NR	LC_{50}/EC_{50}	24702	14067	87	Ham *et al.* 1995
Glossiponia complanta	Leech	NR	NR	R,M	NR	LC_{50}/EC_{50}	480	192.5	122.8	Brown and Pascoe 1988
Limnodrilus hoffmeisteri	Tubificid worm	30-40 mm	NR	FT,M	NR	LC_{50}/EC_{50}	2400	775	152	Williams *et al.* 1985
Lumbriculus variegatus	Worm	Adult	NR	S,M	NR	LC_{50}/EC_{50}	780	130.6	290	Schubauer-Berigan *et al.* 1993
Quistadrilus multisetosus	Tubificid worm	NR	NR	S,M	NR	LC_{50}/EC_{50}	320	3133	5.3	Chapman *et al.* 1982
Rhyacodrilus montana	Tubificid worm	NR	NR	S,M	NR	LC_{50}/EC_{50}	630	6169	5.3	Chapman *et al.* 1982
Spirosperma ferox	Tubificid worm	NR	NR	S,M	NR	LC_{50}/EC_{50}	350	3427	5.3	Chapman *et al.* 1982
Spirosperma nikolskyi	Tubificid worm	NR	NR	S,M	NR	LC_{50}/EC_{50}	450	4406	5.3	Chapman *et al.* 1982
Stylodrilus heringianus	Tubificid worm	NR	NR	S,M	NR	LC_{50}/EC_{50}	550	5386	5.3	Chapman *et al.* 1982
Tubifex tubifex	Tubificid worm	NR	NR	S,M	NR	LC_{50}/EC_{50}	1700	653.8	128	Reynoldson *et al.* 1996

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Worm (cont.)										
Tubifex tubifex	Tubificid worm	NR	NR	S,M	NR	LC_{50}/EC_{50}	3200	1231	128	Reynoldson *et al.* 1996
Tubifex tubifex	Tubificid worm	NR	NR	S,M	NR	LC_{50}/EC_{50}	320	3133	5.3	Chapman *et al.* 1982
Varichaeta pacifica	Tubificid worm	NR	NR	S,M	NR	LC_{50}/EC_{50}	380	3721	5.3	Chapman *et al.* 1982
Additional Data [5]										
Fish										
Acipenser transmontanus	White sturgeon	2 dph	96-h	FT	Mortality & Behavior	MAV [6]	3.07	1.473	103	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	30 dph	96-h	FT	Mortality & Behavior	EC_{10}	29	13.51	106	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	30 dph	96-h	FT	Mortality & Behavior	EC_{20}	45	20.96	106	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	30 dph	96-h	FT	Mortality & Behavior	EC_{50}	103	**47.98**	106	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	30 dph	96-h	FT	Mortality & Behavior	MAV [6]	112	52.18	106	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	44 dph	96-h	FT	Mortality	MAV [6]	28	12.92	107	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	72 dph	96-h	FT	Mortality & Behavior	EC_{50}	5.61	**2.639**	105	Ingersoll and Mebane 2013
Cottus bairdi	Mottled sculpin	Newly hatched	96-h	FT	Mortality	LC_{50}	2.9	**1.391**	103	Besser *et al.* 2007
Cottus bairdi	Mottled sculpin	Swim-up	96-h	FT	Mortality	LC_{50}	7.9	**3.789**	103	Besser *et al.* 2007
Cottus confusus	Shorthead sculpin	30-60 mm	96-h	R	Mortality	LC_{50}	0.93	**2.246**	21	Mebane *et al.* 2012

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid										
Oncorhynchus clarkii lewisi	Cutthroat trout	YOY	96-h	R	Mortality	LC_{50}	0.94	**2.271**	21	Mebane *et al.* 2012
Oncorhynchus clarkii lewisi	Cutthroat trout	YOY	96-h	R	Mortality	LC_{50}	1.2	**1.983**	30.5	Mebane *et al.* 2012
Oncorhynchus clarkii lewisi	Cutthroat trout	YOY	96-h	R	Mortality	LC_{50}	1.5	**2.361**	32	Mebane *et al.* 2012
Oncorhynchus mykiss	Rainbow trout	18 dph	96-h	FT	Mortality	MAV [6]	1.86	0.8834	104	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	18 dph	96-h	FT	Mortality	EC_{50}	2.89	**1.373**	104	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	20-40 mm	96-h	R	Mortality	LC_{50}	0.48	**3.542**	7	Mebane *et al.* 2012
Oncorhynchus mykiss	Rainbow trout	20-40 mm	96-h	R	Mortality	LC_{50}	0.99	**3.894**	13	Mebane *et al.* 2012
Oncorhynchus mykiss	Rainbow trout	20-40 mm	96-h	R	Mortality	LC_{50}	0.34	**0.8213**	21	Mebane *et al.* 2012
Oncorhynchus mykiss	Rainbow trout	20-40 mm	96-h	R	Mortality	LC_{50}	0.8	**1.932**	21	Mebane *et al.* 2012
Oncorhynchus mykiss	Rainbow trout	20-40 mm	96-h	R	Mortality	LC_{50}	1.3	**2.742**	24	Mebane *et al.* 2012
Oncorhynchus mykiss	Rainbow trout	20-40 mm	96-h	R	Mortality	LC_{50}	0.83	**1.47**	28.5	Mebane *et al.* 2012
Oncorhynchus mykiss	Rainbow trout	20-40 mm	96-h	R	Mortality	LC_{50}	0.93	**1.464**	32	Mebane *et al.* 2012
Oncorhynchus mykiss	Rainbow trout	0.8g; 43 mm	24-h	FT	Dominance Ability	MAV [6]	1.27	0.5195	120	Sloman *et al.* 2003
Oncorhynchus mykiss	Rainbow trout	32 dph	96-h	FT	Mortality	EC_{10}	3.09	1.426	107	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	32 dph	96-h	FT	Mortality	EC_{20}	3.6	1.661	107	Ingersoll and Mebane 2013

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid (cont.)										
Oncorhynchus mykiss	Rainbow trout	32 dph	96-h	FT	Mortality	MAV [6]	3.71	1.712	107	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	32 dph	96-h	FT	Mortality	EC_{50}	4.83	**2.229**	107	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	45mm	96-h	FT	Mortality	LC_{50}	3.08	**3.144**	49	Davies *et al.* 1993
Oncorhynchus mykiss	Rainbow trout	45mm	96-h	FT	Mortality	LC_{50}	6.57	**1.431**	224	Davies *et al.* 1993
Oncorhynchus mykiss	Rainbow trout	45mm	96-h	FT	Mortality	LC_{50}	5.92	**0.677**	422	Davies *et al.* 1993
Oncorhynchus mykiss	Rainbow trout	46 dph	96-h	FT	Mortality	EC_{10}	0.84	0.3876	107	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	46 dph	96-h	FT	Mortality	EC_{20}	1.26	0.5814	107	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	46 dph	96-h	FT	Mortality	EC_{50}	2.77	**1.278**	107	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	46 dph	96-h	FT	Mortality	MAV [6]	3.44	1.587	107	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	60 dph	96-h	FT	Mortality	EC_{10}	2.42	1.149	104	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	60 dph	96-h	FT	Mortality	EC_{20}	2.8	1.33	104	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	60 dph	96-h	FT	Mortality	EC_{50}	3.71	1.762	104	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	60 dph	96-h	FT	Mortality & Behavior	EC_{10}	1.31	0.6222	104	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	60 dph	96-h	FT	Mortality & Behavior	EC_{20}	1.83	0.8692	104	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	60 dph	96-h	FT	Mortality & Behavior	EC_{50}	3.48	**1.653**	104	Ingersoll and Mebane 2013

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid (cont.)										
Oncorhynchus mykiss	Rainbow trout	74 dph	96-h	FT	Mortality	MAV [6]	3.66	1.886	96	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	74 dph	96-h	FT	Mortality	EC_{10}	3.67	1.891	96	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	74 dph	96-h	FT	Mortality	EC_{20}	3.95	2.035	96	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	74 dph	96-h	FT	Mortality	EC_{50}	4.54	**2.339**	96	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	95 dph	96-h	FT	Mortality	MAV [6]	1.93	0.9257	103	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	95 dph	96-h	FT	Mortality	EC_{10}	2.41	1.156	103	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	95 dph	96-h	FT	Mortality	EC_{20}	2.58	1.238	103	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	95 dph	96-h	FT	Mortality	EC_{50}	2.96	**1.42**	103	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Steelhead	Fry	96-h	FT	Mortality	LC_{50}	0.7	**3.913**	9.2	Cusimano *et al.* 1986b
Oncorhynchus mykiss	Rainbow trout	Fry	120-h	FT	Mortality	LC_{50}	0.35	**0.6026**	29.3	Hansen *et al.* 2002a
Oncorhynchus mykiss	Rainbow trout	Fry	120-h	FT	Mortality	LC_{50}	0.84	**1.412**	30	Hansen *et al.* 2002a
Oncorhynchus mykiss	Rainbow trout	Fry	120-h	FT	Mortality	LC_{50}	0.35	**0.5843**	30.2	Hansen *et al.* 2002a
Oncorhynchus mykiss	Rainbow trout	Fry	120-h	FT	Mortality	LC_{50}	0.53	**0.8702**	30.7	Hansen *et al.* 2002a
Oncorhynchus mykiss	Rainbow trout	Fry	120-h	FT	Mortality	LC_{50}	0.36	**0.5721**	31.7	Hansen *et al.* 2002a
Oncorhynchus mykiss	Rainbow trout	Fry	120-h	FT	Mortality	LC_{50}	2.07	**1.148**	89.3	Hansen *et al.* 2002a

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid (cont.)										
Oncorhynchus mykiss	Rainbow trout	Juvenile	96-h	FT	Mortality	LC_{50}	5.2	**2.494**	103	Besser *et al.* 2007
Oncorhynchus mykiss	Rainbow trout	Swim-up	96-h	FT	Mortality	LC_{50}	3.7	**1.775**	103	Besser *et al.* 2007
Prosopium williamsoni	Mountain whitefish	Fry	96-h	FT	Mortality	LC_{50}	4.70	**4.92**	47.8	Brinkman and Vieira 2008
Salmo trutta	Brown trout	Fry	96-h	FT	Mortality	LC_{50}	1.23	**2.125**	29.2	Brinkman and Hansen 2007
Salmo trutta	Brown trout	Fry	96-h	FT	Mortality	LC_{50}	3.9	**2.87**	67.6	Brinkman and Hansen 2007
Salmo trutta	Brown trout	Fry	96-h	FT	Mortality	LC_{50}	10.1	**3.284**	151	Brinkman and Hansen 2007
Salvelinus confluentus	Bull trout	Fry	120-h	FT	Mortality	LC_{50}	0.83	**1.429**	29.3	Hansen *et al.* 2002a
Salvelinus confluentus	Bull trout	Fry	120-h	FT	Mortality	LC_{50}	2.41	**4.051**	30	Hansen *et al.* 2002a
Salvelinus confluentus	Bull trout	Fry	120-h	FT	Mortality	LC_{50}	0.83	**1.386**	30.2	Hansen *et al.* 2002a
Salvelinus confluentus	Bull trout	Fry	120-h	FT	Mortality	LC_{50}	0.83	**1.363**	30.7	Hansen *et al.* 2002a
Salvelinus confluentus	Bull trout	Fry	120-h	FT	Mortality	LC_{50}	0.88	**1.399**	31.7	Hansen *et al.* 2002a
Salvelinus confluentus	Bull trout	Fry	120-h	FT	Mortality	LC_{50}	5.23	**2.9**	89.3	Hansen *et al.* 2002a
Invertebrate - ALS insect										
Baetis tricaudatus	Mayfly	Field-collected	96-h	R	Mortality	LC_{50}	74	**178.7**	21	Mebane *et al.* 2012

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - ALS insect (cont.)										
Baetis tricaudatus	Mayfly	Field-collected	96-h	R	Mortality	LC_{50}	16	**13.52**	59	Mebane *et al.* 2012
Chironomus riparius	Midge	2nd instar larvae	48-h	R	Mortality	LC_{50}	2620	**1134**	114	Watts and Pascoe 2000
Chironomus riparius	Midge	2nd instar larvae	96-h	R	Mortality	LC_{50}	1760	**761.4**	114	Watts and Pascoe 2000
Chironomus riparius	Midge	4th instar	NR	R	Mortality	LC_{50}	140000	**55610**	124	Pascoe *et al.* 1990
Chironomus tentans	Midge	2nd instar larvae	48-h	R	Mortality	LC_{50}	9340	**4041**	114	Watts and Pascoe 2000
Chironomus tentans	Midge	2nd instar larvae	96-h	R	Mortality	LC_{50}	1680	**726.8**	114	Watts and Pascoe 2000
Chironomus tentans	Midge	NR	48-h	NR	Mortality	LC_{50}	29560	**88510**	17	Suedel *et al.* 1997
Rhithrogena	Mayfly	Field-collected	96-h	R	Mortality	LC_{50}	157	**317.6**	25	Mebane *et al.* 2012
Rhithrogena hageni	Mayfly	Nymphs	96-h	FT	Mortality	LC_{50}	10500	**10940**	48	Brinkman and Johnston 2008
Invertebrate - Amphipod										
Gammarus pulex	Amphipod	Mature females [7]	48-h	R	Mortality	LC_{50}	140	**73.22**	94.6	McCahon and Pascoe 1988
Gammarus pulex	Amphipod	Mature females [8]	48-h	R	Mortality	LC_{50}	21	**10.98**	94.6	McCahon and Pascoe 1988
Gammarus pulex	Amphipod	Field-collected	48-h	FT	Mortality	LC_{50}	494	**96.23**	249.9	Felten *et al.* 2008
Gammarus pulex	Amphipod	Field-collected	96-h	FT	Mortality	LC_{50}	82.1	**15.99**	249.9	Felten *et al.* 2008
Gammarus pulex	Amphipod	Mature males	48-h	R	Mortality	LC_{50}	210	**109.8**	94.6	McCahon and Pascoe 1988

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Amphipod (cont.)										
Gammarus pulex	Amphipod	Mature males	96-h	R	Mortality	LC_{50}	30	**15.69**	94.6	McCahon and Pascoe 1988
Hyalella azteca	Amphipod	NR	48-h	NR	Mortality	LC_{50}	5.6	**16.77**	17	Suedel *et al.* 1997
Hyalella azteca	Amphipod	NR	96-h	NR	Mortality	LC_{50}	2.8	**8.384**	17	Suedel *et al.* 1997
Invertebrate - Cladoceran										
Ceriodaphnia dubia	Water flea	NR	48-h	NR	Mortality	LC_{50}	63.1	**188.9**	17	Suedel *et al.* 1997
Ceriodaphnia dubia	Water flea	NR	96-h	NR	Mortality	LC_{50}	16.9	**50.6**	17	Suedel *et al.* 1997
Daphnia magna	Water flea	≤ 24-h old	48-h	R	Mortality	LC_{50}	36	**72.83**	25	Schuytema *et al.* 1984
Daphnia magna	Water flea	≤ 24-h old	48-h	R	Mortality	LC_{50}	62	**125.4**	25	Schuytema *et al.* 1984
Daphnia magna	Water flea	NR	48-h	NR	Mortality	LC_{50}	26.4	**16.8**	78	Suedel *et al.* 1997
Daphnia magna	Water flea	NR	96-h	NR	Mortality	LC_{50}	12.7	**8.081**	78	Suedel *et al.* 1997
Invertebrate - Mussel										
Lampsilis rafinesqueana	Neosho mucket	5-d old	96-h	R	Mortality	LC_{50}	20	**23.88**	42	Wang *et al.* 2010
Lampsilis siliquoidea	Fatmucket	5-d old	96-h	R	Mortality	LC_{50}	16	**19.1**	42	Wang *et al.* 2010
Lampsilis ventricosa	Mussel	0-d old	96-h	R	Mortality & Behavior	EC_{50}	72	24.39	145	Lasee 1991
Lampsilis ventricosa	Mussel	0-d old	96-h	R	Mortality	LC_{50}	82	**27.78**	145	Lasee 1991
Lasmigona subviridis	Mussel	Juvenile	48-h	R	Mortality	LC_{50}	94.9	**56**	84	Black 2001

Table A2.1. Summary of compiled acute aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Mussel (cont.)										
Lasmigona subviridis	Mussel	Juvenile	48-h	R	Mortality	LC_{50}	104	**61.37**	84	Black 2001
Lasmigona subviridis	Mussel	Juvenile	48-h	R	Mortality	LC_{50}	123	**72.59**	84	Black 2001
Lasmigona subviridis	Mussel	Juvenile	96-h	R	Mortality	LC_{50}	50.8	**29.98**	84	Black 2001
Lasmigona subviridis	Mussel	Juvenile	96-h	R	Mortality	LC_{50}	55.5	**32.75**	84	Black 2001
Lasmigona subviridis	Mussel	Juvenile	96-h	R	Mortality	LC_{50}	67.0	**39.54**	84	Black 2001
Utterbackia imbecillis	Paper pondshell	Juvenile	48-h	R	Mortality	LC_{50}	63.8	**37.65**	84	Black 2001
Utterbackia imbecillis	Paper pondshell	Juvenile	48-h	R	Mortality	LC_{50}	66.5	**39.24**	84	Black 2001
Utterbackia imbecillis	Paper pondshell	Juvenile	48-h	R	Mortality	LC_{50}	82.7	**48.8**	84	Black 2001
Utterbackia imbecillis	Paper pondshell	Juvenile	96-h	R	Mortality	LC_{50}	19.1	**11.27**	84	Black 2001
Utterbackia imbecillis	Paper pondshell	Juvenile	96-h	R	Mortality	LC_{50}	21.7	**12.81**	84	Black 2001

ALS = aquatic life stage; AWQC = ambient water quality criteria; d = day; dph = days post-hatch; EC = effective concentration; FT = flow-through; GMAV = genus mean acute value; h = hour; LC = lethal concentration; M = measured; MAV = mean acute value; NR = not reported; R = renewal; S = static; SMAV = species mean acute value; U = unmeasured; USEPA = United States Environmental Protection Agency; YOY = young of year.

[1] Effect values normalized to a hardness of 50 mg/L using the pooled slope provided by USEPA (2001).

[2] Data from USEPA (2001) used in the calculation of SMAVs for the AWQC for cadmium. Values were used in the recalculation of SMAVs for this report except where noted.

[3] This value was not used in the recalculation of SMAVs because it is a "greater than" or "less than" value and there are measured values for this species.

[4] This value was used in the recalculation of SMAVs because it is the only value available for this species, but it was not used in the recalculation of GMAVs because there are measured values available for this genus.

[5] Additional data not used in the derivation of the aquatic life AWQC for cadmium (USEPA 2001). Bolded values were used in the recalculation of the SMAV.

[6] MAV = mean acute value; geometric mean of the LOEC and NOEC.

[7] Females carrying eggs in stages 2-6 or embryos.

[8] Females with empty brood pouches, carrying unfertilized eggs or stage 1 eggs.

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Data from USEPA (2001)[2]										
Fish										
Catostomus commersonii	White sucker	ELS	NR	NR	NR	Chronic Value	7.099	7.804	44	Eaton *et al.* 1978a
Esox lucius	Northern pike	ELS	NR	NR	NR	Chronic Value	7.361	8.092	44	Eaton *et al.* 1978a
Jordanella floridae	Flagfish	Life cycle[3]	NR	NR	NR	Chronic Value	4.982	5.175	47.5	Carlson *et al.* 1982
Jordanella floridae	Flagfish	Life cycle[3]	NR	NR	NR	Chronic Value	4.416	4.587	47.5	Carlson *et al.* 1982
Jordanella floridae	Flagfish	Life cycle[3]	NR	NR	NR	Chronic Value	5.763	6.336	44	Spehar 1976a
Lepomis macrochirus	Bluegill sunfish	Life cycle[3]	NR	NR	NR	Chronic Value	49.8	17.38	207	Eaton 1974
Micropterus dolomieu	Smallmouth bass	ELS	NR	NR	NR	Chronic Value	7.39	8.124	44	Eaton *et al.* 1978a
Oreochromis aurea	Blue tilapia	Life cycle[3]	NR	NR	NR	Chronic Value	> 52	> 23.63	145	Papoutsoglou and Abel 1988
Pimephales promelas	Fathead minnow	Life cycle[3]	NR	NR	NR	Chronic Value	45.92	16.38	201	Pickering and Gast 1972a
Fish - Salmonid										
Oncorhynchus kisutch	Coho salmon	ELS	NR	NR	NR	Chronic Value	7.159	7.87	44	Eaton *et al.* 1978a
Oncorhynchus kisutch	Coho salmon	ELS	NR	NR	NR	Chronic Value	2.102	2.311	44	Eaton *et al.* 1978a
Oncorhynchus mykiss	Rainbow trout	270 d old; Life cycle[3]	NR	NR	NR	Chronic Value	4.31	1.308	250	Brown *et al.* 1994
Oncorhynchus tshawytscha	Chinook salmon	ELS	NR	NR	NR	Chronic Value	1.563	2.612	25	Chapman 1975

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid (cont.)										
Salmo salar	Atlantic salmon	ELS	NR	NR	NR	Chronic Value	4.528	7.922	23.5	Rombough and Garside 1982a
Salmo trutta	Brown trout	Life cycle[3]	NR	NR	NR	Chronic Value	16.49	5.004	250	Brown *et al.* 1994
Salvelinus fontinalis	Brook trout	Life cycle[3]	NR	NR	NR	Chronic Value	2.404	2.643	44	Benoit *et al.* 1976
Salvelinus namaycush	Lake trout, siscowet	ELS	NR	NR	NR	Chronic Value	7.357	8.088	44	Eaton *et al.* 1978a
Invertebrate - ALS Insect										
Chironomus tentans	Midge	Life cycle[3]	NR	NR	NR	Chronic Value	10.05	2.804	280	Ingersoll and Kemble Unpublished
Invertebrate - Amphipod										
Hyalella azteca	Amphipod	Life cycle[3]	NR	NR	NR	Chronic Value	0.9844	0.2747	280	Ingersoll and Kemble Unpublished
Invertebrate - Cladoceran										
Ceriodaphnia dubia	Water flea	Life cycle[3]	NR	NR	NR	Chronic Value	13.78	27.17	20	Jop *et al.* 1995
Daphnia magna	Water flea	Life cycle[3]	NR	NR	NR	Chronic Value	7.07	3.133	150	Bodar *et al.* 1988
Daphnia magna	Water flea	Life cycle[3]	NR	NR	NR	Chronic Value	< 1.86	< 0.9163 [4]	130	Borgmann *et al.* 1989
Daphnia magna	Water flea	Life cycle[3]	NR	NR	NR	Chronic Value	0.1523	0.1459	53	Chapman *et al.* Manuscript
Daphnia magna	Water flea	Life cycle[3]	NR	NR	NR	Chronic Value	0.2117	0.1239	103	Chapman *et al.* Manuscript

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Cladoceran (cont.)										
Daphnia magna	Water flea	Life cycle[3]	NR	NR	NR	Chronic Value	0.4371	0.1515	209	Chapman *et al.* Manuscript
Daphnia pulex	Water flea	Life cycle[3]	NR	NR	NR	Chronic Value	7.49	6.167	65	Niederlehner 1984
Invertebrate - Snail										
Aplexa hypnorum	Snail	Life cycle[3]	NR	NR	NR	Chronic Value	5.801	6.241	45.3	Holcombe *et al.* 1984
Aplexa hypnorum	Snail	Life cycle[3]	NR	NR	NR	Chronic Value	3.46	3.723	45.3	Holcombe *et al.* 1984
Invertebrate - Worm										
Aeolosoma headleyi	Oligochaete	Life cycle[3]	NR	NR	NR	Chronic Value	25.19	20.74	65	Niederlehner 1984
Additional Data [5]										
Amphibian										
Ambystoma gracile	Northwestern salamander	3 months (larvae)	10-d	FT	Growth	Chronic Value	155.4	**168.1**	45	Nebeker *et al.* 1995b
Ambystoma gracile	Northwestern salamander	3 months (larvae)	24-d	FT	Growth	Chronic Value	97.17	**105.1**	45	Nebeker *et al.* 1995b
Fish										
Acipenser transmontanus	White sturgeon	27 dph	28-d	FT	Dry weight	Chronic Value	7.9	4.6924	101	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	FT	Dry weight	EC_{10}	5.7	3.3856	101	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	FT	Dry weight	EC_{20}	6.3	3.742	101	Ingersoll and Mebane 2013

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish (cont.)										
Acipenser transmontanus	White sturgeon	27 dph	28-d	FT	Biomass (dry)	Chronic Value	3.8	**2.2571**	101	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	FT	Survival	EC_{20}	5.9	3.5044	101	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	FT	Survival	EC_{10}	4.8	2.8511	101	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	FT	Survival	Chronic Value	7.9	4.6924	101	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	FT	Biomass (dry)	EC_{20}	3.2	1.9007	101	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	FT	Biomass (dry)	EC_{10}	2.4	1.4255	101	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	ELS	27-d (19 dph)	FT	Survival	LC_{20}	8.7	**6.78**	70	Vardy *et al.* 2011
Cottus bairdi	Mottled sculpin	Swim-up	21-d	FT	Survival	Chronic Value	0.8758	**0.5127**	103	Besser *et al.* 2007
Cottus bairdi	Mottled sculpin	Swim-up	21-d	FT	Biomass	EC_{50}	1.77	1.036	103	Besser *et al.* 2007
Cottus bairdi	Mottled sculpin	Swim-up	28-d	FT	Survival	Chronic Value	1.908	**1.117**	103	Besser *et al.* 2007
Cottus bairdi	Mottled sculpin	Swim-up	21-d	FT	Biomass	Chronic Value	0.8758	0.5127	103	Besser *et al.* 2007
Cottus bairdi	Mottled sculpin	Swim-up	21-d	FT	Survival	LC_{50}	1.73	1.013	103	Besser *et al.* 2007
Cottus bairdi	Mottled sculpin	Swim-up	28-d	FT	Survival	LC_{50}	2.9	1.698	103	Besser *et al.* 2007
Pimephales promelas	Fathead minnow	Larvae (4-6 d old)	7-d	R	Survival	LC_{50}	15.43	4.25	285	Castillo and Longley 2001
Pimephales promelas	Fathead minnow	Larvae (4-6 d old)	7-d	R	Survival	LC_{50}	16.99	4.844	272	Castillo and Longley 2001

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish (cont.)										
Pimephales promelas	Fathead minnow	Larvae (4-6 d old)	7-d	R	Growth	Chronic Value	7.43	**2.01**	292	Castillo and Longley 2001
Pimephales promelas	Fathead minnow	Larvae (4-6 d old)	7-d	R	Survival	Chronic Value	15.65	**4.601**	261	Castillo and Longley 2001
Pimephales promelas	Fathead minnow	Larvae (4-6 d old)	7-d	R	Survival	Chronic Value	14.78	**4.213**	272	Castillo and Longley 2001
Pimephales promelas	Fathead minnow	Larvae (4-6 d old)	7-d	R	Survival	Chronic Value	13.65	**3.761**	285	Castillo and Longley 2001
Pimephales promelas	Fathead minnow	3 week old fry	30-d	FT	Survival	Chronic Value	79.18	27.94	204	Pickering and Gast 1972b
Pimephales promelas	Fathead minnow	average 0.23g at start	35-d	FT	Survival	LC_{50}	150	53.51	201	Pickering and Gast 1972b
Pimephales promelas	Fathead minnow	3 week old fry	30-d	FT	Egg hatchability	Chronic Value	39.23	**13.84**	204	Pickering and Gast 1972b
Pimephales promelas	Fathead minnow	0.23g (average)	9 months	FT	Survival	LC_{50}	68	24.26	201	Pickering and Gast 1972b
Pimephales promelas	Fathead minnow	0.23g (average)	63-d	FT	Survival	LC_{50}	89	31.75	201	Pickering and Gast 1972b
Pimephales promelas	Fathead minnow	ELS	NR	NR	NR	Chronic Value	10	**10.99** [6]	44	Spehar and Fiandt 1986
Pimephales promelas	Fathead minnow	NR	7-d	NR	Survival	Chronic Value	4.899	**10.9**	17	Suedel *et al.* 1997
Pimephales promelas	Fathead minnow	NR	14-d	NR	Survival	Chronic Value	2.449	**5.448**	17	Suedel *et al.* 1997
Pimephales promelas	Fathead minnow	NR	10-d	NR	Survival	Chronic Value	1.414	**3.145**	17	Suedel *et al.* 1997
Pimephales promelas	Fathead minnow	NR	10-d	NR	Survival	LC_{50}	1.6	3.558	17	Suedel *et al.* 1997

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish (cont.)										
Pimephales promelas	Fathead minnow	NR	7-d	NR	Survival	LC_{50}	4.4	9.785	17	Suedel *et al.* 1997
Pimephales promelas	Fathead minnow	NR	14-d	NR	Survival	LC_{50}	2.3	5.115	17	Suedel *et al.* 1997
Fish - Salmonid										
Oncorhynchus kisutch	Coho salmon	ELS	82-d	FT	Biomass	Chronic Value	7.159	**7.74**	45	Eaton *et al.* 1978a
Oncorhynchus mykiss	Rainbow trout	Swim-up	28-d	FT	Survival	LC_{50}	5.5	3.22	103	Besser *et al.* 2007
Oncorhynchus mykiss	Rainbow trout	Swim-up	28-d	FT	Survival	Chronic Value	1.873	**1.097**	103	Besser *et al.* 2007
Oncorhynchus mykiss	Rainbow trout	Swim-up	28-d	FT	Biomass	Chronic Value	1.873	1.097	103	Besser *et al.* 2007
Oncorhynchus mykiss	Steelhead	Swim-up	200-h	FT	Survival	LC_{50}	1.3	2.311	23	Chapman 1978b
Oncorhynchus mykiss	Steelhead	Parr	200-h	FT	Survival	LC_{10}	0.7	1.244	23	Chapman 1978b
Oncorhynchus mykiss	Steelhead	Swim-up	200-h	FT	Survival	LC_{10}	1.0	1.778	23	Chapman 1978b
Oncorhynchus mykiss	Steelhead	Parr	200-h	FT	Survival	LC_{50}	0.9	1.6	23	Chapman 1978b
Oncorhynchus mykiss	Steelhead	Fry	7-d	FT	Survival	LC_{50}	< 0.5	< 1.753	9.2	Cusimano *et al.* 1986b
Oncorhynchus mykiss	Steelhead	Fry	7-d	FT	Survival	LC_{50}	0.7	2.454	9.2	Cusimano *et al.* 1986b
Oncorhynchus mykiss	Steelhead	Fry	7-d	FT	Survival	LC_{50}	6.3	22.08	9.2	Cusimano *et al.* 1986b
Oncorhynchus mykiss	Rainbow trout	45mm length	100-d	FT	Survival	Chronic Value	3.581	**1.179**	224	Davies *et al.* 1993

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid (cont.)										
Oncorhynchus mykiss	Rainbow trout	45mm length	100-d	FT	Survival	Chronic Value	3.642	**0.7498**	422	Davies *et al.* 1993
Oncorhynchus mykiss	Rainbow trout	45mm length	100-d	FT	Survival	Chronic Value	1.475	**1.497**	49	Davies *et al.* 1993
Oncorhynchus mykiss	Rainbow trout	Juvenile (1.4g)	30-d	FT	Survival	Chronic Value	5.477	**2.554**	140	Hollis *et al.* 1999
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	FT	Biomass (dry)	EC_{10}	1.5	0.8596	106	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	21-d	FT	Survival	EC_{20}	12	6.9747	104	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	21-d	FT	Survival	EC_{10}	9.8	5.696	104	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	21-d	FT	Survival	Chronic Value	7.8	**4.5336**	104	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	FT	Survival	EC_{20}	5.3	3.0587	105	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	FT	Survival	EC_{10}	4.7	2.7125	105	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	FT	Survival	Chronic Value	7.5	**4.3284**	105	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	FT	Survival	EC_{20}	3.2	1.8339	106	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	FT	Survival	EC_{10}	2.9	1.6619	106	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	FT	Biomass (dry)	EC_{20}	1.9	1.0889	106	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	FT	Biomass (dry)	Chronic Value	3.6	2.0631	106	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	FT	Biomass (dry)	EC_{20}	5.6	3.2319	105	Ingersoll and Mebane 2013

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid (cont.)										
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	FT	Biomass (dry)	EC_{10}	4.8	2.7702	105	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	FT	Biomass (dry)	Chronic Value	7.5	4.3284	105	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	21-d	FT	Biomass (dry)	EC_{10}	9.2	5.3473	104	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	FT	Survival	Chronic Value	3.6	**2.0631**	106	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	ELS	69-d	FT	Survival	EC_{10}	0.89	1.775	19.7	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	69-d	FT	Weight	MATC	1.9	**3.788**	19.7	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	69-d	FT	Length	EC_{10}	2.6	5.184	19.7	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	69-d	FT	Length	EC_{20}	6.8	13.56	19.7	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	62-d	FT	Survival	MATC	1.6	**2.371**	29.4	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	62-d	FT	Survival	EC_{10}	1.6	2.371	29.4	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	62-d	FT	Survival	EC_{20}	2.2	3.261	29.4	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	53-d	FT	Survival	EC_{10}	0.82	1.635	19.7	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	62-d	FT	Weight	EC_{10}	0.15	0.2223	29.4	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	69-d	FT	Length	MATC	4.4	8.773	19.7	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	69-d	FT	Weight	EC_{10}	1.3	2.592	19.7	Mebane *et al.* 2008

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid (cont.)										
Oncorhynchus mykiss	Rainbow trout	ELS	69-d	FT	Survival	EC_{20}	1.2	2.393	19.7	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	69-d	FT	Weight	EC_{20}	1.8	3.589	19.7	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	53-d	FT	Survival	MATC	0.88	**1.755**	19.7	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	ELS	53-d	FT	Survival	EC_{20}	1.2	2.393	19.7	Mebane *et al.* 2008
Oncorhynchus mykiss	Rainbow trout	Juvenile	7-d	FT	Behavior	Chronic Value	1	**0.5228**	120	Scott *et al.* 2003
Oncorhynchus tshawytscha	Chinook salmon	Parr	200-h	FT	Survival	LC_{50}	2.0	3.555	23	Chapman 1978b
Oncorhynchus tshawytscha	Chinook salmon	Swim-up	200-h	FT	Survival	LC_{50}	1.6	2.844	23	Chapman 1978b
Oncorhynchus tshawytscha	Chinook salmon	Swim-up	200-h	FT	Survival	LC_{10}	1.2	2.133	23	Chapman 1978b
Oncorhynchus tshawytscha	Chinook salmon	Parr	200-h	FT	Survival	LC_{10}	1.3	2.311	23	Chapman 1978b
Oncorhynchus tshawytscha	Chinook salmon	ELS	120-d	NR	Survival	Chronic Value	1.57	**2.593**	25.4	Chapman 1982b
Prosopium williamsoni	Mountain whitefish	Fry	30-d	FT	Survival	Chronic Value	3.227	**3.336**	47.8	Brinkman and Vieira 2008
Prosopium williamsoni	Mountain whitefish	Fry	30-d	FT	Biomass	Chronic Value	3.227	3.336	47.8	Brinkman and Vieira 2008
Prosopium williamsoni	Mountain whitefish	ELS	90-d	FT	Survival	Chronic Value	2.411	2.493	47.8	Brinkman and Vieira 2008
Prosopium williamsoni	Mountain whitefish	ELS	90-d	FT	Biomass	Chronic Value	1.254	**1.297**	47.8	Brinkman and Vieira 2008
Prosopium williamsoni	Mountain whitefish	Fry	30-d	FT	Biomass	IC_{20}	3.02	3.122	47.8	Brinkman and Vieira 2008

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid (cont.)										
Prosopium williamsoni	Mountain whitefish	ELS	90-d	FT	Biomass	IC_{20}	1.29	1.334	47.8	Brinkman and Vieira 2008
Salmo salar	Atlantic salmon	ELS	~47-dph	R	Biomass	Chronic Value	0.5657	0.8692	28	Rombough and Garside 1982b
Salmo salar	Atlantic salmon	ELS	~61-dph	FT	Biomass	Chronic Value	5.657	11.59	19	Rombough and Garside 1982b
Salmo salar	Atlantic salmon	ELS	78-d	FT	Percent hatch	Chronic Value	88.49	181.2	19	Rombough and Garside 1982b
Salmo trutta	Brown trout	Fry	30-d	FT	Weight	Chronic Value	1.95	2.905	29.2	Brinkman and Hansen 2007
Salmo trutta	Brown trout	ELS	55-d	FT	Biomass	IC_{20}	2.22	3.194	30.6	Brinkman and Hansen 2007
Salmo trutta	Brown trout	ELS	55-d	FT	Biomass	IC_{20}	4.01	3.083	71.3	Brinkman and Hansen 2007
Salmo trutta	Brown trout	ELS	55-d	FT	Biomass	IC_{20}	13.6	6.056	149	Brinkman and Hansen 2007
Salmo trutta	Brown trout	Fry	30-d	FT	Biomass	IC_{20}	0.87	1.296	29.2	Brinkman and Hansen 2007
Salmo trutta	Brown trout	Fry	30-d	FT	Biomass	IC_{20}	2.18	1.744	67.6	Brinkman and Hansen 2007
Salmo trutta	Brown trout	Fry	30-d	FT	Biomass	IC_{20}	6.62	2.919	151	Brinkman and Hansen 2007
Salmo trutta	Brown trout	Fry	30-d	FT	Survival	Chronic Value	1.02	**1.519**	29.2	Brinkman and Hansen 2007
Salmo trutta	Brown trout	Fry	30-d	FT	Survival	Chronic Value	6.54	**2.884**	151	Brinkman and Hansen 2007
Salmo trutta	Brown trout	Fry	30-d	FT	Weight	Chronic Value	3.4	2.719	67.6	Brinkman and Hansen 2007
Salmo trutta	Brown trout	ELS	55-d	FT	Survival	Chronic Value	3.52	**5.065**	30.6	Brinkman and Hansen 2007

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid (cont.)										
Salmo trutta	Brown trout	ELS	55-d	FT	Survival	Chronic Value	6.36	**4.89**	71.3	Brinkman and Hansen 2007
Salmo trutta	Brown trout	ELS	55-d	FT	Survival	Chronic Value	13.6	**6.056**	149	Brinkman and Hansen 2007
Salmo trutta	Brown trout	Fry	30-d	FT	Survival	Chronic Value	1.83	**1.464**	67.6	Brinkman and Hansen 2007
Salmo trutta	Brown trout	ELS	NR	NR	NR	Chronic Value	6.668	**7.33** [6]	44	Eaton *et al.* 1978b
Salmo trutta	Brown trout	ELS	31-d	FT	Biomass	Chronic Value	6.437	**6.96**	45	Eaton *et al.* 1978b
Salmo trutta	Brown trout	ELS	83-d	FT	Biomass	Chronic Value	6.668	**7.209**	45	Eaton *et al.* 1978b
Salmo trutta	Brown trout	ELS	63-d	FT	Biomass	Chronic Value	2.017	**2.181**	45	Eaton *et al.* 1978b
Salvelinus confluentus	Bull trout	212mg, 30.5mm	55-d	FT	Growth	Chronic Value	0.5396	**0.7764**	30.6	Hansen *et al.* 2002b
Salvelinus confluentus	Bull trout	212mg, 30.5mm	55-d	FT	Survival	Chronic Value	0.5396	0.7764	30.6	Hansen *et al.* 2002b
Salvelinus fontinalis	Brook trout	ELS	NR	NR	NR	Chronic Value	2.045	**2.248** [6]	44	Eaton *et al.* 1978b
Salvelinus fontinalis	Brook trout	ELS	89-d	FT	Biomass	Chronic Value	2.045	**2.21**	45	Eaton *et al.* 1978b
Salvelinus fontinalis	Brook trout	ELS	55-d	FT	Biomass	Chronic Value	6.668	**7.209**	45	Eaton *et al.* 1978b
Salvelinus fontinalis	Brook trout	ELS	NR	NR	NR	Chronic Value	1.732	**2.165** [6]	37	Sauter *et al.* 1976a
Salvelinus fontinalis	Brook trout	Fry	60-d	FT	Survival	Chronic Value	4.243	**5.303**	37	Sauter *et al.* 1976b
Salvelinus fontinalis	Brook trout	Fry	30-d	FT	Growth	Chronic Value	7.746	**9.682**	37	Sauter *et al.* 1976b

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Fish - Salmonid (cont.)										
Salvelinus fontinalis	Brook trout	Fry	60-d	FT	Growth	Chronic Value	9.165	3.435	188	Sauter *et al.* 1976b
Salvelinus fontinalis	Brook trout	Fry	60-d	FT	Growth	Chronic Value	4.243	5.303	37	Sauter *et al.* 1976b
Salvelinus fontinalis	Brook trout	Fry	30-d	FT	Growth	Chronic Value	15.87	**5.95**	188	Sauter *et al.* 1976b
Salvelinus fontinalis	Brook trout	Fry	60-d	FT	Survival	Chronic Value	9.165	**3.435**	188	Sauter *et al.* 1976b
Salvelinus namaycush	Lake trout	ELS	74-d	FT	Biomass	Chronic Value	7.357	**7.954**	45	Eaton *et al.* 1978b
Invertebrate - ALS insect										
Baetis rhodani	Mayfly	Field-collected	5-d	FT	Survival	LC_{50}	1000	1000	50	Gerhardt 1992
Baetis rhodani	Mayfly	Field-collected	5-d	FT	Survival	LC_{50}	2500	2500	50	Gerhardt 1992
Chironomus riparius	Midge	2nd instar	10-d	R	Survival	LC_{50}	700	380.1	114	Watts and Pascoe 2000
Chironomus tentans	Midge	< 24-h	60-d	FT	Percent hatch	IC_{25}	4.0	1.116	280	Ingersoll and Kemble 2001
Chironomus tentans	Midge	< 24-h	60-d	FT	Biomass	Chronic Value	9.753	**2.721**	280	Ingersoll and Kemble 2001
Chironomus tentans	Midge	< 24-h	60-d	FT	Weight	Chronic Value	9.753	2.721	280	Ingersoll and Kemble 2001
Chironomus tentans	Midge	< 24-h	60-d	FT	Percent hatch	Chronic Value	9.753	2.721	280	Ingersoll and Kemble 2001
Chironomus tentans	Midge	< 24-h	60-d	FT	Percent emergence	Chronic Value	9.753	2.721	280	Ingersoll and Kemble 2001
Chironomus tentans	Midge	< 24-h	60-d	FT	Biomass	IC_{25}	10.3	2.874	280	Ingersoll and Kemble 2001

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - ALS insect (cont.)										
Chironomus tentans	Midge	< 24-h	60-d	FT	Percent emergence	IC_{25}	8.1	2.26	280	Ingersoll and Kemble 2001
Chironomus tentans	Midge	< 24-h	60-d	FT	Weight	IC_{25}	9.9	2.763	280	Ingersoll and Kemble 2001
Chironomus tentans	Midge	NR	14-d	NR	Survival	LC_{50}	635	1412	17	Suedel *et al.* 1997
Chironomus tentans	Midge	NR	10-d	NR	Survival	LC_{50}	963	2142	17	Suedel *et al.* 1997
Chironomus tentans	Midge	NR	7-d	NR	Survival	Chronic Value	707.1	1573	17	Suedel *et al.* 1997
Chironomus tentans	Midge	NR	14-d	NR	Survival	Chronic Value	707.1	1573	17	Suedel *et al.* 1997
Chironomus tentans	Midge	NR	10-d	NR	Survival	Chronic Value	707.1	1573	17	Suedel *et al.* 1997
Chironomus tentans	Midge	NR	7-d	NR	Survival	LC_{50}	1700	3781	17	Suedel *et al.* 1997
Chironomus tentans	Midge	2^{nd} instar	10-d	R	Survival	LC_{50}	740	401.8	114	Watts and Pascoe 2000
Leptophlebia marginata	Mayfly	Field-collected	5-d	FT	Survival	LC_{50}	3600	3600	50	Gerhardt 1992
Leptophlebia marginata	Mayfly	Field-collected	5-d	FT	Survival	LC_{50}	4400	4400	50	Gerhardt 1992
Rhithrogena hageni	Mayfly	Nymphs	10-d	FT	Moulting	Chronic Value	2572	2651	48	Brinkman and Johnston 2008
Rhithrogena hageni	Mayfly	Nymphs	10-d	FT	Survival	Chronic Value	2572	**2651**	48	Brinkman and Johnston 2008

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Amphipod										
Gammarus pulex	Amphipod	Field-collected	11-d	FT	Survival	LC_{50}	10.5	3.188	249.9	Felten *et al.* 2008
Gammarus pulex	Amphipod	Field-collected	7-d	FT	Feeding rate	Chronic Value	10.61	3.22	249.9	Felten *et al.* 2008
Gammarus pulex	Amphipod	Field-collected	7-d	FT	Survival	Chronic Value	10.61	**3.22**	249.9	Felten *et al.* 2008
Gammarus pulex	Amphipod	Field-collected	5-d	FT	Survival	LC_{50}	37.1	11.26	249.9	Felten *et al.* 2008
Gammarus pulex	Amphipod	Field-collected	7-d	FT	Survival	LC_{50}	21.6	6.557	249.9	Felten *et al.* 2008
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Survival	IC_{20}	0.52	0.2622	126	Chadwick Ecological Consultants, Inc. 2004
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Biomass	IC_{20}	0.76	0.3319	153	Chadwick Ecological Consultants, Inc. 2004
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Biomass	Chronic Value	1.69	0.7379	153	Chadwick Ecological Consultants, Inc. 2004
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Survival	IC_{20}	0.91	0.3973	153	Chadwick Ecological Consultants, Inc. 2004
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Biomass	IC_{20}	0.5	0.2521	126	Chadwick Ecological Consultants, Inc. 2004
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Survival	Chronic Value	0.74	**0.3731**	126	Chadwick Ecological Consultants, Inc. 2004
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Survival	Chronic Value	1.02	**0.4454**	153	Chadwick Ecological Consultants, Inc. 2004
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Biomass	Chronic Value	2.466	0.688	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Biomass	IC_{25}	0.51	0.1423	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	42-d	FT	Survival	IC_{25}	1.9	0.5302	280	Ingersoll and Kemble 2001

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Amphipod (cont.)										
Hyalella azteca	Amphipod	7-8 d old	42-d	FT	Weight	IC_{25}	2.8	0.7813	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	42-d	FT	Biomass	IC_{25}	1.9	0.5302	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	10-d	FT	Survival	IC_{25}	2.7	0.7534	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	10-d	FT	Biomass	IC_{25}	2.4	0.6697	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	35-d	FT	Survival	IC_{25}	2.0	0.5581	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	10-d	FT	Length	Chronic Value	2.466	0.688	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Survival	IC_{25}	2.1	0.586	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	Day 28 - 42	FT	Reproduction	IC_{25}	1.4	0.3907	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	10-d	FT	Survival	Chronic Value	2.466	0.688	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Length	Chronic Value	2.466	0.688	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Weight	Chronic Value	2.466	0.688	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	35-d	FT	Survival	Chronic Value	2.466	0.688	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	Day 28 - 42	FT	Reproduction	Chronic Value	2.466	0.688	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Length	IC_{25}	2.6	0.7255	280	Ingersoll and Kemble 2001
Hyalella azteca	Amphipod	7-8 d old	28-d	FT	Weight	IC_{25}	0.74	0.2065	280	Ingersoll and Kemble 2001

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Amphipod (cont.)										
Hyalella azteca	Amphipod	NR	14-d	NR	Survival	Chronic Value	0.1581	**0.3516**	17	Suedel *et al.* 1997
Hyalella azteca	Amphipod	NR	14-d	NR	Survival	LC_{50}	0.65	1.446	17	Suedel *et al.* 1997
Invertebrate - Cladoceran										
Ceriodaphnia dubia	Water flea	NR	7-d	NR	Survival	LC_{50}	11.6	25.8	17	Suedel *et al.* 1997
Ceriodaphnia dubia	Water flea	NR	10-d	NR	Survival	LC_{50}	10.6	23.57	17	Suedel *et al.* 1997
Ceriodaphnia dubia	Water flea	NR	14-d	NR	Survival	LC_{50}	10.1	22.46	17	Suedel *et al.* 1997
Ceriodaphnia dubia	Water flea	NR	7-d	NR	Survival	Chronic Value	11.4	25.36	17	Suedel *et al.* 1997
Ceriodaphnia dubia	Water flea	NR	14-d	NR	Survival	Chronic Value	11.4	25.36	17	Suedel *et al.* 1997
Ceriodaphnia dubia	Water flea	NR	7-d	NR	Reproduction	Chronic Value	2	**4.448**	17	Suedel *et al.* 1997
Ceriodaphnia dubia	Water flea	NR	14-d	NR	Reproduction	Chronic Value	2	**4.448**	17	Suedel *et al.* 1997
Ceriodaphnia dubia	Water flea	NR	10-d	NR	Survival	Chronic Value	11.4	25.36	17	Suedel *et al.* 1997
Ceriodaphnia dubia	Water flea	NR	10-d	NR	Reproduction	Chronic Value	2	**4.448**	17	Suedel *et al.* 1997
Ceriodaphnia reticulata	Water flea	< 24-h	7-d	R	Reproduction	MATC	13.7	**4.285**	240	Elnabarawy *et al.* 1986b
Ceriodaphnia reticulata	Water flea	< 24-h	7-d	R	Reproduction	EC_{16}	0.2	0.0626	240	Elnabarawy *et al.* 1986b
Daphnia magna	Water flea	< 24-h	21-d	R	Reproduction	IC_{20}	2.07	2.04	51	Chadwick Ecological Consultants, Inc. 2004

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Cladoceran (cont.)										
Daphnia magna	Water flea	< 24-h	21-d	R	Reproduction	Chronic Value	2.39	**1.441**	99	Chadwick Ecological Consultants, Inc. 2004
Daphnia magna	Water flea	< 24-h	21-d	R	Reproduction	Chronic Value	2.6	**2.562**	51	Chadwick Ecological Consultants, Inc. 2004
Daphnia magna	Water flea	< 24-h	21-d	R	Survival	Chronic Value	4.85	2.924	99	Chadwick Ecological Consultants, Inc. 2004
Daphnia magna	Water flea	< 24-h	21-d	R	Reproduction	IC_{20}	2.23	1.344	99	Chadwick Ecological Consultants, Inc. 2004
Daphnia magna	Water flea	< 24-h	21-d	R	Survival	IC_{20}	2.29	1.381	99	Chadwick Ecological Consultants, Inc. 2004
Daphnia magna	Water flea	< 24-h	14-d	R	Reproduction	EC_{16}	0.5	0.1564	240	Elnabarawy *et al.* 1986b
Daphnia magna	Water flea	< 24-h	14-d	R	Reproduction	EC_{50}	3.5	1.095	240	Elnabarawy *et al.* 1986b
Daphnia magna	Water flea	< 24-h	14-d	R	Reproduction	MATC	4.33	**1.354**	240	Elnabarawy *et al.* 1986b
Daphnia magna	Water flea	NR	10-d	NR	Survival	LC_{50}	9.0	6.474	78	Suedel *et al.* 1997
Daphnia magna	Water flea	NR	7-d	NR	Survival	Chronic Value	7.071	**5.086**	78	Suedel *et al.* 1997
Daphnia magna	Water flea	NR	14-d	NR	Survival	Chronic Value	7.071	**5.086**	78	Suedel *et al.* 1997
Daphnia magna	Water flea	NR	10-d	NR	Survival	Chronic Value	7.071	**5.086**	78	Suedel *et al.* 1997
Daphnia magna	Water flea	NR	14-d	NR	Survival	LC_{50}	8.6	6.186	78	Suedel *et al.* 1997
Daphnia magna	Water flea	NR	7-d	NR	Survival	LC_{50}	9.9	7.121	78	Suedel *et al.* 1997
Daphnia pulex	Water flea	< 24-h	14-d	R	Reproduction	MATC	13.7	**4.285**	240	Elnabarawy *et al.* 1986b

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Cladoceran (cont.)										
Daphnia pulex	Water flea	< 24-h	14-d	R	Reproduction	EC_{16}	0.2	0.0626	240	Elnabarawy *et al.* 1986b
Daphnia pulex	Water flea	< 24-h	60-d	R	Survival	Chronic Value	7.071	**4.052**	106	Ingersoll and Winner 1982
Invertebrate - Decapod										
Orconectes virilis	Crayfish	Intermolt (adult)	10-d	FT	Survival	LC_{50}	1000	1623	26	Mirenda 1986b
Orconectes virilis	Crayfish	Intermolt (adult)	7-d	FT	Survival	LC_{50}	1800	2922	26	Mirenda 1986b
Orconectes virilis	Crayfish	Intermolt (adult)	14-d	FT	Survival	LC_{50}	700	1136	26	Mirenda 1986b
Invertebrate - Hydra										
Hydra viridissima	Hydra (green)	Budding hydra	7-d	R	Population growth	Chronic Value	0.5657	**1.136**	19.5	Holdway *et al.* 2001
Invertebrate - Mussel										
Lampsilis siliquoidea	Fatmucket	Juvenile (2 mo)	28-d	FT	Survival	Chronic Value	6.0	**6.282**	47	Wang *et al.* 2010
Lampsilis siliquoidea	Fatmucket	Juvenile (2 mo)	28-d	FT	Growth (length)	Chronic Value	6.0	6.282	47	Wang *et al.* 2010
Lampsilis siliquoidea	Fatmucket	Juvenile (2 mo)	28-d	FT	Survival	IC_{10}	4.8	5.025	47	Wang *et al.* 2010
Lampsilis siliquoidea	Fatmucket	Juvenile (2 mo)	28-d	FT	Growth (length)	IC_{10}	4.6	4.816	47	Wang *et al.* 2010
Lampsilis siliquoidea	Fatmucket	Juvenile (2 mo)	28-d	FT	Survival	IC_{20}	5.7	5.967	47	Wang *et al.* 2010
Lampsilis siliquoidea	Fatmucket	Juvenile (2 mo)	28-d	FT	Growth (length)	IC_{20}	5.0	5.235	47	Wang *et al.* 2010

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		
Invertebrate - Mussel (cont.)										
Lampsilis siliquoidea	Fatmucket	Juvenile (2 mo)	21-d	FT	Survival	LC_{50}	12	12.56	47	Wang *et al.* 2010
Lampsilis siliquoidea	Fatmucket	Juvenile (2 mo)	28-d	FT	Survival	LC_{50}	8.1	8.48	47	Wang *et al.* 2010
Lampsilis ventricosa	Mussel	Juvenile (0-d old)	7-d	R	Survival	LC_{50}	38	17.27	145	Lasee 1991
Lampsilis ventricosa	Mussel	Juvenile (0-d old)	7-d	R	Percent growth	Chronic Value	17.32	7.87	145	Lasee 1991
Lampsilis ventricosa	Mussel	Juvenile (0-d old)	7-d	R	Length	Chronic Value	17.32	**7.87**	145	Lasee 1991
Lampsilis ventricosa	Mussel	Juvenile (0-d old)	7-d	R	Height	Chronic Value	38.73	17.6	145	Lasee 1991
Lampsilis ventricosa	Mussel	Glochidia	7-d	R	Length	Chronic Value	38.73	17.6	145	Lasee 1991
Lampsilis ventricosa	Mussel	Glochidia	7-d	R	Height	Chronic Value	38.73	**17.6**	145	Lasee 1991
Lampsilis ventricosa	Mussel	Juvenile (0-d old)	7-d	R	Dead and stressed	EC_{50}	24	10.9	145	Lasee 1991
Lampsilis ventricosa	Mussel	Juvenile (0-d old)	7-d	R	Posterior shell length	Chronic Value	38.73	17.6	145	Lasee 1991

ALS = aquatic life stage; AWQC = ambient water quality criteria; d = day; dph = days post-hatch; EC = effective concentration; ELS = early life stage; FT = flow-through; h = hour; IC = inhibition concentration; LC = lethal concentration; MATC = maximum acceptable toxicant concentration; mo = month; NR = not reported; R = renewal; SMCV = species mean chronic value; USEPA = United States Environmental Protection Agency.

[1] Effect values normalized to a hardness of 50 mg/L using the pooled slope provided by USEPA (2001).

[2] Data from USEPA (2001) used in the calculation of SMCVs for the AWQC for cadmium. Values were used in the recalculation of SMCVs for this report except where noted.

[3] Life cycle or partial life cycle test.

[4] This value was not used in the recalculation of SMCVs because it is a "less than" value and there are measured values for this species.

Footnotes continued on next page…

Table A2.2. Summary of compiled chronic aquatic toxicity data for cadmium.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Test Type	Endpoint	Effect Level	Effect Concentration (µg/L)		Hardness	Reference
							Original Effect	Normalized Effect [1]		

[5] Additional data not used in the derivation of the aquatic life ambient water quality criteria for cadmium (USEPA 2001). Bolded values were used in the recalculation of the SMCV.

[6] Data from USEPA (2001). This value was excluded from the SMCV calculation in USEPA (2001) because values were preferentially selected from life cycle tests. This value was included in the recalculation of SMCVs in this document.

List of References

Andros, J.D. and R.R. Garton. 1980. Acute lethality of copper, cadmium, and zinc to northern squawfish. Transactions of the American Fisheries Society 109: 235-238. (As cited in USEPA 2001).

Attar, E.N. and E.J. Maly. 1982. Acute toxicity of cadmium, zinc, and cadmium-zinc mixtures to *Daphnia magna.* Archives of Environmental Contamination and Toxicology 11: 291-296. (As cited in USEPA 2001).

Baird, D.J., I. Barber, M. Bradley, A.M.V.M. Soares and P. Calow. 1991. A comparative study of genotype sensitivity to acute toxic stress using clones of *Daphnia magna* Straus. Ecotoxicological and Environmental Safety 21: 257-265. (As cited in USEPA 2001).

Barata, C., D.J. Baird and S.J. Markich. 1998. Influence of genetic and environmental factors on the tolerance of *Daphnia magna* Straus to essential and non-essential metals. Aquatic toxicology 42: 115-137. (As cited in USEPA 2001). (As cited in USEPA 2001).

Benoit, D.A., E.N. Leonard, G.M. Christensen and J.T. Fiandt. 1976. Toxic effects of cadmium on three generations of brook trout (*Salvelinus fontinalis*). Transactions of the American Fisheries Society 105:550-560.

Bertram, P.E. and B.A. Hart. 1979. Longevity and reproduction of *Daphnia pulex* (deGeer) exposed to cadmium-contaminated food or water. Environmental Pollution 19: 295-305. (As cited in USEPA 2001).

Besser, J.M., C.A. Mebane, D.R. Mount, C.D. Ivey, J.L. Kunz, I.E. Greer, T.W. May and C.G. Ingersoll. 2007. Sensitivity of mottled sculpins (*Cottus bairdi*) and rainbow trout (*Oncorhynchus mykiss*) to acute and chronic toxicity of cadmium, copper, and zinc. Environmental Toxicology and Chemistry 26:1657-1665.

Biesinger, K.E. and G.M. Christensen. 1972. Effects of various metals on survival, growth, reproduction, and metabolism of *Daphnia magna.* Journal of the Fisheries Research Board of Canada 29: 1691-1700. (As cited in USEPA 2001).

Bitton, G., K. Rhodes and B. Koopman. 1996. Ceriofast™: an acute toxicity test based on *Ceriodaphnia dubia* feeding behavior. Environmental Toxicology and Chemistry 15(2): 123-125. (As cited in USEPA 2001).

Black, M.C. 2001. Water quality standards for North Carolina's endangered mussels. Final Report. Department of Health Science, University of Georgia, Athens, GA.

Bodar, C.W.M., C.J. Van Leeuwen, P.A. Voogt and D.L Zandee. 1988. Effect of cadmium on the reproduction strategy of *Daphnia magna.* Aquatic Toxicology 12: 301-310. (As cited in USEPA 2001).

Borgmann, U., K.M. Ralph and W.P. Norwood. 1989. Toxicity test procedures for *Hyalella azteca*, and chronic toxicity of cadmium and pentachlorophenol to *H. azteca*, *Gammarus fasciatus*, and *Daphnia magna*. Archives of Environmental Contamination and Toxicology 18: 756-764. (As cited in USEPA 2001).

Bosnak, A.D. and E.L. Morgan. 1981. Acute toxicity of cadmium, zinc, and total residual chlorine to epigean and hypogean isopods (Asellidae). National Speleological Society Bulletin 43: 12-18. (As cited in USEPA 2001).

Brinkman, S.F. and D.L. Hansen. 2007. Toxicity of cadmium to early life stages of brown trout (*Salmo trutta*) at multiple water hardnesses. Environmental Toxicology and Chemistry 26:1666-1671.

Brinkman, S.F. and W.D. Johnston. 2008. Acute toxicity of aqueous copper, cadmium and zinc to the mayfly *Rhithrogena hageni*. Archives of Environmental Contamination and Toxicology 54:466-472.

Brinkman, S. and N. Vieira. 2008. Water pollution studies: federal aid project F-243-R15. 38 pp.

Brown, A.F. and D. Pascoe. 1988. Studies on the acute toxicity of pollutants to freshwater macroinvertebrates: V. The acute toxicity of cadmium to twelve species of predatory macroinvertebrates. Archiv für Hydrobiologie 114(2): 311-319. (As cited in USEPA 2001).

Brown, V., D. Shurben, W. Miller and M. Crane. 1994. Cadmium toxicity to rainbow trout *Oncorhynchus mykiss* Walbaum and brown trout *Salmo trutta* L. over extended exposure periods. Ecotoxicology and Environmental Safety 29: 38-46. (As cited in USEPA 2001).

Buhl, K.J. 1997. Relative sensitivity of three endangered fishes, Colorado squawfish, bonytail, and razorback sucker, to selected metal pollutants. Ecotoxicology and Environmental Safety 37: 186-192. (As cited in USEPA 2001).

Canton, J.H. and W. Slooff. 1982. Toxicity and accumulation studies of cadmium (Cd^{2+}) with freshwater organisms of different trophic levels. Ecotoxicology and Environmental Safety 6: 113-128. (As cited in USEPA 2001).

Carlson, A.R., J.A. Tucker, V.R. Mattson, G.L. Phipps, P.M. Cook, G.F. Olson and F.A.. Puglisi. 1982. Cadmium and endrin toxicity to fish in waters containing mineral fibers. EPA-600/3-82-053. National Technical Information Service, Springfield, Virginia. (As cited in USEPA 2001).

Carrier, R. and T.L. Beitinger. 1988. Reduction in thermal tolerance of *Notropis lutrensis* and *Pimephales promelas* exposed to cadmium. Water Research 22(4): 511-515. (As cited in USEPA 2001).

Carroll, J.J., S.J. Ellis and W.S. Oliver. 1979. Influences of hardness constituents on the acute toxicity of cadmium to brook trout (*Salvelinus fontinalis*). Bulletin of Environmental Contamination and Toxicology 22:575-581. (As cited in USEPA 2001).

Castillo, V., III and G. Longley. 2001. Comparison of EPA target toxicity aquatic test organisms to the fountain darter: 7 day chronic toxicity test using cadmium chloride, performed 11/12/99-3/6/00 (5 parts). Federal Assistance Agreement No. X-986345-01.

Chadwick Ecological Consultants Inc. 2004. Chronic toxicity of cadmium to freshwater crustaceans at different water hardness concentrations. Chadwick Ecological Consultants, Incorporated 1-64.

Chapman, G.A. 1975. Toxicity of copper, cadmium and zinc to Pacific Northwest salmonids. U.S. Environmental Protection Agency, Corvallis, Oregon. (As cited in USEPA 2001). (As cited in USEPA 2001).

Chapman, G.A. 1978a. Toxicities of cadmium, copper, and zinc to four juvenile stages of chinook salmon and steelhead. Transactions of the American Fisheries Society 107:841-847. (As cited in USEPA 2001).

Chapman, G.A. 1978b. Toxicities of cadmium, copper, and zinc to four juvenile stages of chinook salmon and steelhead. Transactions of the American Fisheries Society 107:841-847.

Chapman, G.A. 1982a. Chinook salmon early life stage tests with cadmium, copper, and zinc. Letter of December 6, 1982 to Charles Stephan, U.S. Environmental Protection Agency Environmental Research Laboratory, Duluth, Corvallis, Oregon. 4 pp. (As cited in USEPA 2001).

Chapman, G.A. 1982b. Chinook salmon early life stage tests with cadmium, copper, and zinc. Letter of December 6, 1982 to Charles Stephan, U.S. Environmental Protection Agency Environmental Research Laboratory, Duluth, Corvallis, Oregon. 4 pp.

Chapman, P.M., M.A. Farrel and R.O. Brinkhurst. 1982. Relative tolerances of selected aquatic oligochaetes to individual pollutants and environmental factors. Aquatic Toxicology 2: 47-67. (As cited in USEPA 2001).

Chapman, G.A., S. Ota and F. Recht. Manuscript. Effects of water hardness on the toxicity of metals to *Daphnia magna.* U.S. Environmental Protection Agency, Corvallis, Oregon. (As cited in USEPA 2001).

Crisinel, A., L. Delaunay, D. Rossel, J. Tarradellas, H. Meyer, H. Saiah, P. Vogel, C. Delisle and C. Blaise. 1994. Cyst-based ecotoxicological tests using anostracans: comparison of two species of *Streptocephalus*. Environmental Toxicology and Water Quality 9(4): 317-326. (As cited in USEPA 2001).

Cusimano, R.F., D.F. Brakke and G.A. Chapman. 1986a. Effects of pH on the toxicities of cadmium, copper, and zinc to steelhead trout (*Salmo gairdneri*). Canadian Journal of Fisheries and Aquatic Sciences 43:1497-1503. (As cited in USEPA 2001.)

Cusimano, R.F., D.F. Brakke and G.A. Chapman. 1986b. Effects of pH on the toxicities of cadmium, copper, and zinc to steelhead trout (*Salmo gairdneri*). Canadian Journal of Fisheries and Aquatic Sciences 43:1497-1503.

Davies, P.H. 1976. Use of dialysis tubing in defining the toxic fractions of heavy metals in natural water. In: R.W. Andrew, *et al.* (eds.), Toxicity to Biota of Metal Forms in Natural Water. International Joint Commission, Windsor, Ontario. p. 110. (As cited in USEPA 2001).

Davies, P.H., W.C. Gorman, C.A. Carlson and S.F. Brinkman. 1993. Effect of hardness on bioavailablity and toxicity of cadmium to rainbow trout. Chemical Speciation and Bioavailability 5(2):67-77.

Diamond, J.M., D.E. Koplish, J. McMahon III and R. Rost. 1997. Evaluation of the water-effect ratio procedure for metals in a riverine system. Environmental Toxicology and Chemistry 16(3):509-520. (As cited in USEPA 2001).

Duncan, D.A. and J.F. Kiaverkamp. 1983. Tolerance and resistance to cadmium in white suckers (*Catostomus commersoni*) previously exposed to cadmium, mercury, zinc, or selenium. Canadian Journal of Fisheries and Aquatic Sciences 40:128-138. (As cited in USEPA 2001).

Eaton, J.G. 1974. Chronic cadmium toxicity to the bluegill (*Lepomis macrochirus* Rafinesque). Transactions of the American Fisheries Society 4: 729-735. (As cited in USEPA 2001).

Eaton, J.G. 1980. Memorandum to C.E. Stephan. U.S. Environmental Protection Agency, Duluth, Minnesota. August 5. (As cited in USEPA 2001).

Eaton, J. G., J. M. McKim and G. W. Holcombe. 1978a. Metal toxicity to embryos and larvae of seven freshwater fish species - I. Cadmium. Bulletin of Environmental Contamination and Toxicology 19:95-103. (As cited in USEPA 2001).

Eaton, J. G., J. M. McKim and G. W. Holcombe. 1978b. Metal toxicity to embryos and larvae of seven freshwater fish species - I. Cadmium. Bulletin of Environmental Contamination and Toxicology 19:95-103.

Elnabarawy, M.T., A.N. Welter and R.R. Robideau. 1986a. Relative sensitivity of three daphnid species to selected organic and inorganic chemicals. Environmental Toxicology and Chemistry 5(393):393-398. (As cited in USEPA 2001).

Elnabarawy, M.T., A.N. Welter and R.R. Robideau. 1986b. Relative sensitivity of three daphnid species to selected organic and inorganic chemicals. Environmental Toxicology and Chemistry 5(393):393-398.

Felten, V., G. Charmantier, R. Mons, A. Geffard, P. Rousselle, and M. Coquery. 2008. Physiological and behavioural responses of *Gammarus pulex* (Crustacea Amphipoda) exposed to cadmium. Aquatic Toxicology 86:413-425.

Finlayson, B.J. and K.M. Verrue. 1982. Toxicities of copper, zinc and cadmium mixtures to juvenile chinook salmon. Transactions of the American Fisheries Society 111: 645-650. (As cited in USEPA 2001).

Gaikwad, S.A. 1989. Effects of mixture and three individual heavy metals on susceptibility of three freshwater fishes. Pollution Research 8(1): 33-35. (As cited in USEPA 2001).

Gerhardt, A. 1992. Acute toxicity of Cd in stream invertebrates in relation to pH and test design. Hydrobiologia 239:93-100.

Ghosh, T.K., J.P. Kotangale and K.P. Krishnamoorthi. 1990. Toxicity of selective metals to freshwater algae, ciliated protozoa and planktonic crustaceans. Environment and Ecology 8(1):356-360. (As cited in USEPA 2001).

Giesy, J.P. Jr., G.J. Leversee and D.R. Williams. 1977. Effects of naturally occurring aquatic organic fractions on cadmium toxicity to *Simocephalus serrulatus* (Daphnidae) and *Gambusia affinis* (poeciliidae). Water Research 11: 1013-1020. (As cited in USEPA 2001).

Guilhermino, L., M.C. Lopes, A.P. Carvalho and A.M.V.M. Soares. 1996. Inhibition of acetylcholinesterase activity as effect criterion in acute tests with juvenile *Daphnia magna.* Chemosphere 32(4): 727-738. (As cited in USEPA 2001).

Hall, W.S., R.L. Paulson, L.W. Hall, Jr. and D.T. Burton. 1986. Acute toxicity of cadmium and sodium pentachlorophenate to daphnids and fish. Bulletin of Environmental Contamination and Toxicology 37: 308-316. (As cited in USEPA 2001).

Ham, L., R. Quinn and D. Pascoe. 1995. Effects of cadmium on the predator-prey interaction between the Turbellarian *Dendrocoelum lacteum* (Muller, 1774) and the isopod crustacean *Asellus aquaticus* (L.). Archives of Environmental Contamination and Toxicology 29: 358-365. (As cited in USEPA 2001).

Hansen, J. A., P.G. Welsh, J. Lipton, D. Cacela and A.D. Dailey. 2002a. Relative sensitivity of bull trout (*Salvelinus confluentus*) and rainbow trout (*Oncorhynchus mykiss*) to acute exposures of cadmium and zinc. Environmental Toxicology and Chemistry 21:67-75.

Hansen, J.A., P.G. Welsh, J. Lipton, and M.J. Suedkamp. 2002b. The effects of long-term cadmium exposure on the growth and survival of juvenile bull trout (*Salvelinus confluentus*). Aquatic Toxicology 58:165-174.

Hatakeyama, S. and M. Yasuno. 1981. Effects of cadmium on the periodicity of parturation and brood size of *Moina macrocopa* (Cladocera). Environmental Pollution (Series A) 26: 111-120. (As cited in USEPA 2001).

Holcombe, G.W., G.L. Phipps and J.W. Marier. 1984. Methods for conducting snail (*Aplexa hypnorum*) embryo through adult exposures: effects of cadmium and reduced pH levels. Archives of Environmental Contamination and Toxicology 13: 627-634. (As cited in USEPA 2001).

Holdway, D.A., K. Lok and M. Semaan. 2001. The acute and chronic toxicity of cadmium and zinc to two Hydra species. Environmental Toxicology 16:557-565.

Hollis, L., J.C. McGeer, D.G. McDonald and C.M. Wood. 1999. Cadmium accumulation, gill Cd binding, acclimation, and physiological effects during long-term sublethal Cd exposure in rainbow trout. Aquatic Toxicology 46:101-119.

Ingersoll, C. and N. Kemble. 2001. Revised description of toxicity data on cadmium: Chronic water-only exposures with the amphipod *Hyalella azteca* and the midge *Chironomus tentans*. Memo from United States Department of the Interior, U.S. Geological Survey, to Cindy Roberts, U.S. Environmental Protection Agency, Health and Ecological Criteria Division. 11 January 2001.

Ingersoll, C.G. and N. Kemble. Unpublished. Methods development for long-term sediment toxicity tests with the amphipod *Hyalella azteca* and the midge *Chironomus tentans.* (As cited in USEPA 2001).

Ingersoll, C.G. and C.A. Mebane (Eds.). 2013. Draft. Acute and chronic sensitivity of white sturgeon (*Acipenser transmontanus*) and rainbow trout (*Oncorhynchus mykiss*) to cadmium, copper, lead, or zinc in water-only laboratory exposures. U.S. Geological Survey. Columbia Environmental Research Center. Columbia, Missouri.

Ingersoll, C.G. and R.W. Winner. 1982. Effect on *Daphnia pulex* (de Geer) of daily pulse exposures to copper and cadmium. Environmental Toxicology and Chemistry 1:321-327.

Jop, K.M., A.M. Askew and R.B. Foster. 1995. Development of a water-effect ratio for copper, cadmium, and lead for the Great Works River in Maine using *Ceriodaphnia dubia* and *Salvelinus fontinalis.* Bulletin of Environmental Contamination and Toxicology 54: 29-33. (As cited in USEPA 2001).

Jude, D.J. 1973. Sublethal effects of ammonia and cadmium on growth of green sunfish. Ph.D. Thesis. Michigan State University. (As cited in USEPA 2001).

Keller, A.E. Unpublished. Personal communication to U.S. Environmental Protection Agency. (As cited in USEPA 2001).

Keller, A.E. and S.G. Zam. 1991. The acute toxicity of selected metals to the freshwater mussel, *Anodonta imbecilis.* Environmental Toxicology and Chemistry 10: 539-546. (As cited in USEPA 2001).

Lasee, B.A. 1991. Histological and ultrastructural studies of larval and juvenile *Lampsilis* (Bivalva) from the Upper Mississippi River. PhD Dissertation. 145 pp.

Lee, S. III, E.J. Na, Y.O. Cho, B. Koopman, and G. Bitton. 1997. Short-term toxicity test based on algal uptake by *Ceriodaphnia dubia.* Water Environmental Research 69(7): 1207-1210. (As cited in USEPA 2001).

Martin, T.R. and D.M. Holdich. 1986. The acute lethal toxicity of heavy metals to peracarid crustaceans (with particular reference to fresh-water asellids and gammarids). Water Research 20(9): 1137-1147. (As cited in USEPA 2001).

McCahon, C.P. and D. Pascoe. 1988. Increased sensitivity to cadmium of the freshwater amphipod *Gammarus pulex* (L.) during the reproductive period. Aquatic Toxicology 13:183-194.

Mebane, C.A., D.P. Hennessy, and F.S. Dillon. 2008. Developing acute-to-chronic toxicity ratios for lead, cadmium, and zinc using rainbow trout, a mayfly, and a midge. Water, Air, and Soil Pollution 188:41-66.

Mebane, C.A., F.S. Dillon and D.O. Hennessy. 2012. Acute toxicity of cadmium, lead, zinc, and their mixtures to stream-resident fish and invertebrates. Environmental Toxicology and Chemistry 31:1334-1348.

Mirenda, R.J. 1986a. Toxicity and accumulation of cadmium in the crayfish, *Orconectes virilis* (Hagen). Archives of Environmental Contamination and Toxicology 15:401-407. (As cited in USEPA 2001).

Mirenda, R.J. 1986b. Toxicity and accumulation of cadmium in the crayfish, *Orconectes virilis* (Hagen). Archives of Environmental Contamination and Toxicology 15:401-407.

Naqvi, S.M. and R.D. Howell. 1993. Toxicity of cadmium and lead to juvenile red swamp crayfish, *Procambarus clarkii*, and effects on fecundity of adults. Bulletin of Environmental Contamination and Toxicology 51: 303-308. (As cited in USEPA 2001).

Nebeker, A.V., G.S. Schuytema and S.L. Ott. 1995a. Effects of cadmium on growth and bioaccumulation in the Northwestern salamander *Ambystoma gracile*. Archives of Environmental Contamination and Toxicology 29:492-499. (As cited in USEPA 2001).

Nebeker, A.V., G.S. Schuytema and S.L. Ott. 1995b. Effects of cadmium on growth and bioaccumulation in the Northwestern salamander *Ambystoma gracile*. Archives of Environmental Contamination and Toxicology 29:492-499.

Niederlehner, B. 1984. A comparison of techniques for estimating the hazard of chemicals in the aquatic environment. M.S. thesis. Virginia Polytechnic Institute and State University. (As cited in USEPA 2001).

Palawski, D., J.B. Hunn and F.J. Dwyer. 1985. Sensitivity of young striped bass to organic and inorganic contaminants in fresh and saline water. Transactions of the American Fisheries Society 114: 748-753. (As cited in USEPA 2001).

Papoutsoglou, S.E. and P.D. Abel. 1988. Sublethal toxicity and accumulation of cadmium in *Tilapia aurea.* Bulletin of Environmental Contamination and Toxicology 41: 404-411. (As cited in USEPA 2001).

Pardue, W.J. and T.S. Wood. 1980. Baseline toxicity data for freshwater bryozoa exposed to copper, cadmium, chromium, and zinc. Journal of the Tennessee Academy of Science 55: 27-31. (As cited in USEPA 2001).

Pascoe, D. and P. Cram. 1977. The effect of parasitism on the toxicity of cadmium to the three-spined stickleback, *Gasterosteus aculeatus* L. Journal of Fisheries Biology 10: 467-472. (As cited in USEPA 2001).

Pascoe, D. and D.L. Mattey. 1977. Studies on the toxicity of cadmium to the three-spined stickleback *Gasterosteus aculeatus* L. Journal of Fisheries Biology 11: 207-215. (As cited in USEPA 2001).

Pascoe, D., A.F. Brown, B.M.J. Evans and C. McKavanagh. 1990. Effects and fate of cadmium during toxicity tests with Chironomus riparius - the influence of food and artificial sediment. Archives of Environmental Contamination and Toxicology 19: 872-877. (As cited in USEPA 2001).

Phipps, G.L. and G.W. Holcombe. 1985. A method for aquatic multiple species toxicant testing: acute toxicity of 10 chemicals to 5 vertebrates and 2 invertebrates. Environmental Pollution (Series A) 38: 141-157. (As cited in USEPA 2001).

Pickering, Q.H. and M.H. Gast. 1972a. Acute and chronic toxicity of cadmium to fathead minnow (*Pimephales promelas*). Journal of the Fisheries Research Board of Canada 29(8):1099-1106. (As cited in USEPA 2001).

Pickering, Q.H. and M.H. Gast. 1972b. Acute and chronic toxicity of cadmium to fathead minnow (*Pimephales promelas*). Journal of the Fisheries Research Board of Canada 29(8):1099-1106.

Pickering, Q.H. and C. Henderson. 1966. The acute toxicity of some heavy metals to different species of warmwater fishes. Water, Air, and Soil Pollution 10: 453-463. (As cited in USEPA 2001).

Reynoldson, T.B., P. Rodriguez and M.M. Madrid. 1996. A comparison of reproduction, growth and acute toxicity in two populations of *Tubifex tubifex* (Muller, 1774) from the North American great lakes and Northern Spain. Hydrobiologia 334: 199-206. (As cited in USEPA 2001).

Rifici, L.M., D.S. Cherry, J.L. Farris and J. Cairns, Jr. 1996. Acute and subchronic toxicity of methylene blue to larval fathead minnows (*Pimephales promelas*): implications for aquatic toxicity testing. Environmental Toxicology and Chemistry 15(8): 1304- 1308. (As cited in USEPA 2001).

Rombough, P.J. and E.T. Garside. 1982a. Cadmium toxicity and accumulation in eggs and alevins of Atlantic salmon *Salmo salar*. Canadian Journal of Zoology 60:2006-2014. (As cited in USEPA 2001).

Rombough, P.J. and E.T. Garside. 1982b. Cadmium toxicity and accumulation in eggs and alevins of Atlantic salmon *Salmo salar*. Canadian Journal of Zoology 60:2006-2014.

Roux, D.J., P.L. Kempster, E. Truter and L. van der Merwe. 1993. Effect of cadmium and copper on survival and reproduction of *Daphnia pulex.* Water SA. 19(4): 269-274. (As cited in USEPA 2001).

Sauter, S., K. S. Buxton, K. J. Macek and S. R. Petrocelli. 1976a. Effects of exposure to heavy metals on selected fresh water fish: Toxicity of copper, cadmium, chromium and lead to eggs and fry of seven fish species. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency. EPA-600/3-76-105. (As cited in USEPA 2001).

Sauter, S., K. S. Buxton, K. J. Macek and S. R. Petrocelli. 1976b. Effects of exposure to heavy metals on selected fresh water fish: Toxicity of copper, cadmium, chromium and lead to eggs and fry of seven fish species. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency. EPA-600/3-76-105.

Schubauer-Berigan, M.K., J.R. Dierkes, P.D. Monson and G.T. Ankley. 1993. pH-dependent toxicity of Cd, Cu, Ni, Pb and Zn to *Ceriodaphnia dubia, Pimephales promelas, Hyalella azteca* and *Lumbriculus variegatus*. Environmental Toxicology and Chemistry 12: 1261-1266. (As cited in USEPA 2001).

Schuytema, G. S., P. O. Nelson, K. W. Malueg, A. V. Nebeker, D. F. Krawczyk, A. K. Ratcliff and J.H. Gakstatter. 1984. Toxicity of cadmium in water and sediment slurries to *Daphnia magna*. Environmental Toxicology and Chemistry 3:293-308.

Scott, G.R., K.A. Sloman, C. Rouleau and C.M. Wood. 2003. Cadmium disrupts behavioural and physiological responses to alarm substance in juvenile rainbow trout (*Oncorhynchus mykiss*). Journal of Experimental Biology 206:1779-1790.

Sloman, K.A., G.R. Scott, Z. Diao, C. Rouleau, C.M. Wood and D.G. McDonald. 2003. Cadmium affects the social behaviour of rainbow trout, *Oncorhynchus mykiss*. Aquatic Toxicology 65:171-185.

Spehar, R.L. 1976a. Cadmium and zinc toxicity to flagfish, *Jordanella floridae*. Journal of the Fisheries Research Board of Canada 33: 1939-1945. (As cited in USEPA 2001).

Spehar, R.L. 1976b. Cadmium and zinc toxicity to *Jordanella floridae*. EPA-600/3-76-096. National Technical Information Service, Springfield, Virginia. (As cited in USEPA 2001).

Spehar, R.L. 1982. Memorandum to J.G. Eaton. U.S. Environmental Protection Agency, Duluth, Minnesota. February 24. (As cited in USEPA 2001).

Spehar, R.L. and A.R. Carlson. 1984a. Derivation of site-specific water quality criteria for cadmium and the St. Louis River Basin, Duluth, Minnesota. PB84-153196. National Technical Information Service, Springfield, Virginia. (As cited in USEPA 2001).

Spehar, R.L. and A.R. Carlson. 1984b. Derivation of site-specific water quality criteria for cadmium and the St. Louis River Basin, Duluth, Minnesota. Environmental Toxicology and Chemistry 3: 651-665. (As cited in USEPA 2001).

Spehar, RL. and J.T. Fiandt. 1986. Acute and chronic effects of water quality criteria-based metal mixtures on three aquatic species. Environmental Toxicology and Chemistry 5: 917-931. (As cited in USEPA 2001).

Stackhouse, R.A. and W.H. Benson. 1988. The influence of humic acid on the toxicity and bioavailability of selected trace metals. Aquatic Toxicology 13: 99-108. (As cited in USEPA 2001).

Stratus Consulting, Inc. 1999. Sensitivity of bull trout (*Salvelinus confluentus*) to cadmium and zinc in water characteristic of the Coeur D'Alene River Basin: acute toxicity report. Final Report to U.S. Environmental Protection Agency Region X. 55 pp. (As cited in USEPA 2001).

Stuhlbacher, A., M.C. Bradley, C. Naylor and P. Calow. 1992. Induction of cadmium tolerance in two clones of *Daphnia magna* Straus. Comparative Biochemistry and Physiology 101C(3): 571-577. (As cited in USEPA 2001).

Suedel, B.C., J.H. Rodgers Jr. and E. Deaver. 1997. Experimental factors that may affect toxicity of cadmium to freshwater organisms. Archives of Environmental Contamination and Toxicology 33:188-193.

Sunderman, F.W., Jr., M.C. Plowman and S.M. Hopfer. 1991. Embryotoxicity and teratogenicity of cadmium chloride in *Xenopus laevis,* assayed by the FETAX procedure. Annals of Clinical and Laboratory Science 21(6):381-391. (As cited in USEPA 2001).

Suresh, A., B. Sivaramakrishna and K. Radhakrishnaiah. 1993. Effect of lethal and sublethal concentrations of cadmium on energetics in the gills of fry and fingerlings of *Cyprinus carpio.* Bulletin of Environmental Contamination and Toxicology 51: 920-926. (As cited in USEPA 2001).

USEPA (United States Environmental Protection Agency). 2001. 2001 Update of ambient water quality criteria for cadmium. EPA-822-R-01-001. Office of Water, Office of Science and Technology. Washington, District of Columbia.

Vardy, D.W., A.R. Tompsett, J. L. Sigurdson, J.A. Doering, X. Zhang, J.P. Giesy and M. Hecker. 2011. Effects of sub-chronic exposure of early life stages of white sturgeon (*Acipenser transmontanus*) to copper, cadmium, and zinc. Environmental Toxicology and Chemistry 30:2497-2505.

Wang, N., C.G. Ingersoll, C.D. Ivey, D.K. Hardesty and T.W. May. 2010. Sensitivity of early life stages of freshwater mussels (Unionidae) to acute and chronic toxicity of lead, cadmium and zinc in water. Environmental Toxicology and Chemistry 29(9):2053-2063.

Warnick, S.L. and H.L. Bell. 1969. The acute toxicity of some heavy metals to different species of aquatic insects. Journal of Water Pollution Control Federation 41: 280-284. (As cited in USEPA 2001).

Watts, M.M. and D. Pascoe. 2000. A comparative study of *Chironomus riparius* Meigen and *Chironomus tentans* Fabricius (Diptera: Chironomidae) in aquatic toxicity tests. Archives of Environmental Contamination and Toxicology 39:299-306.

Wier, C.F. and W.M. Walter. 1976. Toxicity of cadmium in the freshwater snail, *Physa gyrina* Say. Journal of Environmental Quality 5:359-362. (As cited in USEPA 2001).

Williams, K.A., D.W.J. Green and D. Pascoe. 1985. Studies on the acute toxicity of pollutants to freshwater macroinvertebrates; 1: Cadmium. Archiv für Hydrobiologie 102(4): 461-471. (As cited in USEPA 2001).

Appendix 3

Summary of the Compiled Aquatic Toxicity Data for Copper

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Table A3.4 Species and genus mean chronic values used in the derivation and recalculation of the national recommended ambient water quality criteria for copper. A3-36

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Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Data from USEPA (2007)[3]								
Amphibian								
Bufo boreas boreas	Boreal toad	tadpole, 0.012 g	96-h	Mortality	120	47.49	S,M	Dwyer *et al.* 1999
Fish								
Acrocheilus alutaceus	Chiselmouth	4.6 cm, 1.25 g	96-h	Mortality	143	216.3	FT,M	Andros and Garton 1980
Etheostoma flabellare	Fantail darter	3.7 cm	96-h	Mortality	330	117.7	S,M	Lydy and Wissing 1988
Etheostoma flabellare	Fantail darter	3.7 cm	96-h	Mortality	341	121.1	S,M	Lydy and Wissing 1988
Etheostoma flabellare	Fantail darter	3.7 cm	96-h	Mortality	373	122.8	S,M	Lydy and Wissing 1988
Etheostoma flabellare	Fantail darter	3.7 cm	96-h	Mortality	392	136.6	S,M	Lydy and Wissing 1988
Etheostoma fonticola	Fountain darter	2.02 cm, 0.062 g	96-h	Mortality	60	22.74	S,M	Dwyer *et al.* 1999
Etheostoma lepidum	Greenthroat darter	2.26 cm, 0.133 g	96-h	Mortality	260	82.8	S,M	Dwyer *et al.* 1999
Etheostoma nigrum	Johnny darter	3.9 cm	96-h	Mortality	493	167.3	S,M	Lydy and Wissing 1988
Etheostoma nigrum	Johnny darter	3.9 cm	96-h	Mortality	483	164.2	S,M	Lydy and Wissing 1988
Etheostoma nigrum	Johnny darter	3.9 cm	96-h	Mortality	548	183.9	S,M	Lydy and Wissing 1988
Etheostoma nigrum	Johnny darter	3.9 cm	96-h	Mortality	602	200.1	S,M	Lydy and Wissing 1988
Gila elegans	Bonytail chub	larval, 0.29 g	96-h	Mortality	200	63.22	S,M	Dwyer *et al.* 1995
Lepomis macrochirus	Bluegill sunfish	12 cm, 35 g	96-h	Mortality	1100	2305	FT,M	Benoit 1975
Lepomis macrochirus	Bluegill sunfish	2.8-6.8 cm	96-h	Mortality	1000	4200	FT,M	Cairns *et al.* 1981
Lepomis macrochirus	Bluegill sunfish	3.58 cm, 0.63 g	96-h	Mortality	2200	2202	R,M	Blaylock *et al.* 1985
Lepomis macrochirus	Bluegill sunfish	3.58 cm, 0.63 g	96-h	Mortality	1300	1163	FT,M	Blaylock *et al.* 1985
Notemigonus crysoleucas	Golden shiner	NR	96-h	Mortality	84600	107860	FT,M	Hartwell *et al.* 1989
Pimephales promelas	Fathead minnow	adult, 40 mm	96-h	Mortality	120	105.61	S,M	Birge *et al.* 1983
Pimephales promelas	Fathead minnow	adult, 40 mm	96-h	Mortality	310	266.3	S,M	Birge *et al.* 1983
Pimephales promelas	Fathead minnow	adult, 40 mm	96-h	Mortality	390	207.3	S,M	Birge *et al.* 1983; Benson & Birge 1985
Pimephales promelas	Fathead minnow	NR	96-h	Mortality	55	38.08	S,M	Carlson *et al.* 1986

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Fish (cont.)								
Pimephales promelas	Fathead minnow	NR	96-h	Mortality	85	70.71	S,M	Carlson *et al.* 1986
Pimephales promelas	Fathead minnow	larval, 0.32 g	96-h	Mortality	290	73.92	S,M	Dwyer *et al.* 1995
Pimephales promelas	Fathead minnow	larval, 0.45 g	96-h	Mortality	400	103.2	S,M	Dwyer *et al.* 1995
Pimephales promelas	Fathead minnow	larval, 0.56 g	96-h	Mortality	630	157.9	S,M	Dwyer *et al.* 1995
Pimephales promelas	Fathead minnow	larval, 0.39 g	96-h	Mortality	390	161.7	S,M	Dwyer *et al.* 1995
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	27.94	8.69	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	40.06	10.8	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	6.15	10.94	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	18.67	13.61	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	229.81	16.18	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	20.45	17.7	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	245.36	17.75	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	67.72	18.51	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	49.02	20.32	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	109.35	21.07	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	64.26	22.19	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	45.52	23.18	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	195.45	24.4	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	53.96	25.7	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	12.43	28.13	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	59.46	28.59	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	60.01	37.67	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	105.73	37.88	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	4.38	40.09	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	72.34	41.16	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	12.43	45.37	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	82.04	49.27	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	20.32	50.73	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	78	50.83	FT,M	Erickson *et al.* 1996a,b

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Fish (cont.)								
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	79.18	58.74	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	51.33	58.84	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	20.45	59.14	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	26.86	59.43	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	23.16	64.08	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	93.36	67.09	FT,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	26.67	68.24	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	26.67	72.86	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	77.88	72.95	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	120.02	75	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	268.22	78.5	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	27.94	78.99	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	114.55	83.1	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	117.35	85.45	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	126.49	85.82	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	103.76	86.54	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	165.18	87.89	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	146.46	89.18	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	175.26	89.93	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	96.67	93.76	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	34.99	97.49	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	111.76	100.16	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	113.35	100.75	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	127.06	101.01	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	124.43	104.9	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	180.85	105.76	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	71.12	105.76	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	167.32	106.46	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	77.43	106.69	S,M	Erickson *et al.* 1996a,b

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Fish (cont.)								
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	150.24	106.74	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	79.63	108.41	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	752.48	109.8	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	172.72	110	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	125.6	111.87	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	128.02	112.9	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	190.69	113	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	151.89	114.24	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	131.06	114.57	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	99.54	114.7	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	70.08	114.8	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	137.16	114.8	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	182.25	114.8	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	697.55	116.5	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	148.59	120.9	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	81.58	121.5	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	167.32	122	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	268.92	122.1	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	188.91	122.1	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	169.42	122.2	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	653.42	123.2	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	110.87	124.7	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	939.8	124.8	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	157.48	125.9	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	42.06	126.3	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	128.52	127.8	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	176.78	128.8	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	182.88	128.86	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	646.37	129.6	S,M	Erickson *et al.* 1996a,b

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Fish (cont.)								
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	182.88	130.9	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	160.21	131.3	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	644.53	131.9	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	226.7	133.4	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	891.54	135.5	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	166.62	136	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	151.13	136.3	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	223.52	137.6	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	132.72	137.8	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	84.2	138	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	145.29	140.2	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	283.15	142.9	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	62.51	146.5	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	182.88	146.6	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	188.98	147.5	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	163.83	147.7	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	271.27	149.2	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	150.88	153.9	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	199.71	157.4	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	370.08	163.3	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	97.79	165.8	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	101.47	169.6	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	404.81	172.5	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	253.37	176.1	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	757.62	181.4	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	662.56	185	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	995.68	188.3	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	262.13	191.4	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	904.88	197.1	S,M	Erickson *et al.* 1996a,b

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Fish (cont.)								
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	172.47	197.6	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	242.44	201.5	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	292.1	252.2	S,M	Erickson *et al.* 1996a,b
Pimephales promelas	Fathead minnow	NR	96-h	Mortality	88.5	13.27	FT,M	Lind *et al.* manuscript 1978
Pimephales promelas	Fathead minnow	NR	96-h	Mortality	114	17.99	FT,M	Lind *et al.* manuscript 1978
Pimephales promelas	Fathead minnow	NR	96-h	Mortality	121	19.7	FT,M	Lind *et al.* manuscript 1978
Pimephales promelas	Fathead minnow	NR	96-h	Mortality	1001	34.39	FT,M	Lind *et al.* manuscript 1978
Pimephales promelas	Fathead minnow	NR	96-h	Mortality	550	42.76	FT,M	Lind *et al.* manuscript 1978
Pimephales promelas	Fathead minnow	NR	96-h	Mortality	516	50.09	FT,M	Lind *et al.* manuscript 1978
Pimephales promelas	Fathead minnow	NR	96-h	Mortality	1586	66.49	FT,M	Lind *et al.* manuscript 1978
Pimephales promelas	Fathead minnow	NR	96-h	Mortality	1129	73.03	FT,M	Lind *et al.* manuscript 1978
Pimephales promelas	Fathead minnow	NR	96-h	Mortality	436	78.5	FT,M	Lind *et al.* manuscript 1978
Pimephales promelas	Fathead minnow	1.9-4.6 cm, 0.13-1.55 g	96-h	Mortality	311	67.56	S,M	Richards and Beitinger 1995
Pimephales promelas	Fathead minnow	3.0-4.8 cm, 0.23-1.36 g	96-h	Mortality	513	76.36	S,M	Richards and Beitinger 1995
Pimephales promelas	Fathead minnow	2.8-5.1 cm, 0.30-2.38 g	96-h	Mortality	297	77.75	S,M	Richards and Beitinger 1995
Pimephales promelas	Fathead minnow	3.2-5.5 cm, 0.42-3.23 g	96-h	Mortality	450	152.9	S,M	Richards and Beitinger 1995
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	15	11.23	S,M	Schubauer-Berigan *et al.* 1993
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	44	18.03	S,M	Schubauer-Berigan *et al.* 1993
Pimephales promelas	Fathead minnow	<24 h	96-h	Mortality	>200	>24.38 [4]	S,M	Schubauer-Berigan *et al.* 1993
Pimephales promelas	Fathead minnow	30 d, 0.15 g	96-h	Mortality	88.32	39.58	FT,M	Spehar and Fiandt 1986
Pimephales promelas	Fathead minnow	<24 h, 0.68 mg	96-h	Mortality	4.83	5.92	S,M	Welsh *et al.* 1993
Pimephales promelas	Fathead minnow	<24 h, 0.68 mg	96-h	Mortality	83.59	8.22	S,M	Welsh *et al.* 1993
Pimephales promelas	Fathead minnow	<24 h, 0.68 mg	96-h	Mortality	4.82	8.87	S,M	Welsh *et al.* 1993
Pimephales promelas	Fathead minnow	<24 h, 0.68 mg	96-h	Mortality	70.28	13.34	S,M	Welsh *et al.* 1993

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Fish (cont.)								
Pimephales promelas	Fathead minnow	<24 h, 0.68 mg	96-h	Mortality	182	13.91	S,M	Welsh *et al.* 1993
Pimephales promelas	Fathead minnow	<24 h, 0.68 mg	96-h	Mortality	59.83	16.64	S,M	Welsh *et al.* 1993
Pimephales promelas	Fathead minnow	<24 h, 0.68 mg	96-h	Mortality	8.2	16.72	S,M	Welsh *et al.* 1993
Pimephales promelas	Fathead minnow	<24 h, 0.68 mg	96-h	Mortality	21.06	17.67	S,M	Welsh *et al.* 1993
Pimephales promelas	Fathead minnow	<24 h, 0.68 mg	96-h	Mortality	35.97	21.24	S,M	Welsh *et al.* 1993
Pimephales promelas	Fathead minnow	<24 h, 0.68 mg	96-h	Mortality	31.57	25.15	S,M	Welsh *et al.* 1993
Poeciliopsis occidentalis	Gila topminnow	2.72 cm, 0.219 g	96-h	Mortality	160	56.15	S,M	Dwyer *et al.* 1999
Ptychocheilus lucius	Colorado squawfish	larval, 0.32 g	96-h	Mortality	380	88.44	S,M	Dwyer *et al.* 1995
Ptychocheilus lucius	Colorado squawfish	larval, 0.34 g	96-h	Mortality	480	197.6	S,M	Dwyer *et al.* 1995
Ptychocheilus oregonensis	Northern squawfish	7.2 cm, 3.69 g	96-h	Mortality	18	12.54	FT,M	Andros and Garton 1980
Ptychocheilus oregonensis	Northern squawfish	5.0 cm, 1.33 g	96-h	Mortality	23	17.02	FT,M	Andros and Garton 1980
Scaphirhynchus platorynchus	Shovelnose sturgeon	fry, 6.01 cm, 0.719 g	96-h	Mortality	160	69.63	S,M	Dwyer *et al.* 1999
Xyrauchen texanus	Razorback sucker	larval, 0.31 g	96-h	Mortality	220	63.78	S,M	Dwyer *et al.* 1995
Xyrauchen texanus	Razorback sucker	larval, 0.32 g	96-h	Mortality	340	97	S,M	Dwyer *et al.* 1995
Fish - Salmonid								
Oncorhynchus apache	Apache trout	larval, 0.38 g	96-h	Mortality	70	32.54	S,M	Dwyer *et al.* 1995
Oncorhynchus clarkii	Cutthroat trout	8.9 cm, 5.7 g	96-h	Mortality	15.7	10.6	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus clarkii	Cutthroat trout	7.7 cm, 4.4 g	96-h	Mortality	44.4	18.81	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus clarkii	Cutthroat trout	8.5 cm, 5.2 g	96-h	Mortality	91	19.63	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus clarkii	Cutthroat trout	8.8 cm, 9.7 g	96-h	Mortality	36.8	21.87	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus clarkii	Cutthroat trout	7.0 cm, 3.2 g	96-h	Mortality	73.6	39.53	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus clarkii	Cutthroat trout	6.9 cm, 3.2 g	96-h	Mortality	186	44.91	FT,M	Chakoumakos *et al.* 1979

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Fish - Salmonid (cont.)								
Oncorhynchus clarkii	Cutthroat trout	8.1 cm, 4.4 g	96-h	Mortality	232	51.94	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus clarkii	Cutthroat trout	7.4 cm, 4.2 g	96-h	Mortality	367	67.3	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus clarkii	Cutthroat trout	6.8 cm, 2.7 g	96-h	Mortality	162	111.3	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus clarkii henshawi	Lahontan cutthroat	larval, 0.34 g	96-h	Mortality	80	34.26	S,M	Dwyer *et al.* 1995
Oncorhynchus clarkii henshawi	Lahontan cutthroat	larval, 0.57 g	96-h	Mortality	60	24.73	S,M	Dwyer *et al.* 1995
Oncorhynchus gorbuscha	Pink salmon	alevin	96-h	Mortality	87	19.7	FT,M	Servizi and Martens 1978
Oncorhynchus gorbuscha	Pink salmon	alevin (newly hatched)	96-h	Mortality	143	41.65	FT,M	Servizi and Martens 1978
Oncorhynchus gorbuscha	Pink salmon	fry	96-h	Mortality	199	78.76	FT,M	Servizi and Martens 1978
Oncorhynchus kisutch	Coho salmon	6 g	96-h	Mortality	164	106.09	R,M	Buckley 1983
Oncorhynchus kisutch	Coho salmon	adult, 2.7 kg	96-h	Mortality	46	32.66	FT,M	Chapman and Stevens 1978
Oncorhynchus kisutch	Coho salmon	fry	96-h	Mortality	49	12.67	FT,M	Mudge *et al.* 1993
Oncorhynchus kisutch	Coho salmon	fry	96-h	Mortality	58	11.95	FT,M	Mudge *et al.* 1993
Oncorhynchus kisutch	Coho salmon	parr	96-h	Mortality	33	20.94	FT,M	Chapman 1975
Oncorhynchus kisutch	Coho salmon	parr	96-h	Mortality	78	22.98	FT,M	Mudge *et al.* 1993
Oncorhynchus kisutch	Coho salmon	smolt	96-h	Mortality	51	13.19	FT,M	Mudge *et al.* 1993
Oncorhynchus mykiss	Rainbow trout	0.64 g, 4.1 cm	96-h	Mortality	101	39.73	FT,M	Hansen *et al.* 2000
Oncorhynchus mykiss	Rainbow trout	0.29 g, 3.4 cm	96-h	Mortality	54.4	47.69	FT,M	Hansen *et al.* 2000
Oncorhynchus mykiss	Rainbow trout	0.43 g, 3.7 cm	96-h	Mortality	35.9	50.83	FT,M	Hansen *et al.* 2000
Oncorhynchus mykiss	Rainbow trout	0.35 g, 3.4 cm	96-h	Mortality	308	85.83	FT,M	Hansen *et al.* 2000
Oncorhynchus mykiss	Rainbow trout	0.68 g, 4.2 cm	96-h	Mortality	93	95.9	FT,M	Hansen *et al.* 2000
Oncorhynchus mykiss	Rainbow trout	1 g	96-h	Mortality	169	23.41	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus mykiss	Rainbow trout	11.8 cm, 18.7 g	96-h	Mortality	197	28.6	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus mykiss	Rainbow trout	13.4 cm, 25.6 g	96-h	Mortality	243	37.88	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus mykiss	Rainbow trout	13.5 cm, 24.9 g	96-h	Mortality	514	99.97	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus mykiss	Rainbow trout	2.6 g	96-h	Mortality	274	44.54	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus mykiss	Rainbow trout	4.3 g	96-h	Mortality	128	16.51	FT,M	Chakoumakos *et al.* 1979

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Fish - Salmonid (cont.)								
Oncorhynchus mykiss	Rainbow trout	4.9 cm	96-h	Mortality	85.3	10.2	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus mykiss	Rainbow trout	6.0 cm, 2.1 g	96-h	Mortality	83.3	9.93	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus mykiss	Rainbow trout	6.1 cm, 2.5 g	96-h	Mortality	103	12.71	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus mykiss	Rainbow trout	6.7 cm, 2.65 g	96-h	Mortality	2.8	7	FT,M	Cusimano *et al.* 1986
Oncorhynchus mykiss	Rainbow trout	9.2 cm, 9.4 g	96-h	Mortality	221	33.33	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus mykiss	Rainbow trout	9.9 cm, 11.5 g	96-h	Mortality	165	22.7	FT,M	Chakoumakos *et al.* 1979
Oncorhynchus mykiss	Rainbow trout	alevin	96-h	Mortality	28	20.3	FT,M	Chapman 1975, 1978
Oncorhynchus mykiss	Rainbow trout	larval, 0.48 g	96-h	Mortality	50	25.26	S,M	Dwyer *et al.* 1995
Oncorhynchus mykiss	Rainbow trout	larval, 0.50 g	96-h	Mortality	60	29.46	S,M	Dwyer *et al.* 1995
Oncorhynchus mykiss	Rainbow trout	larval, 0.67 g	96-h	Mortality	110	41.64	S,M	Dwyer *et al.* 1995
Oncorhynchus mykiss	Rainbow trout	parr	96-h	Mortality	68	19.73	FT,M	Mudge *et al.* 1993
Oncorhynchus mykiss	Rainbow trout	parr, 8.6 cm, 6.96 g	96-h	Mortality	18	9.87	FT,M	Chapman 1975, 1978
Oncorhynchus mykiss	Rainbow trout	smolt, 18.8 cm, 68.19 g	96-h	Mortality	29	22.48	FT,M	Chapman 1975, 1978
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.17 g	96-h	Mortality	17	12.54	FT,M	Chapman 1975, 1978
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.20-0.24 g	96-h	Mortality	3.4	5.02	R,M	Welsh *et al.* 2000
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.20-0.24 g	96-h	Mortality	8.1	11.97	R,M	Welsh *et al.* 2000
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.20-0.24 g	96-h	Mortality	17.2	13.8	R,M	Welsh *et al.* 2000
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.20-0.24 g	96-h	Mortality	32	23.84	R,M	Welsh *et al.* 2000
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.23 g	96-h	Mortality	5.7	24.8	FT,M	Cacela *et al.* 1996
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.23 g	96-h	Mortality	35	16.16	FT,M	Cacela *et al.* 1996

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Fish - Salmonid (cont.)								
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.23 g	96-h	Mortality	17	24.19	FT,M	Cacela *et al.* 1996
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.25 g	96-h	Mortality	40	10.9	R,M	Cacela *et al.* 1996
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.25 g	96-h	Mortality	19	9.04	R,M	Cacela *et al.* 1996
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.25 g	96-h	Mortality	12	32.15	FT,M	Cacela *et al.* 1996
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.26 g	96-h	Mortality	18	37.66	FT,M	Cacela *et al.* 1996
Oncorhynchus mykiss	Rainbow trout	swim-up, 0.29 g	96-h	Mortality	18	8.1	FT,M	Cacela *et al.* 1996
Oncorhynchus nerka	Sockeye salmon	alevin	96-h	Mortality	200	79.52	FT,M	Servizi and Martens 1978
Oncorhynchus nerka	Sockeye salmon	alevin	96-h	Mortality	100	23.74	FT,M	Servizi and Martens 1978
Oncorhynchus nerka	Sockeye salmon	alevin	96-h	Mortality	110	27.22	FT,M	Servizi and Martens 1978
Oncorhynchus nerka	Sockeye salmon	alevin	96-h	Mortality	130	35.36	FT,M	Servizi and Martens 1978
Oncorhynchus nerka	Sockeye salmon	alevin (newly hatched)	96-h	Mortality	190	71.73	FT,M	Servizi and Martens 1978
Oncorhynchus nerka	Sockeye salmon	fry	96-h	Mortality	150	45.37	FT,M	Servizi and Martens 1978
Oncorhynchus nerka	Sockeye salmon	smolt, 4,8 g	96-h	Mortality	240	114.4	FT,M	Servizi and Martens 1978
Oncorhynchus nerka	Sockeye salmon	smolt, 5.5 g	96-h	Mortality	210	87.77	FT,M	Servizi and Martens 1978
Oncorhynchus nerka	Sockeye salmon	smolt, 5.5 g	96-h	Mortality	170	57.53	FT,M	Servizi and Martens 1978
Oncorhynchus nerka	Sockeye salmon	smolt, 5.5 g	96-h	Mortality	190	71.73	FT,M	Servizi and Martens 1978
Oncorhynchus tshawytscha	Chinook salmon	3 mo, 1.35 g	96-h	Mortality	10.2	19.41	FT,M	Chapman and McCrady 1977
Oncorhynchus tshawytscha	Chinook salmon	3 mo, 1.35 g	96-h	Mortality	24.1	30.91	FT,M	Chapman and McCrady 1977
Oncorhynchus tshawytscha	Chinook salmon	3 mo, 1.35 g	96-h	Mortality	82.5	32.74	FT,M	Chapman and McCrady 1977
Oncorhynchus tshawytscha	Chinook salmon	3 mo, 1.35 g	96-h	Mortality	128.4	20.66	FT,M	Chapman and McCrady 1977
Oncorhynchus tshawytscha	Chinook salmon	alevin, 0.05 g	96-h	Mortality	26	14.48	FT,M	Chapman 1975, 1978

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Fish - Salmonid (cont.)								
Oncorhynchus tshawytscha	Chinook salmon	parr, 9.6 cm, 11.58 g	96-h	Mortality	38	28.3	FT,M	Chapman 1975, 1978
Oncorhynchus tshawytscha	Chinook salmon	smolt, 14.4 cm, 32.46 g	96-h	Mortality	26	20.09	FT,M	Chapman 1975, 1978
Oncorhynchus tshawytscha	Chinook salmon	swim-up, 0.36-0.45 g	96-h	Mortality	7.4	36.49	FT,M	Welsh *et al.* 2000
Oncorhynchus tshawytscha	Chinook salmon	swim-up, 0.36-0.45 g	96-h	Mortality	12.5	30.85	FT,M	Welsh *et al.* 2000
Oncorhynchus tshawytscha	Chinook salmon	swim-up, 0.36-0.45 g	96-h	Mortality	14.3	31.49	FT,M	Welsh *et al.* 2000
Oncorhynchus tshawytscha	Chinook salmon	swim-up, 0.36-0.45 g	96-h	Mortality	18.3	48.56	FT,M	Welsh *et al.* 2000
Oncorhynchus tshawytscha	Chinook salmon	swim-up,0.23 g	96-h	Mortality	19	10.44	FT,M	Chapman 1975, 1978
Salvelinus confluentus	Bull trout	0.130 g, 2.6 cm	96-h	Mortality	228	69.7	FT,M	Hansen *et al.* 2000
Salvelinus confluentus	Bull trout	0.555 g, 4.0 cm	96-h	Mortality	207	63.62	FT,M	Hansen *et al.* 2000
Salvelinus confluentus	Bull trout	0.774 g, 4.5 cm	96-h	Mortality	66.6	74.18	FT,M	Hansen *et al.* 2000
Salvelinus confluentus	Bull trout	1.160 g, 5.2 cm	96-h	Mortality	89	71.11	FT,M	Hansen *et al.* 2000
Salvelinus confluentus	Bull trout	1.520 g, 5.6 cm	96-h	Mortality	50	63.6	FT,M	Hansen *et al.* 2000
Invertebrate - ALS Insect								
Acroneuria lycorias	Stonefly	NR	96-h	Mortality	8300	20636	S,M	Warnick and Bell 1969
Chironomus decorus	Midge	4th instar	96-h	Mortality	739	1987	S,M	Kosalwat and Knight 1987
Invertebrate - Amphipod								
Gammarus sp.	Amphipod	1-3 d	96-h	Mortality	22	10.39	S,M	Arthur and Leonard 1970
Gammarus sp.	Amphipod	1-3 d	96-h	Mortality	19	8.86	S,M	Arthur and Leonard 1970
Hyalella azteca	Amphipod	7-14 d	96-h	Mortality	17	12.19	S,M	Schubauer-Berigan *et al.* 1993
Hyalella azteca	Amphipod	7-14 d	96-h	Mortality	24	9.96	S,M	Schubauer-Berigan *et al.* 1993

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Invertebrate - Amphipod (cont.)								
Hyalella azteca	Amphipod	7-14 d	96-h	Mortality	87	15.77	S,M	Schubauer-Berigan *et al.* 1993
Hyalella azteca	Amphipod	<7 d	96-h	Mortality	24.3	8.26	S,M	Welsh 1996
Hyalella azteca	Amphipod	<7 d	96-h	Mortality	23.8	8.09	S,M	Welsh 1996
Hyalella azteca	Amphipod	<7 d	96-h	Mortality	8.2	15.49	S,M	Welsh 1996
Hyalella azteca	Amphipod	<7 d	96-h	Mortality	10	18.8	S,M	Welsh 1996
Invertebrate - Cladoceran								
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	84	10.74	S,M	Belanger and Cherry 1990
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	28	4.1	S,M	Belanger and Cherry 1990
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	25	7.98	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	17	5.25	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	30	9.8	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	24	7.63	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	28	9.06	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	32	10.56	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	23	7.28	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	20	6.25	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	19	5.91	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	26	3.1	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	21	2.46	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	27	3.24	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	37	4.66	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	34	4.22	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	67	5.5	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	38	2.72	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	78	6.74	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	81	7.1	S,M	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	<4 h	48-h	Mortality	19	10.28	S,M	Carlson *et al.* 1986
Ceriodaphnia dubia	Water flea	<4 h	48-h	Mortality	17	9.19	S,M	Carlson *et al.* 1986

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Invertebrate - Cladoceran (cont.)								
Ceriodaphnia dubia	Water flea	<24 h	48-h	Mortality	5.54	5.03	R,M	Diamond *et al.* 1997
Ceriodaphnia dubia	Water flea	<12 h	48-h	Mortality	13.4	6.19	S,M	Oris *et al.* 1991
Daphnia magna	Water flea	1 d	48-h	Mortality	9.1	3.42	S,M	Nebeker *et al.* 1986a
Daphnia magna	Water flea	1 d	48-h	Mortality	11.7	4.43	S,M	Nebeker *et al.* 1986a
Daphnia magna	Water flea	1 d	48-h	Mortality	11.7	13.46	S,M	Nebeker *et al.* 1986a
Daphnia magna	Water flea	1 d	48-h	Mortality	9.1	4.4	S,M	Nebeker *et al.* 1986a
Daphnia magna	Water flea	<24 h	48-h	Mortality	41.2	21.55	S,M	Baird *et al.* 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	10.5	5.63	S,M	Baird *et al.* 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	20.6	11.31	S,M	Baird *et al.* 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	17.3	9.48	S,M	Baird *et al.* 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	70.7	33.58	S,M	Baird *et al.* 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	31.3	16.9	S,M	Baird *et al.* 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	26	10.34	S,M	Chapman *et al.* manuscript
Daphnia magna	Water flea	<24 h	48-h	Mortality	30	9.04	S,M	Chapman *et al.* manuscript
Daphnia magna	Water flea	<24 h	48-h	Mortality	38	9.84	S,M	Chapman *et al.* manuscript
Daphnia magna	Water flea	<24 h	48-h	Mortality	69	12.31	S,M	Chapman *et al.* manuscript
Daphnia magna	Water flea	<24 h	48-h	Mortality	4.8	1.22	S,M	Long's MS Thesis
Daphnia magna	Water flea	<24 h	48-h	Mortality	7.4	16.29	S,M	Long's MS Thesis
Daphnia magna	Water flea	<24 h	48-h	Mortality	6.5	2.11	S,M	Long's MS Thesis
Daphnia magna	Water flea	<24 h	48-h	Mortality	7.1	2.67	S,M	Meador 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	16.4	4.26	S,M	Meador 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	39.9	5.18	S,M	Meador 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	18.7	3.39	S,M	Meador 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	18.9	1.99	S,M	Meador 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	39.7	3.04	S,M	Meador 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	46	8.93	S,M	Meador 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	71.9	9.97	S,M	Meador 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	57.2	5.76	S,M	Meador 1991
Daphnia magna	Water flea	<24 h	48-h	Mortality	67.8	4.16	S,M	Meador 1991

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Invertebrate - Cladoceran (cont.)								
Daphnia magna	Water flea	<2 h	48-h	Mortality	6.6	2.5	S,M	Nebeker *et al.* 1986a
Daphnia magna	Water flea	<2 h	48-h	Mortality	9.9	3.78	S,M	Nebeker *et al.* 1986a
Daphnia magna	Water flea	<4 h	48-h	Mortality	6.7	8.21	S,M	Nebeker *et al.* 1986a
Daphnia magna	Water flea	<2 h	48-h	Mortality	5.2	2.16	S,M	Nebeker *et al.* 1986a
Daphnia pulicaria	Water flea	NR	48-h	Mortality	11.4	1.63	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	9.06	1.04	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	7.24	0.88	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	10.8	1.13	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	55.4	8.81	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	55.3	6.03	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	53.3	4.12	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	97.2	3.94	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	199	3.01	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	213	7.63	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	165	5.78	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	35.5	1.83	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	78.8	2.36	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	113	1.06	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	76.4	2.36	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	84.7	6.62	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	184	7.14	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	9.3	1.11	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	17.8	2.11	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	23.7	2.67	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	27.3	2.77	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	25.2	2.81	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	25.1	2.6	S,M	Lind *et al.* manuscript 1978
Daphnia pulicaria	Water flea	NR	48-h	Mortality	25.1	2.31	S,M	Lind *et al.* manuscript 1978
Scapholeberis sp.	Water flea	adult	48-h	Mortality	18	9.73	S,M	Carlson et al. 1986

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Invertebrate - Mussel								
Actinonaias pectorosa	Pheasantshell	juvenile	96-h	Mortality	27	10.36	S,M	Keller unpublished
Actinonaias pectorosa	Pheasantshell	juvenile	96-h	Mortality	<29	<12.39 [4]	S,M	Keller unpublished
Utterbackia imbecillis	Freshwater mussel	1-2 d juv	96-h	Mortality	86	177.9	S,M	Keller and Zam 1991
Utterbackia imbecillis	Freshwater mussel	1-2 d juv	96-h	Mortality	199	172.3	S,M	Keller and Zam 1991
Utterbackia imbecillis	Freshwater mussel	juvenile	96-h	Mortality	76	40.96	S,M	Keller unpublished
Utterbackia imbecillis	Freshwater mussel	juvenile	96-h	Mortality	85	43.22	S,M	Keller unpublished
Utterbackia imbecillis	Freshwater mussel	juvenile	96-h	Mortality	41	24.12	S,M	Keller unpublished
Utterbackia imbecillis	Freshwater mussel	juvenile	96-h	Mortality	79	39.04	S,M	Keller unpublished
Utterbackia imbecillis	Freshwater mussel	juvenile	96-h	Mortality	72	39.96	S,M	Keller unpublished
Utterbackia imbecillis	Freshwater mussel	juvenile	96-h	Mortality	38	28.31	S,M	Keller unpublished
Invertebrate - Snail								
Campeloma	Snail	1.1-2.7 cm	96-h	Mortality	2000	4319	FT,M	Arthur and Leonard 1970
Campeloma	Snail	1.1-2.7 cm	96-h	Mortality	1400	2956	FT,M	Arthur and Leonard 1970
Juga plicifera	Snail	adult	96-h	Mortality	15	12.31	FT,M	Nebeker *et al.* 1986b
Lithoglyphus virens	Snail	adult	96-h	Mortality	8	6.67	FT,M	Nebeker *et al.* 1986b
Physa integra	Snail	0.4-0.7 cm	96-h	Mortality	41	21.81	FT,M	Arthur and Leonard 1970
Physa integra	Snail	0.4-0.7 cm	96-h	Mortality	37	19.09	FT,M	Arthur and Leonard 1970

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Invertebrate - Worm								
Lumbriculus variegatus	Worm	adult (mixed age)	96-h	Mortality	130	37.81	S,M	Schubauer-Berigan *et al.* 1993
Lumbriculus variegatus	Worm	adult (mixed age)	96-h	Mortality	270	55.39	S,M	Schubauer-Berigan *et al.* 1993
Lumbriculus variegatus	Worm	adult (mixed age)	96-h	Mortality	500	54.18	S,M	Schubauer-Berigan *et al.* 1993
Additional Data[5]								
Fish								
Acipenser transmontanus	White sturgeon	2 dph	96-h	Mortality & Behavior	2.67	1.51	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	30 dph	96-h	Mortality & Behavior	6.31	4.2	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	44 dph	96-h	Mortality	>49.8	>34.1	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	61 dph	96-h	Mortality & Behavior	30.8	21.98	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	72 dph	96-h	Mortality & Behavior	<86.4	<58.96	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	89 dph	96-h	Mortality & Behavior	21.9	17.25	FT	Ingersoll and Mebane 2013

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Fish - Salmonid								
Oncorhynchus mykiss	Rainbow trout	1 dph	96-h	Mortality & Behavior	62.9	**47.8**	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	96-h	Mortality	62.9	47.8	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	18 dph	96-h	Mortality & Behavior	56.6	**43.4**	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	18 dph	96-h	Mortality	56.6	43.4	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	32 dph	96-h	Mortality & Behavior	59.9	**42.42**	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	32 dph	96-h	Mortality	59.9	42.42	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	46 dph	96-h	Mortality & Behavior	50.1	**37.84**	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	60 dph	96-h	Mortality & Behavior	40.8	**32.21**	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	74 dph	96-h	Mortality & Behavior	60.6	**44.34**	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	74 dph	96-h	Mortality	60.6	44.34	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	95 dph	96-h	Mortality	19.1	**15.24**	FT	Ingersoll and Mebane 2013
Invertebrate - Cladoceran								
Ceriodaphnia dubia	Water flea	<24-h	48-h	Mortality	25	**13**	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	48-h	Mortality	157	**7.3**	R	Wang *et al.* 2011

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Invertebrate - Cladoceran (cont.)								
Ceriodaphnia dubia	Water flea	<24-h	48-h	Mortality	147	**6.7**	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	48-h	Mortality	267	**7**	R	Wang *et al.* 2011
Invertebrate - Mussel								
Epioblasma capsaeformis	Oyster mussel	juvenile	96-h	Mortality	17	**7.9**	NR	Wang *et al.* 2007a
Epioblasma capsaeformis	Oyster mussel	juvenile	96-h	Mortality	6.8	**2.9**	NR	Wang *et al.* 2007a
Lampsilis fasciola	Wavy-rayed lampmussel	juvenile	96-h	Mortality	21	**8.9**	NR	Wang *et al.* 2007a
Lampsilis fasciola	Wavy-rayed lampmussel	juvenile	96-h	Mortality	25	**10**	NR	Wang *et al.* 2007a
Lampsilis rafinesqueana	Neosho mucket	juvenile	96-h	Mortality	43	**19**	NR	Wang *et al.* 2007a
Lampsilis rafinesqueana	Neosho mucket	juvenile	96-h	Mortality	23	**12**	NR	Wang *et al.* 2007a
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	18	**7.2**	R	Wang *et al.* 2007a
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	20	**9.2**	R	Wang *et al.* 2007a
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	21	**7.7**	R	Wang *et al.* 2007a
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	23	**9.2**	R	Wang *et al.* 2007a
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	25	**9.9**	R	Wang *et al.* 2007a
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	27	**6.1**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	56	**2.8**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	56	**1.7**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	127	**2**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	53	**6.4**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	113	**4**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	149	**2.4**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	298	**3.3**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	9.9	**3.9**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	58	**7.7**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	75	**5**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	144	**4.4**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	44	**18**	R	Wang *et al.* 2009

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Invertebrate - Mussel (cont.)								
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	114	**5.8**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	187	**3.6**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	>396	5.3 [6]	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	24	**5**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	66	**3**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	72	**2.5**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	133	**3.6**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	196	**3.4**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	21	**24**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	30	**26**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	26	**11**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	30	**6.9**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	31	**15**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	43	**17**	R	Wang *et al.* 2009
Lampsilis siliquoidea	Fatmucket	juvenile	96-h	Mortality	39	**16**	R	Wang *et al.* 2009
Lasmigona subviridis	Mussels	juvenile	96-h	Mortality	65	**53**	NR	Black 2001
Lasmigona subviridis	Mussels	juvenile	96-h	Mortality	93	**76**	NR	Black 2001
Lasmigona subviridis	Mussels	juvenile	96-h	Mortality	52	**42**	NR	Black 2001
Leptodea leptodon	Mussels	juvenile	96-h	Mortality	22	**9.9**	NR	Wang *et al.* 2007a
Utterbackia imbecillis	Mussels	juvenile	96-h	Mortality	24	**12**	NR	Black 2001
Utterbackia imbecillis	Mussels	juvenile	96-h	Mortality	25	**12**	NR	Black 2001
Utterbackia imbecillis	Mussels	juvenile	96-h	Mortality	19	**8.3**	NR	Black 2001
Utterbackia imbecillis	Mussels	juvenile	96-h	Mortality	39	**23**	NR	Warren 1996
Utterbackia imbecillis	Mussels	juvenile	96-h	Mortality	<20	<9.6	NR	Warren 1996
Utterbackia imbecillis	Mussels	juvenile	96-h	Mortality	36	**21**	NR	Warren 1996
Utterbackia imbecillis	Mussels	juvenile	96-h	Mortality	44	**27**	NR	Warren 1996
Villosa iris	Rainbow mussel	3-month old juveniles	96-h	Mortality	32	**3**	FT	Wang *et al.* 2011

Table A3.1. Summary of compiled acute aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Endpoint	Effect Concentration [1] (µg/L)		Test Type	Reference
					Original Effect	Normalized Effect [2]		
Invertebrate - Mussel (cont.)								
Villosa iris	Rainbow mussel	3-month old juveniles	96-h	Mortality	15	**8.4**	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	96-h	Mortality	65	**3**	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	96-h	Mortality	72	**2.1**	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	juvenile	96-h	Mortality	17	**13**	NR	Wang *et al.* 2007a

ALS = aquatic life stage; AWQC = ambient water quality criteria; d = day; dph = days post-hatch; EC = effect concentration; FT = flow-through; h = hour; LC = lethal concentration; M = measured; NR = not reported; R = renewal; S = static; SMAV = species mean acute value; USEPA = United States Environmental Protection Agency.

[1] All acute toxicity data presented are LC_{50} or EC_{50} values.

[2] Effect value normalized using the Biotic Ligand Model (BLM), as described in USEPA (2007). Only data that had already been BLM-normalized were used in this analysis.

[3] Data from USEPA (2007) used in the calculation of SMAVs for the AWQC for copper. Values were used in the recalculation of SMAVs for this report except where noted. If a study did not report dissolved copper concentrations, USEPA (2007) used a conversion factor of 0.96 to convert total to dissolved copper before using the value in the BLM.

[4] This value was not used in the recalculation of SMAVs because it is a "greater than" or "less than" value and there are measured values for this species.

[5] Additional data not used in the derivation of the aquatic life ambient water quality criteria for copper (USEPA 2007). Bolded values were used in the recalculation of SMAVs.

[6] Only 30% mortality occurred at the highest concentration tested, 396 µg/L. Extrapolated EC_{50} of 475 µg/L was used for calculating BLM-normalized EC_{50}.

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Data from USEPA (2007)[2]										
Fish										
Catostomus commersonii	White sucker	ELS	40-d	Chronic Value	Biomass	20.88	35.68	45.4	NR	McKim *et al.* 1978
Esox lucius	Northern pike	ELS	40-d	Chronic Value	Biomass	60.36	103.2	45.4	NR	McKim *et al.* 1978
Lepomis macrochirus	Bluegill sunfish	Larval	90-d	EC_{20}	Survival	27.15	45.05	47	NR	Benoit 1975
Pimephales notatus	Bluntnose minnow	Life cycle	60-d	Chronic Value	Egg production	18	8.627	201	NR	Horning and Neiheisel 1979
Pimephales promelas	Fathead minnow	ELS	30-d	EC_{20}	Biomass	9.38	16.15	45	NR	Lind *et al.* manuscript 1978
Fish - Salmonid										
Oncorhynchus mykiss	Rainbow trout	ELS	58-d	EC_{20}	Biomass	20.32	11.24	170	NR	Besser *et al.* 2001
Oncorhynchus mykiss	Rainbow trout	Embryo	85-d	EC_{20}	Biomass	27.77	20.68	120	NR	Seim *et al.* 1984
Oncorhynchus tshawytscha	Chinook salmon	Egg to fry	4 months	EC_{20}	Biomass	5.92	13.46	32.5	NR	Chapman 1975, 1982
Salmo trutta	Brown trout	Embryo	72-d	Chronic Value	Biomass	29.91	51.12	45.4	NR	McKim *et al.* 1978
Salvelinus fontinalis	Brook trout	ELS	76-d	Chronic Value	Biomass	31.15	53.23	45.4	NR	McKim *et al.* 1978
Salvelinus fontinalis	Brook trout	ELS	60-d	Chronic Value	Biomass	<5	<10.67 [3]	35	NR	Sauter *et al.* 1976
Salvelinus namaycush	Lake trout	ELS	93-d	Chronic Value	Biomass	30.94	52.88	45.4	NR	McKim *et al.* 1978

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Invertebrate - ALS Insect										
Clistoronia magnifica	Caddisfly	Adult 1st generation	NR	EC_{20}	Emergence	7.67	21.11	26	NR	Nebeker *et al.* 1984
Invertebrate - Cladoceran										
Ceriodaphnia dubia	Water flea	NR	7-d	Chronic Value	Survival and reproduction	24.5	34.47	57	NR	Oris *et al.* 1991
Ceriodaphnia dubia	Water flea	NR	7-d	Chronic Value	Survival and reproduction	34.6	48.68	57	NR	Oris *et al.* 1991
Ceriodaphnia dubia	Water flea	NR	7-d	Chronic Value	Reproduction	8.23	4.355	179	NR	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	NR	7-d	Chronic Value	Reproduction	19.59	45.14 [4]	32	NR	Carlson *et al.* 1986
Ceriodaphnia dubia	Water flea	NR	7-d	EC_{20}	Reproduction	19.36	17.75 [5]	94.1	NR	Belanger *et al.* 1989
Daphnia magna	Water flea	NR	21-d	Chronic Value	Carapace length	21.5	9.358	225	NR	van Leeuwen *et al.* 1988
Daphnia magna	Water flea	NR	14-d	Chronic Value	Reproduction	17.32	17.32	85	NR	Blaylock *et al.* 1985
Daphnia magna	Water flea	<24-h	21-d	EC_{20}	Reproduction	6.06	2.787	211	NR	Chapman *et al.* manuscript
Daphnia magna	Water flea	<24-h	21-d	EC_{20}	Reproduction	19.89	16.74	104	NR	Chapman *et al.* manuscript
Daphnia magna	Water flea	<24-h	21-d	EC_{20}	Reproduction	12.58	19.46	51	NR	Chapman *et al.* manuscript
Daphnia pulex	Water flea	NR	42-d	Chronic Value	Survival	7.07	5.461	115	NR	Winner 1985
Daphnia pulex	Water flea	NR	42-d	EC_{20}	Survival	9.16	3.913	230	NR	Winner 1985
Daphnia pulex	Water flea	NR	42-d	EC_{20}	Survival	2.83	3.952	57.5	NR	Winner 1985

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Invertebrate - Rotifer										
Brachionus calyciflorus	Rotifer	Life cycle	4-d	Chronic Value	Intrinsic growth rate	3.54	3.54	85	R	Janssen *et al.* 1994
Invertebrate - Snail										
Campeloma decisum	Pointed campeloma	Adult	6 weeks	EC_{20}	Survival	8.73	15.03	45	FT	Arthur and Leonard 1970
Campeloma decisum	Pointed campeloma	Adult	6 weeks	EC_{20}	Survival	10.94	18.84	45	FT	Arthur and Leonard 1970
Additional Data[6]										
Fish										
Acipenser transmontanus	White sturgeon	1 dph	24-d	EC_{10}	Survival	2.56	2.209	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	1 dph	24-d	EC_{20}	Survival	3.01	**2.598**	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	1 dph	24-d	MATC	Survival	2.64	2.278	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	EC_{10}	Biomass (dry)	2.03	1.752	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	EC_{10}	Dry weight	2.04	1.76	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	EC_{10}	Survival	3.72	3.21	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	EC_{20}	Biomass (dry)	2.67	**2.304**	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	EC_{20}	Dry weight	2.85	2.459	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	EC_{20}	Survival	4.21	3.633	101	FT	Ingersoll and Mebane 2013

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Fish (cont.)										
Acipenser transmontanus	White sturgeon	27 dph	28-d	MATC	Biomass (dry)	1.32	1.139	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	MATC	Dry weight	1.32	1.139	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	27 dph	28-d	MATC	Survival	4.97	4.289	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	2 dph	53-d	EC_{10}	Biomass (dry)	1.48	1.277	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	2 dph	53-d	EC_{10}	Dry weight	1.19	1.027	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	2 dph	53-d	EC_{10}	Survival	1.9	1.64	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	2 dph	53-d	EC_{20}	Biomass (dry)	1.64	1.415	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	2 dph	53-d	EC_{20}	Dry weight	1.55	**1.338**	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	2 dph	53-d	EC_{20}	Survival	2.13	1.838	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	2 dph	53-d	MATC	Biomass (dry)	2.41	2.08	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	2 dph	53-d	MATC	Dry weight	1.28	1.105	101	FT	Ingersoll and Mebane 2013
Acipenser transmontanus	White sturgeon	2 dph	53-d	MATC	Survival	2.41	2.08	101	FT	Ingersoll and Mebane 2013
Fish - Salmonid										
Oncorhynchus kisutch	Coho salmon	Juvenile	7-d	EC_{50}	Olfactory inhibition	11.1	8.267	120		Sandahl *et al.* 2004
Oncorhynchus mykiss	Rainbow trout	1 dph	21-d	EC_{10}	Biomass (dry)	31	26.09	104	FT	Ingersoll and Mebane 2013

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Fish - Salmonid (cont.)										
Oncorhynchus mykiss	Rainbow trout	1 dph	21-d	EC_{10}	Survival	37	31.14	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	21-d	EC_{20}	Biomass (dry)	36	**30.3**	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	21-d	EC_{20}	Survival	43	36.19	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	21-d	MATC	Biomass (dry)	42	35.35	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	21-d	MATC	Survival	42	35.35	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	EC_{10}	Biomass (dry)	25	21.04	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	EC_{10}	Dry weight	13	10.94	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	EC_{10}	Survival	34	28.62	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	EC_{20}	Biomass (dry)	30	**25.25**	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	EC_{20}	Dry weight	43	36.19	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	EC_{20}	Survival	39	32.82	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	MATC	Biomass (dry)	18	15.15	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	MATC	Dry weight	18	15.15	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	26 dph	28-d	MATC	Survival	38	31.98	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	EC_{10}	Biomass (dry)	30	25.25	104	FT	Ingersoll and Mebane 2013

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Fish - Salmonid (cont.)										
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	EC_{10}	Survival	34	28.62	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	EC_{20}	Biomass (dry)	32	**26.93**	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	EC_{20}	Survival	36	30.3	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	MATC	Biomass (dry)	40	33.67	104	FT	Ingersoll and Mebane 2013
Oncorhynchus mykiss	Rainbow trout	1 dph	52-d	MATC	Survival	40	33.67	104	FT	Ingersoll and Mebane 2013
Invertebrate - Amphipod										
Gammarus pulex	Scud	Various	100-d	MATC	Mean no. of adults	16.3	13.83	103	FT	Maund *et al.* 1992
Gammarus pulex	Scud	Various	100-d	MATC	Mean no. of adults	12.7	10.78	103	FT	Maund *et al.* 1992
Gammarus pulex	Scud	Various	100-d	MATC	Population density	12.7	**10.78**	103	FT	Maund *et al.* 1992
Gammarus pulex	Scud	7 mm	30 min; 10-d Cu exposure	LOEC	Respiratory rate	10.8	8.801	108	FT	Kedwards *et al.* 1996
Invertebrate - Cladoceran										
Ceriodaphnia dubia	Water flea	NR	7-d	EC_{20}	Reproduction	20.17	**18.49**	94.1	NR	Belanger *et al.* 1989
Ceriodaphnia dubia	Water flea	NR	7-d	EC_{20}	Reproduction	9.17	**21.13**	32	NR	Carlson *et al.* 1986
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{10}	No. of young	11	9.183	105	R	Wang *et al.* 2011

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Invertebrate - Cladoceran (cont.)										
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{10}	No. of young	25	20.7 [7]	106	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{10}	No. of young	29	24.01 [8]	106	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{10}	No. of young	34	29.1	102	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{10}	No. of young	46	39.04 [8]	103	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{10}	Survival	10	8.348	105	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{10}	Survival	20	17.11	102	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{10}	Survival	65	53.82 [8]	106	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{10}	Survival	91	77.23 [8]	103	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{10}	Survival	200	165.6 [7]	106	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{20}	No. of young	12	**10.02**	105	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{20}	No. of young	40	**33.12** [8]	106	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{20}	No. of young	41	33.95 [7]	106	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{20}	No. of young	42	35.94	102	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{20}	No. of young	59	**50.07** [8]	103	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{20}	Survival	13	10.85	105	R	Wang *et al.* 2011

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Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Invertebrate - Cladoceran (cont.)										
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{20}	Survival	34	**29.1**	102	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{20}	Survival	83	68.73 [8]	106	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{20}	Survival	98	83.17 [8]	103	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	EC_{20}	Survival	215	178 [7]	106	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	MATC	No. of young	7.9	6.704 [8]	103	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	MATC	No. of young	11	9.183	105	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	MATC	No. of young	14	11.98	102	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	MATC	No. of young	19	15.73 [7]	106	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	MATC	No. of young	35	28.98 [8]	106	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	MATC	Survival	24	20.04	105	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	MATC	Survival	64	54.77	102	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	MATC	Survival	131	111.2 [8]	103	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	MATC	Survival	151	125 [8]	106	R	Wang *et al.* 2011
Ceriodaphnia dubia	Water flea	<24-h	7-d	MATC	Survival	288	238.5 [7]	106	R	Wang *et al.* 2011

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Invertebrate - Mussel										
Epioblasma capsaeformis	Oyster mussel	Juvenile	10-d	EC_{50}	Survival	5.9	3.008	187	R	Wang *et al.* 2007b
Epioblasma capsaeformis	Oyster mussel	Juvenile	10-d	EC_{50}	Survival	15	7.647	187	R	Wang *et al.* 2007b
Epioblasma capsaeformis	Oyster mussel	2 months	28-d	Chronic Value	Growth	4.6	**2.651**	162	FT	Wang *et al.* 2007c
Epioblasma capsaeformis	Oyster mussel	2 months	28-d	Chronic Value	Survival	9.3	5.36	162	FT	Wang *et al.* 2007c
Lampsilis fasciola	Wavy-rayed lampmussel	Juvenile	10-d	EC_{50}	Survival	4.8	2.447	187	R	Wang *et al.* 2007b
Lampsilis fasciola	Wavy-rayed lampmussel	Juvenile	10-d	EC_{50}	Survival	6.7	3.416	187	R	Wang *et al.* 2007b
Lampsilis rafinesqueana	Neosho mucket	Juvenile	10-d	EC_{50}	Survival	8.7	4.435	187	R	Wang *et al.* 2007b
Lampsilis rafinesqueana	Neosho mucket	Juvenile	10-d	EC_{50}	Survival	8.8	4.486	187	R	Wang *et al.* 2007b
Lampsilis siliquoidea	Fatmucket	Juvenile	10-d	EC_{50}	Survival	8.1	4.129	187	R	Wang *et al.* 2007b
Lampsilis siliquoidea	Fatmucket	2 months	28-d	Chronic Value	Growth	8.5	4.822	165	FT	Wang *et al.* 2007c
Lampsilis siliquoidea	Fatmucket	2 months	28-d	Chronic Value	Survival	8.5	**4.822**	165	FT	Wang *et al.* 2007c
Leptodea leptodon	Scaleshell	Juvenile	10-d	EC_{50}	Survival	14	7.137	187	R	Wang *et al.* 2007b
Villosa iris	Rainbow mussel	Juvenile	10-d	EC_{50}	Survival	12	6.118	187	R	Wang *et al.* 2007b
Villosa iris	Rainbow mussel	Juvenile (2 months)	10-d	EC_{50}	Survival	8.6	4.384	187	R	Wang *et al.* 2007b
Villosa iris	Rainbow mussel	Juvenile (2 months)	10-d	EC_{50}	Survival	13	6.627	187	R	Wang *et al.* 2007b

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Invertebrate - Mussel (cont.)										
Villosa iris	Rainbow mussel	2 months	28-d	Chronic Value	Growth	5.1	**2.806**	171	FT	Wang *et al.* 2007c
Villosa iris	Rainbow mussel	2 months	28-d	Chronic Value	Survival	9.8	5.393	171	FT	Wang *et al.* 2007c
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Biomass	5.9	5.224	98	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Biomass	9.2	7.939	101	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Biomass	29	25.24 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Length	11	9.493	101	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Length	11	9.74	98	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Length	42	36.55 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Survival	12	10.36	101	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Survival	21	18.6	98	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Survival	52	45.26 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Weight	3.8	3.365	98	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Weight	6.2	5.35	101	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{10}	Weight	21	18.28 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Biomass	8.8	7.792	98	FT	Wang *et al.* 2011

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Invertebrate - Mussel (cont.)										
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Biomass	10	8.63	101	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Biomass	38	33.07 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Length	21	18.6	98	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Length	83	72.24 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Length	>11	>9.493	101	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Survival	13	11.22	101	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Survival	25	22.14	98	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Survival	61	53.09 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Weight	7.5	**6.641**	98	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Weight	8.3	**7.163**	101	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	EC_{20}	Weight	35	30.46 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Biomass	16	13.81	101	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Biomass	16	14.17	98	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Biomass	39	33.94 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Length	16	14.17	98	FT	Wang *et al.* 2011

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Invertebrate - Mussel (cont.)										
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Length	39	33.94 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Length	>11	>9.493	101	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Survival	16	13.81	101	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Survival	16	14.17	98	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Survival	70	60.92 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Weight	16	14.17	98	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Weight	39	33.94 [7]	100	FT	Wang *et al.* 2011
Villosa iris	Rainbow mussel	3-month old juveniles	28-d	MATC	Weight	>11	>9.493	101	FT	Wang *et al.* 2011
Invertebrate - Snail										
Fluminicola sp.	Pebblesnail	9-11 weeks	7-d	EC_{20}	Survival	7.8	**4.472**	163	FT	Besser *et al.* 2013
Fluminicola sp.	Pebblesnail	9-11 weeks	7-d	EC_{50}	Survival	12.4	7.109	163	FT	Besser *et al.* 2013
Fluminicola sp.	Pebblesnail	9-11 weeks	14-d	EC_{20}	Survival	7.63	4.374	163	FT	Besser *et al.* 2013
Fluminicola sp.	Pebblesnail	9-11 weeks	14-d	EC_{50}	Survival	9.76	5.595	163	FT	Besser *et al.* 2013
Physa gyrina	Pond snail	2-3 weeks	14-d	EC_{20}	Survival	28.7	**16.03**	168	FT	Besser *et al.* 2013
Physa gyrina	Pond snail	2-3 weeks	14-d	EC_{20}	Survival	41	**23.5**	163	FT	Besser *et al.* 2013

Table A3.2. Summary of compiled chronic aquatic toxicity data for copper.

Receptor Group / Scientific Name	Common Name	Life Stage	Test Duration	Effect Level	Toxicity Test Endpoint	Effect Concentration (µg/L)		Original Hardness (mg $CaCO_3$/L)	Test Type	Reference
						Original Effect	Normalized Effect [1]			
Invertebrate - Snail (cont.)										
Physa gyrina	Pond snail	2-3 weeks	28-d	EC_{20}	Length	16.1	**8.995**	168	FT	Besser *et al.* 2013
Physa gyrina	Pond snail	2-3 weeks	28-d	EC_{20}	Length	25.9	**14.85**	163	FT	Besser *et al.* 2013
Physa gyrina	Pond snail	2-3 weeks	28-d	EC_{20}	Survival	25.8	14.41	168	FT	Besser *et al.* 2013
Physa gyrina	Pond snail	2-3 weeks	28-d	EC_{20}	Survival	41	23.5	163	FT	Besser *et al.* 2013
Physa gyrina	Pond snail	2-3 weeks	7-d	EC_{20}	Survival	58	**33.25**	163	FT	Besser *et al.* 2013

ALS = aquatic life stage; AWQC = ambient water quality criteria; d = day; DOC = dissolved organic carbon; dph = days post-hatch; EC = effect concentration; ELS = early life stage; FT = flow-through; h = hour; LOEC = lowest observed effect concentration; MATC = maximum acceptable toxicant concentration; no. = number; NR = not reported; R = renewal; SMCV = species mean chronic value; USEPA = United States Environmental Protection Agency.

[1] Effect value normalized to a hardness of 85 mg/L, using the slope from a previous version of the USEPA AWQC (USEPA 1985).

[2] Data from USEPA (2007) used in the calculation of SMCVs for the AWQC for copper. Values were used in the recalculation of SMCVs for this report except where noted.

[3] This value was not used in the recalculation of SMCVs because it is a "greater than" or "less than" value and there are measured values for this species.

[4] This value was not used in the recalculation of SMCVs because it is a chronic value and USEPA (2007) also presented a lower EC_{20} from the same test.

[5] This value was not used in the recalculation of SMCVs because it is a dissolved value and USEPA (2007) chose to use total values for all other chronic results; the total value was also presented by USEPA (2007).

[6] Additional data not used in the derivation of the aquatic life AWQC for copper (USEPA 2007). Bolded values were used in the recalculation of the SMCV.

[7] This test was performed with 10 mg/L DOC in the water.

[8] This test was performed with 5 mg/L DOC in the water.

Table A3.3. Species and genus mean acute values used in the derivation and recalculation of the national recommended ambient water quality criteria for copper.

Receptor Group / Scientific Name	Common Name	USEPA (2007) Values		Recalculated Values[1]	
		SMAV (µg/L)	GMAV (µg/L)	SMAV (µg/L)	GMAV (µg/L)
Amphibian					
Bufo boreas	Boreal toad	47.49	47.49	47.49	47.49
Fish					
Acrocheilus alutaceus	Chiselmouth	216.3	216.3	216.3	216.3
Etheostoma flabellare	Fantail darter	124.3		124.3	
Etheostoma fonticola	Fountain darter	22.74		22.74	
Etheostoma lepidum	Greenthroat darter	82.8		82.8	
Etheostoma nigrum	Johnny darter	178.3	80.38	178.3	80.38
Gila elegans	Bonytail chub	63.22	63.22	63.22	63.22
Lepomis macrochirus	Bluegill sunfish	2231	2231	2231	2231
Notemigonus crysoleucas	Golden shiner	107860	107860	107860	107860
Pimephales promelas	Fathead minnow	69.63	69.63	**70.13**	**70.13**
Poeciliopsis occidentalis	Gila topminnow	56.15	56.15	56.15	56.15
Ptychocheilus lucius	Colorado squawfish	132.2		132.2	
Ptychocheilus oregonensis	Northern squawfish	14.61	43.94	14.61	43.94
Scaphirhynchus platorynchus	Shovelnose sturgeon	69.63	69.63	69.63	69.63
Xyrauchen texanus	Razorback sucker	78.66	78.66	78.66	78.66
Fish - Salmonid					
Oncorhynchus apache	Apache trout	32.54		32.54	
Oncorhynchus clarkii henshawi	Lahontan cutthroat trout	32.97		32.97	
Oncorhynchus gorbuscha	Pink salmon	40.13		40.13	
Oncorhynchus kisutch	Coho salmon	22.93		22.93	
Oncorhynchus mykiss	Rainbow trout	22.19		**23.92**	
Oncorhynchus nerka	Sockeye salmon	54.82		54.82	
Oncorhynchus tshawytscha	Chinook salmon	25.02	31.39	25.02	**31.50**
Salvelinus confluentus	Bull trout	68.31	68.31	68.31	68.31
Invertebrate - ALS Insect					
Acroneuria lycorias	Stonefly	20636	20636	20636	20636
Chironomus decorus	Midge	1987	1987	1987	1987
Invertebrate - Amphipod					
Gammarus pseudolimnaeus	Amphipod	9.6	9.6	9.6	9.6
Hyalella azteca	Amphipod	12.07	12.07	12.07	12.07
Invertebrate - Cladoceran					
Ceriodaphnia dubia	Cladoceran	5.93	5.93	**6.211**	**6.211**
Daphnia magna	Cladoceran	6		6	
Daphnia pulicaria	Cladoceran	2.73	4.05	2.73	4.05
Scapholeberis sp.	Cladoceran	9.73	9.73	9.73	9.73

Table A3.3. Species and genus mean acute values used in the derivation and recalculation of the national recommended ambient water quality criteria for copper.

Receptor Group / Scientific Name	Common Name	USEPA (2007) Values		Recalculated Values[1]	
		SMAV (µg/L)	GMAV (µg/L)	SMAV (µg/L)	GMAV (µg/L)
Invertebrate - Mussel					
Actinonaias pectorosa	Pheasantshell	11.33	11.33	**10.36**	**10.36**
Epioblasma capsaeformis	Oyster mussel	ND		**4.786**	**4.786**
Lampsilis fasciola	Wavy-rayed lampmussel	ND		**9.434**	
Lampsilis rafinesqueana	Neosho mucket	ND		**15.1**	
Lampsilis siliquoidea	Fatmucket	ND		**6.078**	**9.531**
Lasmigona subviridis	Green floater	ND		**55.31**	**55.31**
Leptodea leptodon	Scaleshell mussel	ND		**9.9**	**9.9**
Utterbackia imbecillis	Pondshell mussel	52.51	52.51	**31.39**	**31.39**
Villosa iris	Rainbow mussel	ND		**4.602**	**4.602**
Invertebrate - Snail					
Campeloma decisum	Pointed campeloma	3573	3573	3573	3573
Juga plicifera	Snail	12.31	12.31	12.31	12.31
Lithoglyphus virens	Snail	6.67	6.67	6.67	6.67
Physa integra	Snail	20.41	20.41	20.41	20.41
Invertebrate - Worm					
Lumbriculus variegatus	Worm	48.41	48.41	48.41	48.41

GMAV = genus mean acute value; ND = no data; SMAV = species mean acute value; USEPA = United States Environmental Protection Agency.

[1] Bolded values indicate recalculated SMAVs/GMAVs (i.e., values are different than the values used in USEPA 2007).

Table A3.4. Species and genus mean chronic values used in the derivation and recalculation of the national recommended ambient water quality criteria for copper.

Receptor Group / Scientific Name	Common Name	USEPA (2007) Values[1]		Recalculated Values[2]	
		SMCV (µg/L)	GMCV (µg/L)	SMCV (µg/L)	GMCV (µg/L)
Fish					
Acipenser transmontanus	White sturgeon	ND		**2.001**	**2.001**
Catostomus commersoni	White sucker	20.9	20.9	**35.68**	**35.68**
Esox lucius	Northern pike	60.4	60.4	**103.2**	**103.2**
Lepomis macrochirus	Bluegill sunfish	27.2	27.2	**45.05**	**45.05**
Pimephales notatus	Bluntnose minnow	18		**8.627**	
Pimephales promelas	Fathead minnow	9.38	13	**16.15**	**11.8**
Fish - Salmonid					
Oncorhynchus mykiss	Rainbow trout	23.8		**21.68**	
Oncorhynchus tshawytscha	Chinook salmon	5.92	11.9	**13.46**	**17.08**
Salmo trutta	Brown trout	29.9	29.9	**51.12**	**51.12**
Salvelinus fontinalis	Brook trout	12.5		**53.23**	
Salvelinus namaycush	Lake trout	30.9	19.7	**52.88**	**53.05**
Invertebrate - ALS Insect					
Clistoronia magnifica	Caddisfly	7.67	7.67	**21.11**	**21.11**
Invertebrate - Amphipod					
Gammarus pulex	Scud	ND		**10.78**	**10.78**
Invertebrate - Cladoceran					
Ceriodaphnia dubia	Cladoceran	19.3	19.3	**22.33**	**22.33**
Daphnia magna	Cladoceran	14.1		**10.8**	
Daphnia pulex	Cladoceran	5.68	8.96	**4.387**	**6.885**
Invertebrate - Mussel					
Epioblasma capsaeformis	Oyster mussel	ND		**2.651**	**2.651**
Lampsilis siliquoidea	Fatmucket	ND		**4.822**	**4.822**
Villosa iris	Rainbow mussel	ND		**5.111**	**5.111**
Invertebrate - Rotifer					
Brachionus calyciflorus	Rotifer	3.54	3.54	**3.54** [3]	**3.54** [3]
Invertebrate - Snail					
Campeloma decisum	Snail	9.77	9.77	**16.83**	**16.83**
Fluminicola sp.	Pebblesnail	ND		**4.472**	**4.472**
Physa gyrina	Pond snail	ND		**17.57**	**17.57**

ACR = acute-chronic ratio; AWQC = ambient water quality criteria; GMCV = genus mean chronic value; ND = no data; SMCV = species mean chronic value; USEPA = United States Environmental Protection Agency.

[1] USEPA (2007) calculated the chronic AWQC using the ACR, so these SMCVs and GMCVs were not normalized to a common hardness.

[2] Data from USEPA (2007) as well as additional data were normalized to a hardness of 85 mg/L prior to calculating these SMCVs and GMCVs (bolded values indicate recalculated SMCVs/GMCVs).

[3] The recalculated value is the same as the value from USEPA (2007) because this test was originally performed at a hardness of 85 mg/L.

List of References

Andros, J.D. and R.R. Garton. 1980. Acute lethality of copper, cadmium, and zinc to northern squawfish. Transactions of the American Fisheries Society 109: 235. (As cited in USEPA 2007).

Arthur, J.W. and E.N. Leonard. 1970. Effects of copper on *Gammarus pseudolimnaeus*, *Physa integra*, and *Campeloma decisum* in soft water. Journal of the Fisheries Research Board of Canada 27:1277-1283. (As cited in USEPA 2007).

Baird, D.J., I. Barber, M. Bradley, A.M.V.M. Soares and P. Calow. 1991. A comparative study of genotype sensitivity to acute toxic stress using clones of *Daphnia magna* Straus. Ecotoxicological and Environmental Safety 21(3): 257-265. (As cited in USEPA 2007).

Belanger, S.E. and D.S. Cherry. 1990. Interacting effects of pH acclimation, pH, and heavy metals of acute and chronic toxicity to *Ceriodaphnia dubia* (Cladoceran). Journal of Crustacean Biology 10(2):225-235. (As cited in USEPA 2007).

Belanger, S.E., J.L. Farris and D.S. Cherry. 1989. Effects of diet, water hardness, and population source on acute and chronic copper toxicity to *Ceriodaphnia dubia*. Archives of Environmental Contamination and Toxicology 18(4):601-611. (As cited in USEPA 2007).

Benoit, D.A. 1975. Chronic effects of copper on survival, growth, and reproduction of bluegill (*Lepomis macrochirus*). Transactions of the American Fisheries Society 104(2):353-358. (As cited in USEPA 2007).

Benson, W.H. and W.J. Birge. 1985. Heavy metal tolerance and metallothionein induction in fathead minnows: Results from field and laboratory investigations. Environmental Toxicology and Chemistry 4(2):209-217. (As cited in USEPA 2007).

Besser, J.M., J.F. Dwyer, C.G. Ingersoll and N. Wang. 2001. Early life-stage toxicity of copper to endangered and surrogate fish species. EPA Project No. DW14937809-01-0. Office of Research and Development, Washington, DC. (As cited in USEPA 2007).

Besser, J., R. Warbritton, and C. Ingersoll. 2013. Data summary for project, "Development of methods for propagation of ESA-listed and surrogate species of freshwater snails for use in toxicity testing." Draft. Columbia Environmental Research Center, U.S. Geological Survey, Columbia, MO.

Birge, W.J., W.H. Benson and J.A. Black. 1983. The induction of tolerance to heavy metals in natural and laboratory populations of fish. PB84-111756. National Technical Information Service, Springfield, VA. (As cited in USEPA 2007).

Black, M.C. 2001. Water quality standards for North Carolina's endangered mussels. Final Report. Department of Health Science, University of Georgia, Athens, GA. (As cited in Wang *et al.* 2009).

Blaylock, B.G., M.L. Frank and J.F. McCarthy. 1985. Comparative toxicity of copper and acridine to fish, *Daphnia* and algae. Environmental Toxicology and Chemistry 4(1):63-71. (As cited in USEPA 2007).

Buckley, J.A. 1983. Complexation of copper in the effluent of a sewage treatment plant and an estimate of its influence on toxicity to coho salmon. Water Research 17(12):1929-1934. (As cited in USEPA 2007).

Cacela, D., R. Hudson, J. Lipton, J. Marr, T. Podrabsky and P. Welsh. 1996. Preliminary Toxicological Evaluation. U.S. v. Iron Mountain Mines, Inc. Prepared by Hagler Bailly Consulting, Inc. Boulder, CO. (As cited in USEPA 2007).

Cairns, J., Jr., K.W. Thompson and A.C. Hendricks. 1981. Effects of fluctuating, sublethal applications of heavy metal solutions upon the gill ventilation response of bluegills (*Lepomis macrochirus*). EPA-600/3-81-003. National Technical Information Service, Springfield, VA. (As cited in USEPA 2007).

Carlson, A.R., H. Nelson and D. Hammermeister. 1986. Development and validation of site-specific water quality criteria for copper. Environmental Toxicology and Chemistry 5(11):997-1012. (As cited in USEPA 2007).

Chakoumakos, C., R.C. Russo and R.V. Thurston. 1979. The toxicity of copper to cutthroat trout (*Salmo clarki*) under different conditions of alkalinity, pH, and hardness. Environmental Science and Technology 13:213-219. (As cited in USEPA 2007).

Chapman, G.A. 1975. Toxicity of copper, cadmium and zinc to Pacific Northwest salmonids. U.S. Environmental Protection Agency, Corvallis, Oregon. (As cited in USEPA 2007).

Chapman, G.A. 1978. Toxicities of cadmium, copper, and zinc to four juvenile stages of chinook salmon and steelhead. Transactions of the American Fisheries Society 107:841-847. (As cited in USEPA 2007).

Chapman, G.A. 1982. Chinook salmon early life stage tests with cadmium, copper, and zinc. Letter of December 6, 1982 to Charles Stephan, U.S. Environmental Protection Agency Environmental Research Laboratory, Duluth, Corvallis, Oregon. 4 pp. (As cited in USEPA 2007).

Chapman, G.A. and J.K. McCrady. 1977. Copper toxicity: A question of form. In: Recent advances in fish toxicology. Tubb, R.A. (Ed.). EPA-600/3-77-085. National Technical Information Service, Springfield, VA. p. 132. (As cited in USEPA 2007).

Chapman, G.A. and D.G. Stevens. 1978. Acute lethal levels of cadmium, copper, and zinc to adult male coho salmon and steelhead. Transactions of the American Fisheries Society 107:837-840. (As cited in USEPA 2007).

Chapman, G.A., S. Ota and F. Recht. Manuscript. Effects of water hardness on the toxicity of metals to *Daphnia magna*. U.S. EPA, Corvallis, OR. (As cited in USEPA 2007).

Cusimano, R.F., D.F. Brakke and G.A. Chapman. 1986. Effects of pH on the toxicities of cadmium, copper, and zinc to steelhead trout (*Salmo gairdneri*). Canadian Journal of Fisheries and Aquatic Sciences 43:1497-1503. (As cited in USEPA 2007).

Diamond, J.M., D.E. Koplish, J. McMahon III and R. Rost. 1997. Evaluation of the water-effect ratio procedure for metals in a riverine system. Environmental Toxicology and Chemistry 16(3):509-520. (As cited in USEPA 2007).

Dwyer, F.J., L.C. Sappington, D.R. Buckler and S.B. Jones. 1995. Use of surrogate species in assessing contaminant risk to endangered and threatened fishes. Final Report - September, 1995. U.S. Environmental Protection Agency, Office of Research and Development. Gulf Breeze, Florida. EPA/600/R-96/029. (As cited in USEPA 2007).

Dwyer, F.J., D.K. Hardesty, C.E. Henke, C.G. Ingersoll, D.W. Whites, D.R. Mount and C.M. Bridges. 1999. Assessing contaminant sensitivity of endangered and threatened species: Toxicant classes. EPA/600/R-99/098. (As cited in USEPA 2007).

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

Erickson, R.J., D.A. Benoit, V.R. Mattson, H.P. Nelson, Jr. and E.N. Leonard. 1996b. The effects of water chemistry on the toxicity of copper to fathead minnows. Environmental Toxicology and Chemistry 15(2):181-193. (As cited in USEPA 2007).

Hansen, J.A., J. Lipton, P.G. Welsh and D. Cacela. 2000. Relationship between exposure duration, tissue residues, growth, and mortality in rainbow trout (*Oncorhynchus mykiss*) sub-chronically exposed to copper. Final Report. Stratus Consulting Inc. September 20, 2000. (As cited in USEPA 2007).

Hartwell, S.I., J.H. Jin, D.S. Cherry and J. Cairns, Jr. 1989. Toxicity versus avoidance response of golden shiner, *Notemigonus crysoleucas*, to five metals. Journal of Fish Biology 35(3):447-456. (As cited in USEPA 2007).

Horning, W.B. and T.W. Neiheisel. 1979. Chronic effect of copper on the bluntnose minnow, *Pimephales notatus* (Rafinesque). Archives of Environmental Contamination and Toxicology 8:545-552. (As cited in USEPA 2007).

Ingersoll, C.G. and C.A. Mebane (Eds.). Draft. Acute and chronic sensitivity of white sturgeon (*Acipenser transmontanus*) and rainbow trout (*Oncorhynchus mykiss*) to cadmium, copper, lead, or zinc in water-only laboratory exposures. U.S. Geological Survey. Columbia Environmental Research Center. Columbia, Missouri.

Janssen, C.R., G. Persoone and T.W. Snell. 1994. Cyst-based toxicity tests. VIII. Short-chronic toxicity tests with the freshwater rotifer *Brachionus calyciflorus*. Aquatic Toxicology 28:243-258. (As cited in USEPA 2007).

Kedwards, T.J., S.J. Blockwell, E.J. Taylor and D. Pascoe. 1996. Design of an electronically operated flow-through respirometer and its use to investigate the effects of copper on the respiration rate of the amphipod *Gammarus pulex* (L.). Bulletin of Environmental Contamination and Toxicology 57(4):610-616.

Keller, A.E. Unpublished. Personal Communication to U.S. EPA. (As cited in USEPA 2007).

Keller, A.E. and S.G. Zam. 1991. The acute toxicity of selected metals to the freshwater mussel, *Anodonta imbecilis*. Environmental Toxicology and Chemistry 10: 539-546. (As cited in USEPA 2007).

Kosalwat, P. and A.W. Knight. 1987. Acute toxicity of aqueous and substrate-bound copper to the midge, *Chironomus decorus*. Archives of Environmental Contamination and Toxicology 16(3):275-282. (As cited in USEPA 2007).

Lind, D., Alto and Chatterton. Manuscript (1978). Regional copper-nickel study: Aquatic toxicology study. Preliminary draft report, Minnesota Environmental Quality Board, St. Paul, MN. (As cited in USEPA 2007).

Long's MS Thesis. (As cited in USEPA 2007).

Lydy, M.J. and T.E. Wissing. 1988. Effect of sublethal concentrations of copper on the critical thermal maxima (CTMax) of the fantail (*Etheostoma flabellare*) and johnny (*E. nigrum*) darters. Aquatic Toxicology 12(4):311-321. (As cited in USEPA 2007).

Maund, S.J., E.J. Taylor and D. Pascoe. 1992. Population responses of the freshwater amphipod crustacean *Gammarus pulex* (L.) to copper. Freshwater Biology 28(1):29-36.

McKim, J.M., J.G. Eaton and G.W. Holcombe. 1978. Metal toxicity to embryos and larvae of eight species of freshwater fish - II. Copper. Bulletin of Environmental Contamination and Toxicology 19:608-616. (As cited in USEPA 2007).

Meador, J.P. 1991. The interaction of pH, dissolved organic carbon, and total copper in the determination of ionic copper and toxicity. Aquatic Toxicology 19(1):13-31. (As cited in USEPA 2007).

Mudge, J.E., T.E. Northstrom, G.S. Jeane, W. Davis and J.L. Hickam. 1993. Effect of varying environmental conditions on the toxicity of copper to salmon. In: Environmental toxicology and risk assessment. Gorsuch, J.W., F.J. Dwyer, C.G. Ingersoll and T.W. LaPoint (Eds.). ASTM STP 1216. American Society for Testing and Materials, Philadelphia, PA. pp. 19-33. (As cited in USEPA 2007).

Nebeker, A.V., C. Savonen, R.J. Baker and J.K. McCrady. 1984. Effects of copper, nickel and zinc on the life cycle of the caddisfly *Clistoronia magnifica* (limnephilidae). Environmental Toxicology and Chemistry 3(4):645-649. (As cited in USEPA 2007).

Nebeker, A.V., M.A. Cairns, S.T. Onjukka and R.H. Titus. 1986a. Effect of age on sensitivity of *Daphnia magna* to cadmium, copper and cyanazine. Environmental Toxicology and Chemistry 5(6):527-30. (As cited in USEPA 2007).

Nebeker, A.V., A. Stinchfield, C. Savonen and G.A. Chapman. 1986b. Effects of copper, nickel and zinc on three species of Oregon freshwater snails. Environmental Toxicology and Chemistry 5(9):807-811. (As cited in USEPA 2007).

Oris, J.T., R.W. Winner and M.V. Moore. 1991. A four-day survival and reproduction toxicity test for *Ceriodaphnia dubia*. Environmental Toxicology and Chemistry 10(2):217-224. (As cited in USEPA 2007).

Richards, V.L. and T.L. Beitinger. 1995. Reciprocal influences of temperature and copper on survival of fathead minnows, *Pimephales promelas*. Bulletin of Environmental Contamination and Toxicology 55(2):230-6. (As cited in USEPA 2007).

Sandahl, J.F., D.H. Baldwin, J.J. Jenkins and N.L. Scholz. 2004. Odor-evoked field potentials as indicators of sublethal neurotoxicity in juvenile coho salmon (*Onchorhynchus kisutch*) exposed to copper, chlorpyrifos, or esfenvalerate. Canadian Journal of Fisheries and Aquatic Sciences 61:404-413.

Sauter, S., K. S. Buxton, K. J. Macek and S. R. Petrocelli. 1976. Effects of exposure to heavy metals on selected fresh water fish: Toxicity of copper, cadmium, chromium and lead to eggs and fry of seven fish species. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency. EPA-600/3-76-105. (As cited in USEPA 2007).

Schubauer-Berigan, M.K., J.R. Dierkes, P.D. Monson and G.T. Ankley. 1993. pH-dependent toxicity of Cd, Cu, Ni, Pb and Zn to *Ceriodaphnia dubia*, *Pimephales promelas*, *Hyalella azteca* and *Lumbriculus variegatus*. Environmental Toxicology and Chemistry 12: 1261-1266. (As cited in USEPA 2007).

Seim, W.K., L.R. Curtis, S.W. Glenn and G.A. Chapman. 1984. Growth and survival of developing steelhead trout (*Salmo gairdneri*) continuously or intermittently exposed to copper. Canadian Journal of Fisheries and Aquatic Sciences 41(3):433-438. (As cited in USEPA 2007).

Servizi, J.A. and D.W. Martens. 1978. Effects of selected heavy metals on early life of sockeye and pink salmon. International Pacific Salmon Fisheries Commission, New Westminster, B.C., Canada, Progress Report No. 39. (As cited in USEPA 2007).

Spehar, RL. and J.T. Fiandt. 1986. Acute and chronic effects of water quality criteria-based metal mixtures on three aquatic species. Environmental Toxicology and Chemistry 5(10): 917-931. (As cited in USEPA 2007).

USEPA (United States Environmental Protection Agency). 1985. Ambient water quality criteria for copper - 1984. EPA 440/5-84-031. Office of Water, Office of Research and Development, Washington, D.C.

USEPA (United States Environmental Protection Agency). 2007. Aquatic life ambient freshwater quality criteria - copper. 2007 Revision. EPA-822-R-07-001. CAS Registry Number 7440-50-8. Office of Water, Office of Science and Technology, Washington, D.C.

van Leeuwen, C.J., J.L. Buchner and H. van Dijk. 1988. Intermittent flow system for population toxicity studies demonstrated with *Daphnia* and copper. Bulletin of Environmental Contamination and Toxicology 40(4):496-502. (As cited in USEPA 2007).

Wang, N., C.G. Ingersoll , D.K. Hardesty, C.D. Ivey, J.L. Kunz, T.W. May, F.J. Dwyer, A.D. Roberts, T. Augspurger, C.M. Kane, R.J. Neves and M.C. Barnhart. 2007a. Contaminant sensitivity of freshwater mussels: Acute toxicity of copper, ammonia, and chlorine to glochidia and juveniles of freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10): 2036-2047. (As cited in Wang *et al.* 2009).

Wang, N., C.G. Ingersoll , D.K. Hardesty, C.D. Ivey, J.L. Kunz, T.W. May, F.J. Dwyer, A.D. Roberts, T. Augspurger, C.M. Kane, R.J. Neves and M.C. Barnhart. 2007b. Contaminant sensitivity of freshwater mussels: Acute toxicity of copper, ammonia, and chlorine to glochidia and juveniles of freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10): 2036-2047.

Wang, N., C.G. Ingersoll, D.K. Hardesty, I.E. Greer, D.J. Hardesty, C.D. Ivey, J.L. Kunz, W.G. Brumbaugh, F.J. Dwyer, A.D. Roberts, J.T. Augspurger, C.M. Kane, R.J. Neves and M.C. Barnhart. 2007c. Contaminant sensitivity of freshwater mussels: Chronic toxicity of copper and ammonia to juvenile freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10): 2048-2056.

Wang, N., C.A. Mebane, J.L. Kunz, C.G. Ingersoll, T.W. May, W.R. Arnold, R.C. Santore, T. Augspurger, F.J. Dwyer and M.C. Barnhart. 2009. Evaluation of acute copper toxicity to juvenile freshwater mussels (fatmucket, *Lampsilis siliquoidea*) in natural and reconstituted waters. Environmental Toxicology and Chemistry 28(11):2367-2377.

Wang, N., C.A. Mebane, J.L. Kunz, C.G. Ingersoll, W.G. Brumbaugh, R.C. Santore, J.W. Gorsuch and W.R. Arnold. 2011. Influence of dissolved organic carbon on toxicity of copper to a unionid mussel (*Villosa iris*) and a cladoceran (*Ceriodaphnia dubia*) in acute and chronic water exposures. Environmental Toxicology and Chemistry 30(9):2115-2125.

Warnick, S.L. and H.L. Bell. 1969. The acute toxicity of some heavy metals to different species of aquatic insects. Journal of Water Pollution Control Federation 41: 280. (As cited in USEPA 2007).

Warren, L.W. The use of juvenile mussels, *Utterbackia imbecillis* Say (Bivalvia: Unionidea), as a standardized toxicity testing organism. 1996. PhD dissertation. Clemson University, Clemson, SC, USA. (As cited in Wang *et al.* 2009).

Welsh, P.G. 1996. Influence of dissolved organic carbon on the speciation, bioavailability and toxicity of metals to aquatic biota in soft water lakes. Ph.D. Thesis, University of Waterloo. Waterloo, Ontario, Canada. (As cited in USEPA 2007).

Welsh, P.G., J.F. Skidmore, D.J. Spry, D.G. Dixon, P.V. Hodson, N.J. Hutchinson and B.E. Hickie. 1993. Effect of pH and dissolved organic carbon on the toxicity of copper to larval fathead minnow (*Pimephales promelas*) in natural lake waters of low alkalinity. Canadian Journal of Fisheries and Aquatic Sciences 50(7):1356-1362. (As cited in USEPA 2007).

Welsh, P.G., J. Lipton, G.A. Chapman and T.L. Podrabsky. 2000. Relative importance of calcium and magnesium in hardness-based modification of copper toxicity. Environmental Toxicology and Chemistry 19(6):1624-1631. (As cited in USEPA 2007).

Winner, R.W. 1985. Bioaccumulation and toxicity of copper as affected by interactions between humic acid and water hardness. Water Research 19(4):449-455. (As cited in USEPA 2007).

Appendix 4

Development of a Management Framework for Bioaccumulative Substances

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List of Acronyms

AWQC	ambient water quality criteria
BAF	bioaccumulation factor
BCF	bioconcentration factor
BCMOE	British Columbia Ministry of Environment
CCC	criterion continuous concentration
CCME	Canadian Council of Ministers of the Environment
CMC	criterion maximum concentration
COPC	chemical of potential concern
EPA	Environmental Protection Agency
FWS	Fish and Wildlife Service
I&M	Inventory and Monitoring
K_{ow}	octanol-water partition coefficient
NWR	National Wildlife Refuge
NWRS	National Wildlife Refuge System
PBDE	polybrominated diphenyl ether
PCB	polychlorinated biphenyl
RSWQT	refuge-specific water quality target
WQG	water quality guideline

1.0 Introduction

Water quality and water quantity are critical issues in many areas of the United States. Not surprisingly, National Wildlife Refuges (NWRs) are facing increasing challenges in terms of ensuring that water resources of sufficient quality and quantity are available to conserve and protect fish and wildlife, as well as the habitats upon which they depend. The Fish and Wildlife Service (FWS) has responded to this challenge by developing a framework for assessing the acceptability of wastewater, stormwater, and biosolids that provides a basis for evaluating risks to ecological receptors associated with exposure to contaminants. The *Handbook for Assessing Risks to Fish and Wildlife Associated with the Potential Use of Water, Treated Wastewater, Stormwater, Sediment, Soil, Biosolids, or Other Materials on Units of the National Wildlife Refuge System* (the *Handbook*; MacDonald *et al.* 2014), and the associated Excel-Based Assessment Tool, are intended to provide users with practical guidance for conducting expedited and detailed assessments of these materials to guide decisions that could affect environmental quality conditions on NWRs.

The procedures described in the *Handbook* are appropriate and relevant for conducting assessments of water resources. However, an assessment tool for evaluating existing refuge water supplies needs to have a higher level of site-specificity than the framework described in the *Handbook* to ensure that decisions related to the management of water resources explicitly address the resources of concern on NWRs, including threatened and endangered species and/or major taxa of concern to the Department of the Interior. The main report describes procedures for establishing refuge-specific water quality targets (RSWQTs) that can be used to evaluate water quality relative to the conditions required to protect the receptors that use aquatic habitats within the National Wildlife Refuge System (NWRS). However, a different approach to the development of RSWQTs is required for bioaccumulative substances (e.g., mercury and selenium) because the primary exposure pathway for these substances is typically through the diet (Neely *et al.* 1974). Therefore, these substances are

typically evaluated using benchmarks for invertebrate and/or fish tissues (CCME 2000; BCMOE 2014a; USEPA 2014a). However, there may be valid reasons for monitoring of bioaccumulative substances in the water column. For example, there may be regulatory requirements to measure certain substances (e.g., dissolved selenium) in the water column to support loading calculations (Toll *et al.* 2005; Presser and Luoma 2010). While the factors that influence bioaccumulation are highly site-specific and may not be easily predicted, water quality guidelines (WQGs) or criteria have been promulgated for certain bioaccumulative substances, such as mercury, polychlorinated biphenyls (PCBs), and selenium (e.g., BCMOE 2014b; CCME 2014; USEPA 2014b). In addition, tools have been developed, validated, and applied to determine protective concentrations of bioaccumulative substances in the water column using information on site-specific factors or empirical data. This appendix provides guidance on the selection of appropriate thresholds for application as preliminary RSWQTs for bioaccumulative substances and on the development of site-specific tools for determining bioaccumulation potential to support the development of final RSWQTs.

1.1 Intended Scope and Approach

This appendix is intended to provide refuge staff, FWS Contaminants Specialists, and FWS Water Resource Branch staff with guidance on the development of RSWQTs for bioaccumulative substances (with a focus on mercury and selenium) that will protect the ecological receptors that use aquatic habitats within the NWRS. This appendix also supports the evaluation of water quality in water bodies classified as Waters of Special Significance, Sensitive Waters, or Typical Waters, as described in the main report. In addition, the procedures described in this appendix will provide data and information that are appropriate and relevant for inclusion in comprehensive Inventory and Monitoring (I&M) programs.

1.2 Bioaccumulative Substances of Concern

Bioaccumulative substances are substances that accumulate in the tissues of aquatic organisms, such that the concentration within the tissues of the organisms exceeds the average concentration within the diet (i.e., the rate of uptake exceeds the rate of excretion). Bioaccumulative substances have a log octanol-water partition coefficient (K_{ow}) $\geq$ 3.5 or a bioconcentration factor (BCF) $\geq$ 5000. An important consequence of bioaccumulation is the potential for biomagnification of these substances with increasing trophic level in the food web. Bioaccumulative substances of importance in many aquatic ecosystems include mercury, selenium, PCBs, dioxins and furans, polybrominated diphenyl ethers (PBDEs), and organochlorine pesticides.

1.2.1 Mercury in the Aquatic Environment

Mercury is typically transported to aquatic environments through deposition of emissions from both natural sources (e.g., erosion, forest fires, volcanoes, and volatilization from freshwater bodies and oceans; Schroeder and Munthe 1998) and anthropogenic sources, including chlor-alkali manufacturing, coal combustion, metal production, refuse incineration, and wood combustion (Nriagu and Pacyna 1988), as well as direct discharges of process water from coal-burning power plants, metal manufacturing, and other industries (Nriagu and Pacyna 1988).

In the tissues of higher trophic-level aquatic organisms and aquatic-dependent wildlife, the majority (i.e., 90 - 100%) of the mercury concentration in muscle tissue is in the form methylmercury (CCME 2003). In aquatic ecosystems, mercury undergoes transformation to methylmercury via microbial processes (Winfrey and Rudd 1990). Simultaneously, methylmercury may become demethylated via similar microbial processes (Winfrey and Rudd 1990) and photodegradation (Sellers *et al.* 1996). The rates of methylation and demethylation are largely controlled by water quality and sediment quality conditions, including redox potential, pH, water temperature, and the concentrations of mercury, iron,

and sulfate (Winfrey and Rudd 1990). Wetland ecosystems are important sources of methylmercury (St. Louis *et al.* 1994) and thus the evaluation of methylmercury is an important component of the evaluation of contaminant conditions throughout the NWRS.

1.2.2 Selenium in the Aquatic Environment

Selenium is a rare trace element (Adriano 2001) that primarily originates from sedimentary rocks of marine origin and is typically found with coal and sulfur deposits (Sharma *et al.* 2014). Selenium is transported to aquatic ecosystems by erosion and as a result of various anthropogenic activities, including power generation, oil refining, metal refining, coal mining, and irrigation drainage (Presser *et al.* 2004; Sharma *et al.* 2014).

Selenium is an essential nutrient for most organisms, but is toxic at elevated concentrations. Exposure to elevated levels of selenium leads to adverse effects on reproduction and growth, increases the incidence of deformities, and decreases survival (BCMOE 2014a). Inorganic selenium enters the food web through uptake by bacteria, fungi, and primary producers, replacing sulfur during protein synthesis (Stadtman 1974). This organic selenium subsequently bioaccumulates and biomagnifies in aquatic organisms and aquatic-dependent wildlife of higher trophic levels. The uptake and transformation of selenium from the water column to the base of the food web is governed by a number of site-specific factors, including site hydrology, pH and redox potential (which affect selenium speciation), and the nature of the base of the food web (i.e., community composition; Presser and Luoma 2010). The dual nature of selenium (i.e., being both an essential nutrient and a toxicant) is an important consideration in the assessment of contaminant conditions in aquatic ecosystems. The "switch" between essentiality and toxicity (through bioaccumulation) occurs over a very narrow range of exposure concentrations. Therefore, the management of selenium

is an important component of the evaluation of contaminant conditions throughout the NWRS.

1.2.3 Other Bioaccumulative Substances

Persistent, bioaccumulative, and toxic substances such as PCBs, dioxins and furans, PBDEs, and organochlorine pesticides are important concerns in the management of aquatic ecosystems. While the production of some of these substances (e.g., PCBs) has been banned in North America, they remain within many aquatic ecosystems due to their persistence in the environment (CCME 2001). In addition, other substances (e.g., dioxins and furans) are by-products of many industrial processes and continue to be produced today. The compilation of appropriate tissue and dietary thresholds for these substances for application in the NWRS is beyond the scope of this appendix. However, Canadian and U.S. agencies have developed tissue- and diet-based thresholds for many of these substances and are useful sources of information for appropriate thresholds. Similarly, the methods described in Section 3.0 of this appendix offer guidance on methods that are recommended for use to derive site-specific thresholds that could be used for these substances.

2.0 Selection of Appropriate Targets for Evaluating Effects Related to Exposure to Bioaccumulative Substances

To ensure adequate protection of aquatic life and aquatic-dependent wildlife, refuge staff, FWS Contaminants Specialists, and FWS Water Resource Branch staff should adopt tissue-based benchmarks for evaluating the potential for adverse effects to aquatic life (i.e., fish) and aquatic-dependent wildlife (including birds and mammals) associated with exposure to bioaccumulative substances. The

following section provides information on draft and promulgated thresholds that are recommended for use as RSWQTs for mercury and selenium. A similar process could be used to develop RSWQTs for other bioaccumulative substances (e.g., PCBs) that are not addressed here.

2.1 Mercury Thresholds

The Environmental Protection Agency (EPA) has not promulgated tissue-based criteria for mercury or methylmercury in fish tissue for the protection of aquatic life (i.e., fish) or for the protection of aquatic-dependent wildlife (e.g., birds and mammals). However, ambient water quality criteria (AWQC) have been promulgated for total mercury in the water column. The current criterion continuous concentration (CCC) for total mercury is 0.77 µg/L. The CCC is defined as the concentration in the water column at which no adverse effects to aquatic life are expected during indefinite exposure (USEPA 2014b). For the purposes of evaluating water quality conditions against the CCC, the four-day mean concentration should not exceed the CCC more than once in three years (USEPA 2014b). The EPA has also developed a short-term maximum criterion, the criterion maximum concentration (CMC). The current CMC for total mercury is 1.4 µg/L. The CMC is defined as the maximum concentration at which no adverse effects to aquatic life are expected during brief exposure (USEPA 2014b). For the purposes of evaluating water quality conditions against the CMC, the one-hour mean concentration should not exceed the CMC more than once in three years (USEPA 2014b). Neither the CMC nor CCC has been derived to account for the potential of bioaccumulation. In water bodies with a moderate to high potential for methylmercury production (e.g., reservoirs, wetlands, etc.) these criteria are likely to be under-protective (USEPA 2014b).

The Canadian Council of Ministers of the Environment (CCME) has not promulgated tissue-based criteria for mercury or methylmercury in fish tissue to protect aquatic life. However, WQGs for the protection of aquatic life have been

promulgated for both mercury and methylmercury. The guideline for total mercury in freshwater is 0.026 µg/L (CCME 2003; 2014). The guideline for methylmercury in freshwater is 0.004 µg/L (CCME 2003; 2014). However, neither of these guidelines account explicitly for bioaccumulation and biomagnification. Therefore, concentrations below these guidelines may result in the accumulation of methylmercury in the tissues of fish and aquatic-dependent wildlife to levels that may result in adverse effects. To protect against adverse effects to aquatic-dependent wildlife, CCME has promulgated a tissue-based methylmercury guideline in the diet of wildlife of 0.033 mg/kg wet weight (Table A4.1; CCME 2000).

The British Columbia Ministry of Environment (BCMOE) has adopted the tissue-based guideline for the protection of wildlife of 0.033 mg/kg wet weight (BCMOE 2014b). However, BCMOE has not developed tissue-based guidelines for the protection of aquatic life. Long-term average WQGs have been developed by BCMOE that are dependent upon the proportion (i.e., percentage) of methylmercury relative to total mercury in the water column. To protect aquatic life, the WQGs are: 0.02 µg/L at 0.5 % methylmercury, 0.01 µg/L at 1.0% methylmercury, and 0.00125 µg/L for waters with 8% or greater methylmercury.

To support the development of tissue-based dose-response curves for mercury in fish tissue, Dillon *et al.* (2010) conducted a meta-analysis, using compiled information on the toxicity of mercury to freshwater and marine fishes. These data were integrated into an effects-based dataset and dose-response models were developed for both juvenile/adult fish and early life stages of fish. Using lethality-equivalent endpoints, percent injury was estimated for a range of tissue concentrations. The effects thresholds from Dillon *et al.* (2010) were reviewed to support the selection of tissue-based RSWQTs to protect aquatic life. For juvenile and adult fish, the lowest tissue concentration that resulted in injury to fish (based on the lower 95% confidence level) was a whole-body tissue concentration of 0.3 mg/kg total mercury wet weight, which resulted in 8.2% injury (range of 0.6 - 15.8%). For early life stages of fish, the lowest tissue concentration that resulted

in injury to fish (based on the lower 95% confidence level) was a whole-body tissue concentration of 0.1 mg/kg total mercury wet weight, which resulted in 19.8% injury (range of 0.07 - 35.5%).

The recommended mercury thresholds for use on NWRs are provided in Table A4.1. These RSWQTs could be applied to all water classifications (i.e., Waters of Special Significance, Sensitive Waters, and Typical Waters) to evaluate the potential for adverse effects to fish and aquatic-dependent wildlife associated with accumulation of mercury in fish tissues. However, refuge managers and FWS Contaminants Specialists may require alternative benchmarks for evaluating the potential for risks to ecological receptors associated with exposure to bioaccumulative substances in water on the NWRs. Therefore, for Typical Waters, measurement of mercury in the water column and comparison to the current EPA AWQC (Table A4.2) may afford an adequate level of protection. For water bodies classified as Sensitive Waters, the CCME long-term guideline for the protection of aquatic life (i.e., 0.026 µg/L) could be adopted. For waters classified as Waters of Special Significance, the background approach (see the main report and Appendix 5) could be used for deriving protective RSWQTs. While adoption of generic AWQC or use of the background approach is a practical and efficient means of setting RSWQTs for refuges, the use of these RSWQTs to evaluate risks to aquatic life and aquatic-dependent wildlife may or may not afford an adequate level of protection due to site-specific factors that influence bioaccumulation (Presser and Luoma 2010). In addition, the thresholds compiled from these sources may not be protective against the bioaccumulation and biomagnification of mercury in aquatic-dependent wildlife, such as birds and mammals. Therefore, it may be appropriate to derive water-based RSWQTs using a site-specific bioaccumulation modeling approach. Guidance on the development of thresholds for such an approach is described in Section 3.0 of this appendix.

2.2 Selenium Thresholds

In 2014, EPA released draft AWQC for selenium in freshwater ecosystems. These draft criteria contain both tissue-based and water-based benchmarks for the protection of aquatic life (i.e., fish). Specifically, the tissue-based selenium thresholds include an instantaneous maximum (i.e., any single measured fish) for fish egg or ovary tissue (i.e., 15.2 mg/kg dry weight), an instantaneous maximum for whole-body fish concentrations of 8.1 mg/kg dry weight, and an instantaneous maximum for fish muscle tissue of 11.8 mg/kg dry weight. In addition to the tissue-based criteria, USEPA (2014a) has proposed 30-day average water-based criteria of 1.3 µg/L dissolved selenium for lentic systems and 4.8 µg/L dissolved selenium for lotic systems. Currently, the CCC for selenium is 5.0 µg/L. The tissue-based criteria are thresholds never to be exceeded whereas the water-based criteria are not to be exceeded more than once in three years on average.

In 2014, BCMOE promulgated WQGs for the protection of aquatic life for selenium. The guidelines include thresholds for the water column, dietary concentrations (i.e., in invertebrate tissue) for the protection of fish health, and fish-tissue based benchmarks (egg and ovary tissue, whole-body tissue, and muscle tissue) for the protection of fish. Specifically, BCMOE has developed a 30-day average guideline of 2 µg/L for the water column (with attainment being evaluated with a minimum of 5 samples collected over 30 days). In addition, alert concentrations of 1 µg/L in the water column or 2 mg/kg dry weight in sediments are also included, which can be used to trigger adaptive management scenarios or site-specific evaluations. The alert concentration was included in the suite of benchmarks because in some lentic environments selenium can bioaccumulate in fish and aquatic-dependent wildlife to levels that may result in adverse effects at relatively low concentrations in water (i.e., < 2 µg/L). Dietary thresholds for the protection of fish health of 4 mg/kg dry weight for invertebrate tissue are reported. In addition, tissue-based benchmarks of 11 mg/kg dry weight for eggs or ovaries, 4 mg/kg dry weight in whole-body tissues, and 4 mg/kg dry weight in muscle tissues (interim guideline only) are provided to protect fish species.

The recommended thresholds for use on NWRs are provided in Table A4.1. These RSWQTs could be applied to all water classifications (i.e., Waters of Special Significance, Sensitive Waters, and Typical Waters) to evaluate the potential for adverse effects to fish and aquatic-dependent wildlife. However, refuge managers and FWS Contaminants Specialists may require a more practical and efficient solution to evaluating the potential risks to ecological receptors associated with exposure to selenium on NWRs. Therefore, measurement of selenium in the water column and comparison to the current EPA AWQC (Table A4.2) may afford an adequate level of protection for Typical Waters. For water bodies classified as Sensitive Waters, the CCME long-term guideline for the protection of aquatic life (i.e., 1 µg/L) is recommended to protect against the potential risks to fish and aquatic-dependent birds and mammals associated with bioaccumulation of selenium. For waters classified as Waters of Special Significance, the background approach (see the main report and Appendix 5) is recommended for deriving protective RSWQTs. While adoption of generic AWQC is a practical and efficient means of setting RSWQTs for refuges, the use of generic AWQC to evaluate risks to aquatic life and aquatic-dependent wildlife may or may not afford an adequate level of protection due to site-specific factors that influence bioaccumulation (Presser and Luoma 2010). In addition, the thresholds compiled from USEPA (2014a) and BCMOE (2014a) may not be protective against the bioaccumulation and biomagnification of selenium in aquatic-dependent wildlife, such as birds and mammals. Therefore, it may be appropriate to derive water-based RSWQTs using a site-specific bioaccumulation modeling approach. Guidance on the development of thresholds for such an approach is briefly described in Section 3.0 of this appendix.

3.0 Guidance on the Development of Refuge-Specific Water Quality Targets for Bioaccumulative Substances

Estimates of threshold-effect water concentrations for bioaccumulative substances have been developed and implemented using multiple approaches, including empirical models (e.g., BCFs, bioaccumulation factors [BAFs]) and probability distribution functions (Presser and Luoma 2010). Mechanistic modeling approaches, such as the biotic ligand models for some metals, have typically not been used for developing bioaccumulation models due to the lack of understanding of the factors influencing chemical speciation and/or the complexity of the resultant models for regulatory use (Toll *et al.* 2005). However, a hybrid (i.e., mechanistic and empirical) ecosystem-based approach has recently been proposed for the development of threshold-effect concentrations for selenium that is based on quantifying model inputs that affect the bioaccumulation of selenium (Presser and Luoma 2010). The following sections provide an overview of two procedures that are recommended for use in the development of RSWQTs.

3.1 Empirical Approaches

Empirically-based approaches for estimating BCFs (i.e., estimates of uptake though respiratory or dermal contact) or BAFs (i.e., estimates of uptake through all exposure pathways, including diet) can be developed using various techniques, including using the ratio of the tissue concentration to the water-column concentration (Arnot and Gobas 2006), regression modeling (Arnot and Gobas 2006), and probability distribution functions (Brix *et al.* 2005; Toll *et al.* 2005).

To calculate BCFs and/or BAFs, empirical data are collected on the concentrations of the bioaccumulative substances in the environmental media (e.g., water column) and in tissues of aquatic organisms, such as fish. Using the empirical ratio

method, BCFs are typically calculated as the concentration in the organism divided by the total concentration in the media (e.g., water concentration) during laboratory testing. Calculation of the BCF in this way assumes that the concentrations of chemicals of potential concern (COPCs) in the organism and in the environment are at steady state and homogenously mixed within the respective compartments (i.e., organismal tissues and the water column). The BAF is typically calculated using data collected from the field and takes into account chemical exposure through all routes, including diet. By measuring bioaccumulation in this way, biomagnification of the substance in question is inherently considered (Arnot and Gobas 2006). Similar to the assumptions of the BCF, the calculation of the BAF assumes that the organism and its environment are at steady state and the substance is homogenously mixed in the respective compartments.

Another approach to develop BCFs and/or BAFs is the development of probability distribution functions (Brix *et al.* 2005; Toll *et al.* 2005). Toll *et al.* (2005) provide a methodology for developing site-specific water-quality thresholds using bioaccumulation data collected from the site of interest, as well as other similar sites. By incorporating data from similar sites, BAFs can be estimated across a range of concentrations. This is an important consideration, as BAFs for many substances are concentration-dependent (Toll *et al.* 2005). In the methodology proposed by Toll *et al.* (2005) and used in the development of site-specific thresholds for selenium (Brix *et al.* 2005), probability distribution functions derived from Monte Carlo simulations define a set of likely BAFs from the larger data set (i.e., data from multiple sites). Using Bayesian statistical methods, the pool of BAFs is evaluated to determine the set of sites that provide data consistent with the site of interest. The results of the analysis are used to determine a site-specific water quality threshold that will be protective of aquatic life. Detailed information on the specific analytical methods and model development can be found in Toll *et al.* (2005) and Brix *et al.* (2005).

3.2 Ecosystem-Based Approach for Setting Site-Specific Water Quality Targets for Selenium

Presser and Luoma (2010) have developed an ecosystem-based hybrid (i.e., mechanistic and empirical) modeling approach to estimate selenium exposure, predict the presence or absence of toxicity due to selenium exposure, and develop water quality thresholds to manage the bioaccumulation (and therefore toxicity) of selenium on a site-by-site basis. Furthermore, this approach allows for the evaluation of the efficacy of various mitigation actions on the bioaccumulation potential of selenium.

Application of this approach requires the collection of environmental samples to characterize the concentrations of the various forms of selenium in the relevant environmental compartments (e.g., water column, periphyton) and the concentrations of selenium in the biotic and abiotic compartments at the base of the invertebrate food web. Additionally, information on food web transfer factors and tissue residue thresholds that describes effect concentrations for predator organisms (i.e., fish and aquatic-dependent wildlife) can be collected or derived from the scientific literature. One limitation of this approach is expense. However, the approach represents a major step in the understanding of selenium partitioning in the aquatic environment, leading to robust estimates of water thresholds that are protective of the aquatic environment. Detailed information on the specific analytical methods and model development can be found in Presser and Luoma (2010).

4.0 Summary and Recommendations

This appendix was intended to provide refuge staff, FWS Contaminants Specialists, and FWS Water Resource Branch staff with guidance on the development of RSWQTs for bioaccumulative substances (with a focus on mercury and selenium) that will protect the ecological receptors that use aquatic

habitats within the NWRS. This appendix also supports the evaluation of water quality in water bodies classified as Waters of Special Significance, Sensitive Waters, or Typical Waters, as described in the main report. To ensure adequate protection of aquatic life and aquatic-dependent wildlife, refuge staff, FWS Contaminants Specialists, and FWS Water Resource Branch staff should adopt tissue-based benchmarks for evaluating the potential for adverse effects to aquatic life (i.e., fish) and aquatic-dependent wildlife (including birds and mammals) associated with exposure to bioaccumulative substances. However, refuge managers and FWS Contaminants Specialists may require alternative benchmarks for evaluating the potential for risks to ecological receptors associated with exposure to bioaccumulative substances in water on the NWRs. Therefore, water-based thresholds for the protection of aquatic life have been provided for use in water bodies on refuges that are classified as Typical Waters or Sensitive Waters. For waters classified as Waters of Special Significance, the background approach (see the main report and Appendix 5) could be used for deriving protective RSWQTs.

While adoption of generic AWQC or use of the background approach is a practical and efficient means of setting RSWQTs for refuges, the use of these RSWQTs to evaluate risks to aquatic life and aquatic-dependent wildlife may or may not afford an adequate level of protection due to site-specific factors that influence bioaccumulation (Presser and Luoma 2010). Therefore, it may be appropriate to derive water-based RSWQTs using one of the site-specific bioaccumulation modeling approaches identified in Section 3.0.

5.0 References

Adriano, D.C. 2001. Trace elements in terrestrial environments: biogeochemistry, bioavailability, and risks of metals. Springer Science & Business Media. 867 pp.

Arnot, J.A. and F.A.P.C. Gobas. 2006. A review of bioconcentration factor (BCF) and bioaccumulation factor (BAF) assessments for organic chemicals in aquatic organisms. Environmental Reviews 14:257-297.

BCMOE (British Columbia Ministry of Environment). 2014a. Ambient Water Quality Guidelines for Selenium: Technical Report Update. Prepared by J.M. Beatty and G.A. Russo of the Water Protection and Sustainability Branch, Environmental Sustainability and Strategic Policy Division, British Columbia Ministry of Environment.

BCMOE (British Columbia Ministry of Environment). 2014b. Water Quality: Water Quality Guidelines (Criteria) Reports. Approved Water Quality Guidelines. Environmental Protection Division. Available at http://www.env.gov.bc.ca/wat/wq/wq_guidelines.html.

Brix, K.V., J.E. Toll, L.M. Tear, D.K. DeForest, and W.J. Adams. 2005. Setting site-specific water-quality standards by using tissue residue thresholds and bioaccumulation data. Part 2. Calculating site-specific selenium water-quality standards for protecting fish and birds. Environmental Toxicology and Chemistry 24(1):231-237.

CCME (Canadian Council of Ministers of the Environment). 2000. Canadian tissue residue guidelines for the protection of wildlife consumers of aquatic biota: Methylmercury. In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg.

CCME (Canadian Council of Ministers of the Environment). 2001. Canadian sediment quality guidelines for the protection of aquatic life: Polychlorinated biphenyls (PCBs). Updated. In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg.

CCME (Canadian Council of Ministers of the Environment). 2003. Canadian water quality guidelines for the protection of aquatic life: Inorganic mercury and methylmercury. In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg.

CCME (Canadian Council of Ministers of the Environment). 2014. Canadian Environmental Quality Guidelines Summary Table. Water quality guidelines for the protection of aquatic life. Canadian Environmental Quality Guidelines. Winnipeg, Manitoba. Available at http://st-ts.ccme.ca/en/index.html?chems=all&chapters=1

Dillon, T., N. Beckvar, and J. Kern. 2010. Residue-based mercury dose-response in fish: an analysis using lethality-equivalent test endpoints. Environmental Toxicology and Chemistry 29(11):2559-2565.

MacDonald, D.D., M.A. Crawford, H.J. Prencipe, J.A. Sinclair, A. Schein, and M.B. Meneghetti. 2014. Handbook for Assessing Risks to Fish and Wildlife Associated with the Potential Use of Water, Treated Wastewater, Stormwater, Sediment, Soil, Biosolids, or Other Materials on Units of the National Wildlife Refuge System. Volumes I-IV. Prepared for U.S. Fish and Wildlife Service, Vancouver, Washington. Prepared by MacDonald Environmental Sciences Ltd., Nanaimo, British Columbia.

Neely, W.B., D.R. Branson, and G.E. Blau. 1974. Partition coefficient to measure bioconcentration potential of organic chemicals in fish. Environmental Science and Technology 8:1113-1115.

Nriagu, J.O. and J.M. Pacyna. 1988. Quantitative assessment of worldwide contamination of air, water and soils by trace metals. Nature 333:134-139.

Presser, T.S., D.Z. Piper, K.J. Bird, J.P. Skorupa, S.J. Hamilton, S.J. Detwiler, and M.A. Huebner. 2004. The Phosphoria Formation: A model for forecasting global selenium sources to the environment. In: Hein, J.R, editor. Life cycle of the phosphoria formation: from deposition to post-mining environment. New York: Elsevier. pp. 299-319.

Presser, T.S. and S.N. Luoma. 2010. A methodology for ecosystem-scale modeling of selenium. Integrated Environmental Assessment and Management 6(4):685-710.

Schroeder, W.H. and J. Munthe. 1998. Atmospheric mercury - an overview. Atmospheric Environment 32(5):809-822.

Sellers, P., C.A. Kelly, J.W.M. Rudd, and A.R. MacHutchon. 1996. Photodegradation of methylmercury in lakes. Nature 380:694-697.

Sharma, V.K., T.J. McDonald, M. Sohn, G.A.K. Anquandah, M. Pettine, and R. Zboril. 2014. Biogeochemistry of selenium. A review. Environmental Chemistry Letters DOI 10.1007/s10311-014-0487-x.

St. Louis, V.L, J.W.M. Rudd, C.A. Kelly, K.G. Beaty, N.S. Bloom, and R.J. Flett. 1994. Importance of wetlands as sources of methyl mercury to boreal forest ecosystems. Canadian Journal of Fisheries and Aquatic Sciences 51(5):1065-1076.

Stadtman, T.C. 1974. Selenium biochemistry. Science 183:915-922.

Toll, J.E., L.M. Tear, D.K. DeForest, K.V. Brix, and W.J. Adams. 2005. Setting site-specific water-quality standards by using tissue residue criteria and bioaccumulation data. Part 1. Methodology. Environmental Toxicology and Chemistry 24(1):224-230.

USEPA (United States Environmental Protection Agency). 2014a. External Peer Review Draft Aquatic Life Ambient Water Quality Criterion for Selenium - Freshwater 2014. Office of Water. Office of Science and Technology. Washington, D.C. EPA 822-P-14-001. May 2014. 637 pp.

USEPA (United States Environmental Protection Agency). 2014b. National Recommended Water Quality Criteria. Office of Water. Office of Science and Technology. Washington, D.C. Available at http://water.epa.gov /scitech/swguidance/standards/criteria/current/index.cfm.

Winfrey, M.R. and J.W.M. Rudd. 1990. Environmental factors affecting the formation of methylmercury in low pH lakes. Environmental Toxicology and Chemistry 9(7):853-869.

Tables

Table A4.1. Recommended fish-tissue based refuge-specific water quality targets for selenium and mercury to protect aquatic life and aquatic-dependent wildlife.

Chemical of Potential Concern	Protection of Aquatic Life				Protection of Aquatic-Dependent Wildlife
	Dietary	Egg/Ovary	Whole-body	Muscle	Dietary
Selenium (mg/kg dry weight)					
USEPA[1]	N/A	15.2	8.1	11.8	N/A
BCMOE	4 [2]	11	4	4 [2]	N/A
Recommended Threshold	4 [2]	11	4	4 [2]	N/A
Mercury (mg/kg wet weight)					
BCMOE	N/A	N/A	N/A	N/A	0.033[3]
CCME	N/A	N/A	N/A	N/A	0.033[3]
Dillon *et al.* 2010	N/A	N/A	0.3[4] / 0.1[5]	N/A	N/A
Recommended Threshold	N/A	N/A	0.3[4] / 0.1[5]	N/A	0.033[3]

BCMOE = British Columbia Ministry of Environment; CCME = Canadian Council of Ministers of the Environment; N/A = not applicable; USEPA = United States Environmental Protection Agency.

[1] These are draft guidelines, currently under review (USEPA 2014a).

[2] Interim guidelines (BCMOE 2014a).

[3] Measured as methylmercury.

[4] Whole-body tissue concentration corresponding to 8.2% lethal equivalent effects in juvenile and adult fish (Dillon *et al.* 2010).

[5] Whole-body tissue concentration corresponding to 19.8% lethal equivalent effects in early life-stage fish (Dillon *et al.* 2010).

Table A4.2. Recommended refuge-specific water quality targets for three classes of waters on National Wildlife Refuges.

Chemical of Potential Concern	RSWQTs for Waters of Special Significance		RSWQTs for Sensitive Waters [1]		RSWQTs for Typical Waters [2]		Units
	Chronic	Acute	Chronic	Acute	Chronic	Acute	
Mercury (Inorganic)	Background approach or site-specific bioaccumulation modeling	Background approach or site-specific bioaccumulation modeling	0.026 [3] or site-specific bioaccumulation modeling	1.4 [4] or site-specific bioaccumulation modeling	0.77	1.4	µg/L
Selenium	Background approach or site-specific bioaccumulation modeling	Background approach or site-specific bioaccumulation modeling	1 [3] or site-specific bioaccumulation modeling	Equation [4, 5, 6] or site-specific bioaccumulation modeling	5.0 [6]	Equation [5, 6]	µg/L

AWQC = ambient water quality criteria; CCME = Canadian Council of Ministers of the Environment; CMC = criterion maximum concentration; EPA = Environmental Protection Agency; NWR = National Wildlife Refuge; RSWQT = refuge-specific water quality target; WQG = water quality guideline; WQS = water quality standard.

[1] The lowest chronic value from those compiled in Table 3 of the main text was chosen for the chronic RSWQT and the lowest acute value from those compiled in Table 3 of the main text was chosen for the acute RSWQT.

[2] USEPA (2014b) AWQC are recommended as RSWQTs for Typical Waters. If the NWR of interest is in a state with lower WQSs than the EPA AWQC, the state WQSs should be used instead.

[3] CCME (2014) WQG for the protection of aquatic life.

[4] USEPA (2014b) AWQC for the protection of aquatic life.

[5] The CMC [acute AWQC] = 1/[(f1/CMC1) + (f2/CMC2)] where f1 and f2 are the fractions of total selenium that are treated as selenite and selenate, respectively, and CMC1 and CMC2 are 185.9 µg/L and 12.82 µg/L, respectively (USEPA 2014b).

[6] EPA is in the process of updating this selenium criterion to reflect the latest scientific information. See the following website for more information: http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/selenium/index.cfm

Appendix 5

Guidance on the Design of Baseline Monitoring Programs to Support the Derivation of Refuge-Specific Water Quality Targets

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List of Acronyms

AWQC	-	ambient water quality criteria
BCMOE	-	British Columbia Ministry of Environment
CAP	-	Contaminants Assessment Program
CCP	-	Comprehensive Conservation Plan
COPC	-	chemical of potential concern
DQO	-	data quality objective
EPA	-	Environmental Protection Agency
FWS	-	Fish and Wildlife Service
HMP	-	Habitat Management Plan
I&M	-	Inventory and Monitoring
K_{oc}	-	organic carbon partition coefficient
K_{ow}	-	octanol-water partition coefficient
NWR	-	National Wildlife Refuge
NWRS	-	National Wildlife Refuge System
RPD	-	relative percent difference
RSWQT	-	refuge-specific water quality target
S_w	-	water solubility
TIE	-	toxicity identification evaluation
UCL	-	upper confidence limit
WCS	-	water classification system
WRIA	-	Water Resources Inventory and Assessment

1.0 Introduction

Water quality and water quantity are critical issues in many areas of the United States. Not surprisingly, National Wildlife Refuges (NWRs) are facing increasing challenges in terms of ensuring that water resources of sufficient quality and quantity are available to conserve and protect fish and wildlife, as well as the habitats upon which they depend. The Fish and Wildlife Service (FWS) has responded to this challenge by developing a framework for assessing the acceptability of wastewater, stormwater, and biosolids that provides a basis for evaluating risks to ecological receptors associated with exposure to contaminants. The *Handbook for Assessing Risks to Fish and Wildlife Associated with the Potential Use of Water, Treated Wastewater, Stormwater, Sediment, Soil, Biosolids, or Other Materials on Units of the National Wildlife Refuge System* (the *Handbook*; MacDonald *et al.* 2014), and the associated Excel-based Assessment Tool, are intended to provide users with practical guidance for conducting expedited and detailed assessments of these materials to guide decisions that could affect environmental quality conditions on NWRs.

The procedures described in the *Handbook* are appropriate and relevant for conducting assessments of water resources. However, an assessment tool for evaluating existing refuge water supplies needs to have a higher level of site-specificity than the framework described in the *Handbook* to ensure that decisions related to the management of water resources explicitly address the resources of concern on NWRs, including threatened and endangered species and/or major taxa of concern to the United States Department of the Interior.

1.1 Intended Scope and Approach

This appendix is intended to provide refuge staff, FWS Contaminants Specialists, and FWS Water Resource Branch staff with detailed guidance on the development and implementation of baseline monitoring programs to support assessments of water quality conditions and the derivation of refuge-specific water quality targets (RSWQTs) to protect critical habitats for aquatic-obligate state or federally listed

threatened or endangered species (i.e., Waters of Special Significance; described in more detail in Section 2.0). For these waters, a primary water management goal is to maintain and protect the quality of these special waters and the associated water uses. In addition, the procedures for designing and implementing baseline monitoring programs described in this document will provide data and information that is appropriate and relevant for use in the Inventory and Monitoring (I&M) programs. The guidance presented in this appendix was developed using a step-wise process that included:

- Conducting focused reviews of the scientific literature on the design and implementation of baseline monitoring programs;
- Compiling information on the development of baseline monitoring programs;
- Establishing guiding principles for baseline monitoring;
- Describing current best practices related to evaluating background conditions in aquatic ecosystems; and,
- Establishing a framework for designing and implementing effective baseline monitoring programs.

1.2 Organization of Appendix 5

This appendix has been organized into the following sections to provide specific guidance on each of the aspects of the baseline monitoring program development and implementation process:

- Introduction (Section 1);
- Guiding Principles for Developing and Implementing Baseline Monitoring Programs (Section 2);
- Recommended Framework for Designing Baseline Monitoring Programs (Section 3);

- Identification of Issues and Concerns Associated with Land- or Water-Use Management Activities (Section 4);
- Development of Data Quality Objectives (DQOs) and Sampling Design (Section 5);
- Evaluation, Compilation, and Interpretation of Baseline Monitoring Program Data (Section 6);
- Summary and Recommendations (Section 7); and,
- References Cited (Section 8).

2.0 Guiding Principles for Developing and Implementing Baseline Monitoring Programs

The management of water resources and associated aquatic habitats is a primary focus of the National Wildlife Refuge System (NWRS). On many NWRs, management activities are focused on addressing issues related to water quantity. However, water quality can also represent an important concern relative to the conservation and protection of aquatic organisms and/or aquatic-dependent wildlife. To support such water management activities, the FWS has developed a system for classifying and evaluating existing and potential water supplies that considers the receptors that utilize habitats within receiving water bodies. The three classes of surface waters defined by the water classification system (WCS) and the narrative objectives that apply to each class of surface water are described below:

- *Waters of Special Significance* – such waters meet the following characteristics:
    - Provide critical habitat for state or federally listed endangered species;
    - Support listed or endangered species with the potential for extinction;

- Include habitats that support listed or endangered species through their entire life cycle;
- Support aquatic-obligate listed or endangered species; or,
- Include designated or proposed wilderness/natural areas.

For these waters, a primary water management goal is to maintain and protect the quality of these special waters and the associated water uses (i.e., water quality conditions should not be degraded or impaired by human activities).

- *Sensitive Waters* – such waters support sensitive species or taxa of concern. For these waters, a primary water management goal is to protect all life stages of sensitive species or taxa of concern (which may include listed or endangered species with limited exposure to the water body of interest), as well as the occupied habitats upon which they depend, from adverse effects associated with exposure to a chemical or a chemical mixture for an indefinite period of time (i.e., entire life cycle). Ambient water quality criteria (AWQC) developed by the Environmental Protection Agency (EPA) may or may not offer the level of protection needed to protect sensitive species utilizing these waters (Appendix 6). Appendix 7 describes in detail the rationale and methods for deriving RSWQTs for Sensitive Waters.
- *Typical Waters* - such waters support other resources of concern. For these waters, a primary water management goal is to protect the designated uses of surface water resources, including protection of aquatic life and aquatic-dependent wildlife. An additional goal is the recovery of waters that have been degraded so that they are able to support designated uses, including the protection of aquatic life and aquatic-dependent wildlife.

For Waters of Special Significance, RSWQTs need to be established to define water quality conditions that need to be met, now and in the future. Such RSWQTs need to be established at levels that are consistent with baseline water quality conditions. The background-concentration procedure is typically used to derive RSWQTs that define baseline conditions. Implementation of this procedure involves determination of the

natural background concentrations of chemicals of potential concern (COPCs) in water, and utilization of the resultant data to define acceptable water quality conditions at the site under consideration. Application of this procedure is based on the premise that surface water systems that support critical habitats for threatened or endangered species should not be degraded.

2.1 Objectives of Baseline Monitoring Programs

Baseline monitoring programs are designed and implemented to characterize background water quality conditions for surface and/or groundwater supplies located on a refuge. More specifically, baseline monitoring programs are intended to define conditions within the aquatic environment in the absence of substantial land- or water-use activities. However, in cases where habitat management efforts have already been implemented, baseline characterization should be informed by the collection of data and information from hydrologically and biogeochemically similar water bodies in or nearby the NWR that have not been anthropogenically influenced. For the purpose of deriving numerical RSWQTs using the background-concentration approach, there is a need to collect sufficient quantities of water chemistry data to characterize the spatial and temporal variation of water quality conditions for all of the water bodies requiring RSWQTs. However, the baseline monitoring program may also provide the data and information that are needed to support additional objectives, which may include:

- The prediction of impacts on water quality from habitat management activities;
- The impact-mitigation measures required to minimize the effects of habitat management activities; and/or,
- The evaluation of the cumulative effects on the aquatic environment that may occur due to anthropogenic activities that occur within the area or region that a refuge is located.

2.2 Guiding Principles for Developing Baseline Monitoring Programs

These guiding principles provide a general framework for the development and implementation of baseline monitoring programs. Baseline monitoring programs that are developed in accordance with the following guiding principles are likely to be generally acceptable for supporting the derivation of RSWQTs for Waters of Special Significance:

- Baseline monitoring programs should be developed in a rigorous and scientifically-defensible manner;
- Baseline monitoring programs should have clearly defined objectives;
- The evaluation and selection of sampling locations should be considered to be an integral component of the overall baseline monitoring program design process;
- Baseline monitoring programs should provide a basis for distinguishing between natural variability and effects related to land- or water-use management activities on aquatic ecosystems;
- The design of baseline monitoring programs should be completed prior to initiating collection of baseline data to ensure consistency and comparability through the life of the monitoring program;
- The implementation of baseline monitoring programs should be guided by detailed site-specific survey protocols; and,
- The data and information generated through the implementation of baseline monitoring programs must be evaluated, compiled, managed, synthesized, and reported in a manner that ensures their quality and accessibility by refuge staff, FWS Contaminants Specialists, and FWS Water Resource Branch staff.

3.0 Recommended Framework for Designing Baseline Monitoring Programs

The recommended framework is intended to provide a step-wise process for guiding the development of a baseline monitoring program for characterizing the biogeochemical conditions of aquatic ecosystems within which habitat management activities have been, or are proposed to be, conducted. The recommended framework consists of the following elements:

- Identify issues and concerns associated with habitat management activities and/or upstream land and water uses;
- Develop DQOs;
- Develop and document the sampling program design (i.e., the site-specific survey protocols);
- Implement the baseline monitoring program; and,
- Evaluate, compile, and interpret the data collected.

Each of these steps in the baseline monitoring program development and implementation process is detailed in the subsequent sections of this appendix.

4.0 Identification of Issues and Concerns Associated with Land- or Water-Use Management Activities

The first step in the development of a baseline monitoring program involves identification of the issues and concerns associated with the potential on-refuge habitat management activities and/or upstream land- or water-use activities (i.e., within the region of hydrological influence). Typical sources for this information include Contaminant Assessment Process (CAP) reports, contaminant investigations, Comprehensive Conservation Plans (CCPs), Habitat Management Plans (HMPs), refuge water management plans, Water Resource Inventory and Assessment (WRIA)

plans, and I&M plans (e.g., BLNWR and USFWS 2013; USFWS 2013a; USFWS 2014). The activities that need to be undertaken at this stage of the baseline monitoring program development process include:

- Description of the habitat management activities and/or upstream land- and water-use activities; and,
- Compilation of the available data and information on the NWR under consideration.

Each of these tasks is described in the following sections.

4.1 Description of Land-Use, Water-Use, and Habitat Management Activities

The first step in the issues and concerns identification process involves preparation of a description of the land-use, water-use, and habitat management activities within and nearby the refuge under consideration (i.e., within the watershed and airshed that contain the refuge). While it is understood that the list of potential and ongoing activities is likely to be refined over time, the description that is initially developed should be as detailed as possible to understand the nature and scope of the land-use, water-use, and/or habitat management activities that could influence water quality conditions. The key types of information that should be acquired at this stage of the baseline monitoring program development process include:

- Overview of the potential or existing land-use, water-use, and/or habitat management activities;
- Description of the study area location;
- Detailed description of the proposed land-use, water-use, and/or habitat management activities (including activity schedule); and,
- Detailed description of the sources of water that need to be managed in the study area.

While it is understood that the preliminary description may not have all of the detailed information needed to fully support the identification of issues and concerns, the preliminary description should be sufficiently detailed to permit the identification of key issues and concerns. Atmospheric inputs of COPCs (e.g., mercury) should also be considered as potential issues and concerns, including identification of the classes of contaminants that could be released to surface water or groundwater.

4.2 Compilation of Background Data and Information

The identification of water quality issues and concerns requires detailed information on the NWR. More specifically, information is needed on characteristics of the receiving water body, on historic and current uses of the NWR, regional land- and water-use patterns, and on local hydrological conditions. To expedite this process and facilitate the use of this information in other NWR-related programs, the compilation of data and information should follow the protocols used in the CAP. Subsequent integration of the compiled information provides an informed basis for identifying issues and concerns in the study area.

4.2.1 Characteristics of the Receiving Water Body

The effects of land-use, water-use, and habitat management activities on aquatic resources depend not only on the nature and scope of the activity, but also on the characteristics of the receiving water bodies or water supplies. For example, salmonid fishes (e.g., trout) tend to be more sensitive to the effects of many COPCs than are cyprinids (e.g., minnows) or catostomids (i.e., suckers). Similarly, many metals are more toxic in soft waters (i.e., those with low water hardness) than they are in harder waters. Accordingly, an important step in the development of a baseline monitoring program is to obtain, evaluate, and compile historical data and information on the physical, chemical, and biological characteristics of the water body (or water supply) under consideration. For detailed information on procedures for characterizing prospective water supplies, refer to the "*Handbook for assessing risks to fish and wildlife associated with the potential use of water, treated wastewater, stormwater,*

sediment, soils, biosolids, or other materials on units of the NWRS" (MacDonald *et al.* 2014). The following types of information should be sought during this stage of the baseline monitoring program development process:

- Climate data;
- Surface water quantity;
- Surface water chemistry;
- Sediment chemistry;
- Fish and invertebrate tissue chemistry; and,
- Structure of aquatic plant and animal communities.

4.2.2 Land Use Patterns in the Study Area

Evaluation of issues and concerns relative to the quality and quantity of aquatic resources also requires information on local and regional land patterns. The nature of the activities conducted within the study area may determine which substances have been released, are currently being released, and/or could be released into the environment. Information on land use patterns within the study area also provides a basis for identifying potential sources of chemical substances to aquatic ecosystems. In turn, information on potential sources provides a basis for identifying the substances that may have been released into aquatic ecosystems. This type of information also provides a basis for identifying non-contaminant stressors in the watershed (e.g., fluctuating water levels).

4.2.3 Identification of Chemicals of Potential Concern

When used together, the information on regional land use patterns and/or historical data provides a basis for identifying preliminary COPCs. However, further refinement of this list may require data and information on the physical, chemical, and toxicological properties of the preliminary COPCs, including: octanol-water partition coefficients (K_{ow}), organic carbon partition coefficients (K_{oc}), water solubility (S_w),

toxicity thresholds, and bioconcentration factors. Substances with low log K_{ow} or log K_{oc} values (i.e., < 3.5) and/or those that are soluble in water are the most likely to occur in surface water and groundwater. The preliminary COPCs that have a high potential for occurring in water should be identified as the water-borne COPCs at the site. Those COPCs with higher log K_{ow} or log K_{oc} values (i.e., > 3.5) and/or those that are not soluble in water are most likely to occur in sediment and/or biological tissues. In cases where historical or existing land-use, water-use and/or habitat management activities have resulted in the degradation of water quality, toxicity identification and evaluation (TIE) studies may be employed to identify the primary drivers of toxicity at the site in order to support the refinement of the identified COPCs.

In addition to information on the sources and fates of chemical substances, historical water, sediment, and tissue chemistry data provide a basis for identifying water-borne, sediment-associated, and tissue-associated COPCs. Probable sources of this type of information include CAP reports, refuge-specific investigation reports, I&M surveys, and U.S. Geological Survey reconnaissance investigations (e.g., Schroeder *et al.* 1988; Messinger 2004; Dickerson *et al.* 2011). However, evaluating the relevance and quality of historical data is an important step. For example, historical datasets may include only a limited suite of chemical analytes, which restricts their use for identifying COPCs. In addition, the applicability of the chemistry data may be further restricted by high analytical detection limits. Furthermore, spatial coverage of the study area may not include areas that are most likely to be affected by previous land- or water-use management activities. Due to these potential limitations, historical datasets should be used with caution for eliminating substances (i.e., COPCs) that could be of interest in the baseline monitoring program.

Baseline monitoring programs must be designed to include all of the COPCs that are identified. At minimum, the baseline monitoring program needs to include:

- Conventional variables (e.g., temperature, pH, total suspended solids, dissolved oxygen, and dissolved organic carbon);
- Nutrients (e.g., total and dissolved phosphorus, orthophosphate, total nitrogen, ammonia, nitrate, and nitrite);

- Major ions (e.g., bicarbonate, calcium, chloride, magnesium, sodium, potassium, and sulfate); and,
- Total and dissolved metals.

4.2.4 Identification of Areas of Potential Concern

The information that was assembled to support the identification of COPCs also provides a relevant basis for identifying areas of potential concern within a NWR. More specifically, information on the historical and current anthropogenic activities on the NWR, and on regional land-use patterns, provides a basis for identifying the areas of potential concern on the refuge (i.e., areas that may have contaminated surface water and/or groundwater or areas subject to low-flow conditions). In addition, information on local hydrological conditions should be considered when evaluating the study area, as should the distribution of any contaminants that have been released or may be released in the future as a result of land- or water-use management activities.

5.0 Development of Data Quality Objectives and Sampling Design

In the environment, a variety of plant and animal species can be exposed to COPCs. Each of these receptors (i.e., species) or receptor groups (i.e., groups of similar species) may be exposed to a chemical through different exposure routes or pathways, and may exhibit different types and severities of effects. While information on the effects of each chemical on each component of the ecosystem would provide comprehensive information for evaluating water quality conditions, it is neither practical nor feasible to directly evaluate the suitability of water quality conditions for every component of the ecosystem (USEPA 1997). For this reason, monitoring activities should be focused on evaluating conditions relative to the receptors or receptor groups that represent valued ecosystem components (e.g., threatened and endangered species, taxa of concern) and on the receptors that support valued

ecosystem functions (e.g., carbon processing by the microbial community). Of particular interest are those receptors or receptor groups that are most likely to be adversely affected by the presence of the COPCs that occur in the study area (USEPA 1998). The DQOs process, described in the subsequent sections, provides a systematic framework for developing a baseline monitoring program that is sufficiently robust to support the characterization of background conditions for the COPCs that occur in the study area.

5.1 Development of Data Quality Objectives

The process for defining DQOs is a seven-step planning approach that is used to design a sampling plan for collecting data of sufficient quality and quantity to support the goals of the study (USEPA 2006). The steps in the DQOs process include:

- State the problem to be investigated;
- Identify the goal(s) of the study;
- Identify the information inputs required to achieve the study goal;
- Define the boundaries of the study;
- Develop the analytical approach;
- Specify performance or acceptance criteria; and,
- Develop the detailed design for obtaining data.

The following guidance on the development of DQOs for baseline monitoring programs was adapted from the guidance that has been issued by USEPA (2000a; 2006). The reader is directed to the USEPA (2000a; 2006) guidance documents for further information and more detailed guidance on the development of DQOs.

5.1.1 Stating the Problem

The first step in the DQOs process involves stating the problem. Because off-refuge land- and water- use activities and on-refuge habitat management activities can have diverse and sometimes unexpected effects on aquatic ecosystems, it is recommended that a multi-disciplinary planning team of experts be engaged in formulating the problem and establishing a plan for obtaining the data and information needed to characterize background conditions on the NWR. Next, one or more meetings of the planning team should be convened to facilitate identification of the human activities that could influence aquatic resources and the questions that will be posed relative to the potential effects on the aquatic ecosystem. As part of this activity, the planning team should identify data sources, review all of the relevant information, and evaluate its reliability.

It is important for the planning team to identify and discuss alternative approaches to data collection at this stage of the process. In addition, a summary of the available resources (i.e., budget and personnel) and relevant deadlines for the study (i.e., schedule for planning, data collection, and data analysis) should be prepared and distributed to the planning team.

This step in the DQOs process should result in the preparation of a concise description of the problem including the types of data that need to be collected and how they will be used to characterize background conditions, a list of planning team members and their responsibilities, and a summary of the available resources and relevant deadlines for the study.

5.1.2 Identifying the Goals of the Study

The second step in the DQOs process involves identifying the principal (i.e., key) questions and alternative actions that the study will attempt to address. Principal study questions can address either decision problems or estimation problems. Decision problems are those that require both monitoring data and action levels to resolve (i.e., comparison of measured COPC concentrations to a selected benchmark to assess risks or hazards to receptors). By comparison, estimation problems are those

that require only monitoring data to resolve. The guidance provided in this section will be focused on estimation problems.

5.1.3 Identifying the Information Inputs

The third step in the DQOs process involves identifying information inputs. More specifically, this step in the DQOs process necessitates:

- Identification of the types and sources of data needed to characterize background conditions; and,
- Selection of appropriate sampling and analysis methods for generating the requisite data.

As part of this step in the DQOs development process, the candidate sources of data and information are identified and documented. These sources may include historical data, regulatory guidance, professional judgment, scientific literature, and/or the generation of new data. For new data, the baseline monitoring program represents the primary source of data and information that will be used to characterize background water quality conditions. Finally, a list of sampling and analytical methods is developed that may be appropriate for the problem being investigated. These methods should be selected to avoid or minimize the ten major sources of biases in environmental sampling and analysis, including:

- Non-representative sampling;
- Instability of samples between sampling and analysis;
- Interferences and matrix effects in analysis;
- Inability to determine the relevant forms of a COPC being measured;
- Failure to calibrate instrumentation;
- Failure to correct for analytical results of blank samples;
- Sample misidentification;

- Pseudo-replication;
- Use of data below the level of quantification; and,
- Method differences between labs and method changes over time.

The following outputs are anticipated upon completion of this step in the DQOs process. First, types of data and information that are required to support the estimation of a population parameter for a selected indicator of background conditions (e.g., mean of nitrate levels in a water body) will have been identified. Furthermore, the sources of the requisite data and information will have been identified. Lastly, sampling and analysis methods will have been identified.

5.1.4 Defining the Boundaries of the Study

The fourth step in the DQOs process involves defining the boundaries of the study. The activities that need to be undertaken during this step of the DQOs development process include:

- Defining the target population;
- Determining the spatial and temporal boundaries for the target population;
- Identifying practical constraints on sampling activities; and,
- Defining the scale of inference for the estimation problems.

Defining the target population represents the first activity in this step of the DQOs process. The target population is usually defined as the set of all environmental samples. For the water quality component of a baseline monitoring program, for example, the target population consists of all possible samples of surface water that, collectively, comprise the total volume of the surface water system under investigation. A sampling unit from this target population would correspond to, for example, a 250 mL sample of surface water, submitted for laboratory analysis.

Next, the spatial and temporal boundaries of the baseline monitoring program are defined. Spatial boundaries define the physical area to be studied and the general locations where samples will be collected. By comparison, temporal boundaries define the time frame within which the baseline monitoring program will be conducted and when the samples should be collected. This information is needed to define the entire geographic area within which the samples are to be collected (i.e., defined by spatial coordinates). In addition, this information is required to divide the target population into subsets that have relatively homogeneous characteristics. Determination of the period of time that the data are intended to represent or the time-frame for which the estimate is relevant provides a basis for establishing the temporal boundaries.

Historical data and information (i.e., baseline data and/or data collected for other purposes) are important for establishing the spatial and temporal boundaries of target populations because they can help define the extent of the study area in time and space (i.e., for existing land- or water-use management activities). Additionally, this information is important in understanding variability in the system and, hence, defining spatial boundaries and time frames appropriate for collecting data and making management decisions.

The practical constraints associated with the proposed data collection activities also need to be identified during this step in the DQOs development process. Similarly, issues related to the availability and operation of equipment need to be identified and, if possible, addressed. In most cases, solutions to these constraints can be found once they have been identified.

Finally, the scale of inference needs to be defined during this step in the DQOs development process. The scale of inference refers to the manner in which the smallest sub-population, area, volume, or time over which data will be collected, analyzed, aggregated, and interpreted to produce an estimate is delineated (USEPA 2006). For estimation problems, the consequences of making inaccurate estimates of environmental conditions should be considered when establishing the scale of the sampling units that are selected.

Overall, the outputs that are expected through definition of the boundaries of the study area include:

- Definition of the target population, with detailed descriptions of the geographic boundaries of the study area;
- Detailed descriptions of the sampling units that will be included in the baseline monitoring program (e.g., areas of interest, stream reaches, etc.);
- Definition of the time frame that is appropriate for collecting data and making the decision or estimate, together with those practical constraints that may interfere with data collection; and,
- Definition of the appropriate scale for estimation of parameters that describe the status of the selected indicators of background conditions.

5.1.5 Developing the Analytical Approach

The fifth step in the DQOs process involves developing the analytical approach that will be used to draw conclusions from the baseline monitoring program results. This step in the DQOs process typically involves selecting the population parameter(s) that will be used to make inferences about the target population.

The population parameter that is used to characterize the target population is dependent on the goals of the study. For the derivation of RSWQTs for Waters of Special Significance, the objective of the baseline monitoring program is to characterize the levels of COPCs or other variables under background conditions (i.e., to support application of the background-concentration approach to derive RSWQTs). Derivation of numerical RSWQTs using the background-concentration procedure requires estimation of both the central tendency and upper limit of background concentrations for each of the COPCs. The estimate of central tendency of the background concentrations is used to establish a chronic (typically 30-day average) RSWQT, while the upper limit of background conditions is used to establish the acute (i.e., short-term maximum) RSWQT for each water quality variable. As such, water quality conditions for each of the identified COPCs should be characterized by

determining the central tendency, calculated as the 95% upper confidence limit (UCL) of the mean (or the arithmetic mean if fewer than 10 measurements are available), and upper limit of natural conditions, calculated as the 95th percentile of concentrations. Dependent upon the hydrological conditions at the NWR, RSWQTs may be derived for specific stages of the hydrograph (e.g., low-flow conditions, ascending hydrograph) or for specific times of year (e.g., during the presence of migratory birds).

For estimation problems, a specification for the estimator of the population parameter is also developed during this step of the process. This activity is completed by combining the selected population parameter with the scale of estimation and other population boundaries (e.g., low-flow conditions). For example,

> *"The average monthly concentration of ammonia in the NWR will be estimated for each month between 2014 and 2017. This estimate of the central tendency of the ammonia concentration data will be generated using the monthly concentrations measured under the baseline monitoring program. These results will be used to recommend a chronic (i.e., long-term) RSWQT for application on the NWR."*

One of the key outputs of this step in the DQOs process is the verification of the population parameters that are most relevant for making inferences regarding the target population and deriving numerical RSWQTs. In addition, the estimator that will be used to describe the selected population parameter is identified, including the scale of estimation and other population boundaries.

5.1.6 Specifying Performance or Acceptance Criteria

The penultimate step in the DQOs process involves derivation of the performance or acceptance criteria that will be used to specify tolerable limits on decision errors.

The first activity in this step involves determining the sources of variability in the sample dataset. While there may be many factors contributing to error, two main

types of errors are typically identified. These are sampling errors, which can lead to imprecision (i.e., random errors) or bias (i.e., systematic errors) in the estimates of population parameters, and measurement error, which arises from imperfections in the measurement and analysis system. Next, the plausible range of values for each variable is estimated by determining the likely upper and lower bounds based on the available data, professional judgment, and/or other information.

The principal output from this step of the DQOs process is a set of performance or acceptance criteria that the data should achieve in order to minimize uncertainty in estimates of population parameters (USEPA 2006). More specifically, these performance or acceptance criteria will likely include:

- Specification of the range of possible true values for the measurement endpoints that correspond to the baseline condition;
- Specification of the gray region containing possible true values of the measurement endpoints that fall within the alternative condition and for which high probabilities of making false acceptance decision errors is tolerable; and,
- Specification of a set of tolerable decision error limits at selected true values of the measurement endpoints.

Establishment of appropriate performance criteria provides an objective and consistent basis for evaluating the measurement data generated in the sampling program. Such performance criteria for measurement data typically are defined using five indicators of data usability, including accuracy, precision, completeness, representativeness, and method sensitivity.

Accuracy is a measure of the bias of a system or measurement. It is the closeness of agreement between an observed value and an accepted value. Accuracy of chemical analysis is usually determined through the analysis of matrix spikes and standard reference materials. Matrix spikes are environmental samples into which known quantities of surrogates are added and their concentrations are subsequently measured.

Information on the percent recovery of surrogate spikes is used directly to assess analytical accuracy. Standard reference materials are environmental samples that have been analyzed by numerous laboratories and the results are used to define the true concentrations of analytes. Method blanks can be used to measure contamination associated with laboratory processing and analyses.

Precision is a measure of mutual agreement among individual measurements of the same property, usually under prescribed similar conditions. Analytical precision is usually determined by the analysis of laboratory duplicates and matrix spike duplicates. Laboratory duplicates are prepared by splitting environmental samples in the laboratory, and carrying the sub-samples through the entire analytical process. Matrix spike duplicates are prepared by splitting a matrix spike sample in the laboratory, and carrying the sub-samples through the entire analytical process. Precision can be expressed in terms of the relative percent difference (RPD) of all analyses where duplicates are performed:

$$RPD = \frac{|C_1 - C_2|}{(C_1 + C_2)/2} \times 100$$

where: C_1 = larger measured value; and,
C_2 = smaller measured value.

Completeness is a measure of the amount of valid data obtained from a measurement system compared to the amount that was expected to be obtained under normal conditions. Target completeness values are typically in the range of 90% for chemical analyses of water and are defined as the ratio of valid results to the number of results that were targeted in the monitoring program design.

$$\%\ C = 100 \times \frac{V}{n}$$

% C = percent completeness

V = number of measurements judged valid

n = total number of measurements necessary to achieve a specified statistical level of confidence in decision making

Representativeness expresses the degree to which data accurately and precisely represent a characteristic of a population, parameter variations at a sampling point, a process condition, or an environmental condition. Representativeness is addressed primarily in the experimental design and through the selection of appropriate sampling and analytical procedures. Representativeness can also be ensured by the proper handling and storage of samples and by analysis within the accepted holding times so that the material analyzed reflects the material collected as accurately as possible (USEPA 2000b; ASTM International 2013).

Sensitivity is the capability of methodology or instrumentation to discriminate among measurement responses for quantitative differences of a parameter of interest. Sensitivity is usually defined as the detection limit that is achieved for a chemical analysis. The detection limit is the minimum concentration of a substance that can be measured and reported. Detection limits vary among analytical methods and are a primary determinant in the selection of analytical methods for a water quality monitoring program (i.e., detection limits must be below effect levels and background levels of COPCs).

5.1.7 Developing the Plan for Obtaining Data

The final step in the DQOs process involves developing a plan for obtaining data under the baseline monitoring program. More specifically, the goal of this step of the process is to develop a resource-efficient design for collecting and analyzing environmental samples or for generating other types of information needed to support the baseline monitoring program. While more detailed guidance on the design of baseline monitoring programs is provided in Section 5.2, general guidance is provided here to enhance consistency with the DQOs process. The steps involved in this stage of the DQOs process include:

- Gathering information that is required to develop an efficient and effective baseline monitoring program;
- Identifying one or more candidate designs from which to select the final baseline monitoring program design;
- Determining the "optimal" amount of information to collect for the potential design, considering both cost and statistical factors; and,
- Preparing a resource-efficient information collection plan that meets the requirements for the baseline monitoring program.

5.2 Development of the Sampling Design

This section describes the recommended steps for designing the baseline monitoring program. Importantly, this step in the process should be initiated prior to collecting baseline data to ensure that the data that are collected will be consistent with, and comparable to, data collected throughout the baseline monitoring program.

5.2.1 Compilation of Supporting Information

To develop a detailed sampling design to support the objectives of the baseline monitoring program, refuge staff, FWS Contaminants Specialists, and FWS Water Resource Branch staff will need to assemble the outputs of Steps 1 through 6 of the DQO process, including:

- The objectives of the baseline monitoring program and the intended uses of the resultant data (e.g., estimation of population parameters);
- Background information on the study area, characteristics of the contaminants and media, regulatory requirements, and spatial and temporal patterns of contamination;
- Expected variability for the data based on similar studies and/or professional judgment; and,

- Preliminary information on the underlying distributions of the data that will impact calculations on the minimum amounts of data to collect.

Collectively, this information provides a basis for identifying the types of data that need to be collected, for selecting a temporal and spatial sampling design to reduce sampling variability, and for choosing analytical measurement techniques that will reduce analytical variability.

5.2.2 Development of the Conceptual Monitoring Program Design

Probability-based sampling designs are recommended for use as each possible sampling unit has a known probability of being selected and only those sampling units selected will provide data for the study (USEPA 2006). Probability-based sampling designs are required when statistical inference techniques are to be applied to the resultant data (e.g., estimations of population parameters, confidence interval calculations).

As sound, science-based decisions are based on accurate information, the following issues must be addressed in the conceptual baseline monitoring program design (USEPA 2002):

- The appropriateness and accuracy of the sample collection and handling methods;
- The effect of measurement error on the results;
- The quality and appropriateness of the laboratory analyses; and,
- The representativeness of the data with respect to the objectives of the study.

While the first three issues can be effectively addressed through Steps 1 to 6 of the DQOs process, representativeness must be addressed through the selection of an appropriate sampling design. In this context, representativeness can be considered as a measure of the degree to which data accurately and precisely represent a characteristic of a population, parameter variations at a sampling point, a process

condition, or an environmental condition (USEPA 2002). Considerations for sampling design include variability in monitoring data, sampling frequency, and sampling duration.

Water quality conditions are known to vary substantially on temporal and spatial bases. This underlying variability in water quality data makes it challenging to distinguish patterns in water quality conditions from apparent noise in the system. For this reason, it is important to incorporate design elements that facilitate characterization of the various sources of variability and support interpretation of the resultant data. Potential sources of variability and strategies to address them are identified below:

- *Small-scale spatial variability* - Conduct replicate sampling to assess homogeneity over small distances (i.e., using a replicate sampler);
- *Variability with depth* - Conduct depth-integrated sampling and grab sampling at various water depths and compare the results using statistical methods. Alternatively, conduct only grab sampling at various water depths and compare the results using statistical methods;
- *Cross-sectional variability* - Conduct a station evaluation to determine if water quality varies significantly along a cross-section of a river. Data collected along the transect are compared using statistical methods;
- *Longitudinal variability* - Conduct an intensive water quality survey to collect water samples at numerous locations within a watershed. Data collected at the various stations are compared using statistical methods;
- *Diurnal variability* - Conduct intensive sampling at multiple times during a 24-hour period during station evaluations under various flow conditions (i.e., high, moderate, and low);
- *Seasonal variability* - Conduct sampling over the course of a year, with intensive sampling conducted during freshet events. Use graphical and statistical techniques to evaluate seasonal variability;

- *Inter-annual variability* - Conduct long-term sampling at a fixed frequency at fixed stations. Use graphical and statistical techniques to evaluate long-term trends; and,
- *Variability due to regional and global influences* - Conduct long-term monitoring at a fixed frequency at fixed reference stations. Use graphical and statistical techniques to evaluate long-term trends.

Acquisition and evaluation of data on the sources of variability in water quality conditions provide a means of designing and optimizing sampling programs for assessing status and trends. In general, monitoring for characterizing background conditions involves the collection of water samples for analysis at a fixed frequency over an extended time period (i.e., a minimum of three years). However, determination of the appropriate sampling frequency necessitates balancing the costs of data collection against the need for comprehensive data. More specifically, the objective is to make the sampling interval long enough to minimize sampling costs, but short enough to ensure that the extremes of the natural variability are adequately sampled. For this reason, it is important to gain an understanding of the short-term variability of water quality conditions (i.e., diurnal and seasonal variability) to support the design of a baseline monitoring program. Therefore, it is recommended that an initial short-term water quality survey be initiated during the sampling design phase. While compilation, evaluation, and analysis of historical water quality data can provide such an understanding, it may be necessary to design and implement such a short-term water quality survey to provide the information needed to establish sampling frequencies for a long-term monitoring program. Such short-term surveys can also be designed to evaluate spatial variability (i.e., cross-sectional, depth, and longitudinal variability) in water quality conditions to identify the most appropriate locations for siting long-term monitoring stations.

Guidance provided by other agencies, such as the British Columbia Ministry of Environment (BCMOE), states that monitoring programs developed for the collection of baseline data should consist, at minimum, of monthly sampling events conducted for a period of one year. However, it is recommended by BCMOE that two years of data are collected (BCMOE 2012). Furthermore, the monitoring program should

include two 5-in-30 day sampling events, collected annually, corresponding to distinct periods of the hydrograph (e.g., low-flow conditions and freshet; BCMOE 2012). These sampling events are defined as the collection of five samples at approximately six-day intervals over a 30 day period. While two years of baseline data may be adequate in some situations, a program of this duration may not capture the inter-annual variability that needs to be characterized to reduce uncertainty in the estimates of the population parameters. Therefore, to characterize background conditions for use in the derivation of RSWQTs for NWRs, it is recommended that monthly sampling of all water bodies be conducted for a minimum of three years. Further, it is recommended that two 5-in-30 day sampling events are collected annually, corresponding to low-flow conditions and freshet.

5.2.3 Development of Site-Specific Survey Protocols

The site-specific survey protocol translates the conceptual monitoring program design and associated analysis plan into a more tangible set of procedures that can be followed by staff involved in field sampling, laboratory analysis, and data validation, compilation, and interpretation. The site-specific survey protocol typically consists of eight elements, including:

- Introduction;
- Sampling Design;
- Field Methods and Sample Processing Methods;
- Data Management and Analysis;
- Reporting;
- Personnel Requirements and Training;
- Operational Requirements; and,
- References.

For detailed information on the development of a site-specific survey protocol, please refer to "*How to Develop Survey Protocols: A Handbook*" (USFWS 2013b).

5.3 Implementation of the Baseline Monitoring Program

Before the baseline monitoring program is implemented, it is important to verify that samples specified in the site-specific survey protocol can be collected at the site. Furthermore, it is important to determine if the selected sampling methods are appropriate and applicable to the conditions at the site. In this way, the level of effort necessary to collect the required number of samples can be determined. At this stage of the process, it is prudent to develop a number of contingency plans that can be used to direct field sampling efforts if unexpected conditions are encountered.

Field sampling activities should be audited to ensure that environmental samples are being collected using the agreed-to methods and procedures. In addition, the laboratories that have been selected by refuge staff, FWS Contaminants Specialists, or FWS Water Resource Branch staff should be periodically audited to confirm that they are generating reliable data. Ultimately, the performance criteria for measurement data provide the basis for evaluating the extent to which the data generated meet the objectives of the baseline monitoring program.

6.0 Evaluation, Compilation, and Interpretation of Baseline Monitoring Program Data

The data must be evaluated relative to the project DQOs to determine if they can be used in the characterization of background conditions in the study area. The results of such an evaluation will determine if the data can be used directly, if the data need to be qualified prior to use, or if the data should be rejected. The data that are generated under the baseline monitoring program should subsequently be compiled in a format that facilitates access by FWS Contaminants Specialists and FWS Water Resource Branch staff. The procedures for interpreting the baseline monitoring program data specified in the analysis plan should then be conducted.

6.1 Evaluation of Baseline Monitoring Data

Data evaluation represents a key step in the overall quality assurance process. The DQOs that were established early in the monitoring program development process define the data requirements for supporting characterization of water quality conditions. As part of the site-specific survey protocol development process, performance criteria for measurement data were established that define acceptable levels of accuracy, precision, completeness, representativeness, and method sensitivity. The data generated in the baseline sampling program need to be evaluated to determine if they meet the needs for assessing water quality conditions in the study area using these performance criteria for measurement data. In addition, any issues related to sample holding times, instrument calibration, and related factors need to be considered in the verification and validation of project data.

6.2 Compilation of Baseline Monitoring Data

Data compilation describes the activities associated with collating information collected in the field and the data generated in laboratory analyses. This activity represents a key step in the overall water quality assessment because it assembles data and information in a form suitable to support data analysis and interpretation. Although there are many ways of compiling monitoring data, GIS-compatible relational databases have become the industry standard because of the ability to query and extract subsets of the data efficiently. A wide range of database systems are available; however, Microsoft Access is recommended because most data users have access to this software and because it is sufficiently powerful to store this type of environmental data. In addition, Microsoft Access is compatible with most electronic data delivery systems (i.e., systems used by analytical laboratories to deliver data to clients), which reduces the need for manual data entry. Nevertheless, all of the data that are compiled in the project database need to be verified against the original data source to ensure data quality. Such databases should be designed and populated with the needs of data users in mind. Because data are typically generated in multiple batches over the duration of the baseline monitoring program, databases must be constantly updated and users apprised of the changes that have been made. Periodic

database auditing is also recommended to ensure that the underlying data used in data analyses are correct and internally consistent. Guidance on data verification and validation is provided by Clark *et al.* (1996) and USEPA (1994; 1999; 2001a; 2001b).

6.3 Interpretation of Baseline Monitoring Data

For Waters of Special Significance, the objective of the baseline monitoring program is to characterize the levels of COPCs or other variables under background conditions, such that the background-concentration approach can be employed to derive RSWQTs. Derivation of numerical RSWQTs using the background-concentration procedure requires estimation of both the central tendency and upper limit of background concentrations of each of the COPCs. The estimate of central tendency of the background concentrations is used to establish a chronic (typically 30-day average) RSWQT, whereas the upper limit of background conditions is used to establish the acute (i.e., short-term maximum) RSWQT for a water quality variable. The mathematical procedures described in Section 5.1.5 should be used to calculate the estimates of central tendency and upper limit of background conditions. The estimates generated from the data collected during the baseline monitoring program can be used directly in the derivation of RSWQTs for Waters of Special Significance. Furthermore, these estimates should be used to inform decisions regarding the development of RSWQTs for Sensitive Waters or Typical Waters (i.e., to determine if effects-based RSWQTs are achievable on the refuge, based on background conditions).

7.0 Summary and Recommendations

This appendix is intended to provide detailed guidance on the development and implementation of baseline monitoring programs to support the derivation of RSWQTs for Waters of Special Significance. In addition, data generated using this guidance could be used to characterize background conditions to support the derivation of RSWQTs for Sensitive Waters or Typical Waters. To that end, a

framework has been developed to provide users with step-by-step guidance for developing baseline monitoring programs that involves identification of issues and concerns associated with off-refuge land- or water-use management activities and on-refuge habitat management activities, development of DQOs and a detailed sampling design, implementation of the baseline monitoring program, and finally guidance on the evaluation, compilation, and interpretation of the generated data. By adhering to the principles and guidance presented in this appendix, the data generated during the baseline monitoring program are likely to be appropriate and relevant for inclusion in a comprehensive I&M program.

It is recommended that baseline monitoring programs developed to characterize background conditions include monthly sampling of all water bodies for a minimum of three years. Further, it is recommended that two 5-in-30 day sampling events be conducted annually, corresponding to periods of low-flow and high-flow conditions.

At minimum, the baseline monitoring program needs to include:

- Conventional variables (e.g., temperature, pH, total suspended solids, total dissolved solids, dissolved oxygen, and dissolved organic carbon);
- Nutrients (e.g., total and dissolved phosphorus, orthophosphate, total nitrogen, ammonia, nitrate, and nitrite);
- Major ions (e.g., bicarbonate, calcium, chloride, magnesium, sodium, potassium, and sulfate); and,
- Total and dissolved metals.

Additional variables need to be included based on the results of the COPCs identification step of the monitoring program design process.

Characterization of background conditions requires determination of both the central tendency and upper limit of background concentrations of the selected COPCs. The estimate of central tendency of the background concentrations is used to characterize average water quality conditions, while the upper limit of background conditions is used to characterize the upper end of the distribution for each water quality variable.

An estimate of the average water quality condition should be calculated by determining the 95% UCL of the mean concentration using all available data on the concentrations of a water quality variable (if 10 or more measurements are available) or the arithmetic mean concentration (if fewer than 10 measurements are available). An estimate of the upper limit of background is calculated by determining the 95th percentile concentration for each water quality variable. Water quality conditions can be characterized on a monthly basis, annual basis, or for specific stages of the hydrograph (e.g., low flow conditions, ascending limb of the hydrograph), using the water chemistry data that were collected during that flow condition. The same mathematical procedures would be applied to characterize these conditions.

8.0 References

ASTM International. 2013. Guide for collection, storage, characterization, and manipulation of sediments for toxicological testing and for selection of samplers used to collect benthic invertebrates. ASTM E1391-03(2008). Annual Book of ASTM Standards Volume 11.06. West Conshohocken, Pennsylvania.

BCMOE (British Columbia Ministry of Environment). 2012. Water and air baseline monitoring guidance document for mine proponents and operators. Environmental Protection Division. Victoria, British Columbia.

BLNWR and USFWS (Bear Lake National Wildlife Refuge and United States Fish and Wildlife Service). 2013. Bear Lake National Wildlife Refuge and Oxford Slough Waterfowl Production Area – Comprehensive Conservation Plan. Montpelier, Idaho and Portland, Oregon.

Clark, M.J., M.C. Laidlaw, S.C. Ryneveld, and M.I. Ward. 1996. Estimating sampling variance and local environmental heterogeneity for both known and estimated analytical variance. Chemosphere 32(6):1133-1151.

Dickerson, K., K.J. Nelson, and C. Zeeman. 2011. Characterizing contaminant exposure of mountain plovers on eintering grounds in California and breeding grounds in Colorado, Wyoming, and Montana. Contaminants Report Number: R6&R8/725C/11. U.S. Fish and Wildlife Service, Region 6, Environmental Contaminants Program. 164 p. Available at http://www.fws.gov/contaminants/DisplayLibrary.cfm?ID=573879F4-D264-3D9D-51093F4C8A83C594&Verify=0

MacDonald, D.D., M.A. Crawford, H.J. Prencipe, J.A. Sinclair, A. Schein, and M.B. Meneghetti. 2014. Handbook for assessing risks to fish and wildlife associated with the potential use of water, treated wastewater, stormwater, sediment, soil, biosolids, or other materials on units of the National Wildlife Refuge System. Volumes I-IV. Prepared for U.S. Fish and Wildlife Service. Vancouver, Washington. Prepared by MacDonald Environmental Sciences Ltd., Nanaimo, British Columbia.

Messinger, T. 2004, Polycyclic aromatic hydrocarbons in bottom sediment and bioavailability in streams in the New River Gorge National River and Gauley River National Recreation Area, West Virginia, 2002: U.S. Geological Survey Scientific Investigations Report 2004-5045, 24 p. Available at http://pubs.usgs.gov/sir/2004/5045/pdf/sir2004-5045.pdf.

Schroeder, R.A., D.U. Palawski, and J.P. Skorupa. 1988. Reconnaissance investigation of water quality, bottom sediment, and biota associated with irrigation drainage in the Tulare Lake bed area, southern San Joaquin Valley, California, 1986-87. U.S. Geological Survey Water-Resources Investigations Report: 88-4001. Available at http://pubs.er.usgs.gov/publication/wri884001.

USEPA (United States Environmental Protection Agency). 1994. USEPA Contract Laboratory Program: National functional guidelines for inorganic data review. EPA 540/R-94/013. PB 94-963502. 9240.1-05-01. USEPA (United States Environmental Protection Agency). Office of Emergency and Remedial Response. Washington, District of Columbia. 118 pp.

USEPA (United States Environmental Protection Agency). 1997. Ecological risk assessment guidance for Superfund: Process for designing and conducting ecological risk assessments. Environmental Response Team. Edison, New Jersey.

USEPA (United States Environmental Protection Agency). 1998. Guidelines for ecological risk assessment. Risk Assessment Forum. EPA/630/R-95/002F. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 1999. USEPA Contract Laboratory Program: National functional guidelines for organic data review. EPA 540/R-99/008. PB 99-963506. 9240.1-05A-P. USEPA (United States Environmental Protection Agency). Office of Emergency and Remedial Response. Washington, District of Columbia. 118pp.

USEPA (United States Environmental Protection Agency). 2000a. Guidance for the data quality objectives process. EPA QA/G-4.EPA/600/R-96/055.Office of Environmental Information. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 2000b. Methods for measuring the toxicity and bioaccumulation of sediment-associated contaminants with freshwater invertebrates. Second edition.EPA 600/R-99/064.Office of Research and Development. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 2001a. EPA requirements for quality assurance project plans. EPA QA/R-5.EPA/240/B-01/003. United States Environmental Protection Agency. Office of Environmental Information. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 2001b. USEPA Contract Laboratory Program: National functional guidelines for low concentration organic data review. Final.EPA 540-R-00-006.OSWER 9240.1-34. USEPA (United States Environmental Protection Agency). Office of Emergency and Remedial Response. Washington, District of Columbia. 110 pp.

USEPA (United States Environmental Protection Agency). 2002. Guidance for choosing a sampling design for environmental data collection for use in developing a quality assurance project plan. EPA QA/G-5S.EPA/240/R-02/005.Office of Environmental Information. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 2006. Guidance on systematic planning using the data quality objectives process. EPA QA/G-4.EPA/240/B-06/001.Office of Environmental Information. Washington, District of Columbia

USFWS (United States Fish and Wildlife Service). 2013a. Water quality assessment plan. Department of the Interior, US Fish and Wildlife Service, Bear Lake National Wildlife Refuge. Montpelier, Idaho.

USFWS (United States Fish and Wildlife Service). 2013b. How to develop survey protocols, a handbook (Version 1.0). Fort Collins, Colorado, US Department of Interior, Fish and Wildlife Service, National Wildlife Refuge System, National Resource Program Center.

USFWS (United States Fish and Wildlife Service). 2014. Inventory and monitoring plan. Department of the Interior, US Fish and Wildlife Service, Malheur National Wildlife Refuge. Princeton, Oregon.

Appendix 6

Evaluation of the Environmental Protection Agency Ambient Water Quality Criteria for Ammonia and Cadmium

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List of Acronyms

ACR	-	acute-chronic ratio
AWQC	-	ambient water quality criteria
BCMOE	-	British Columbia Ministry of Environment
CCC	-	criterion continuous concentration
CCME	-	Canadian Council of Ministers of the Environment
CMC	-	criterion maximum concentration
EC_x	-	effective concentration affecting x% of the population
ELS	-	early life stage
EPA	-	Environmental Protection Agency
FAV	-	final acute value
FCV	-	final chronic value
FWS	-	Fish and Wildlife Service
GMAV	-	genus mean acute value
GMCV	-	genus mean chronic value
IC_x	-	inhibitory concentration causing an x% inhibition in tested organisms
LC_x	-	lethal concentration affecting x% of the population
LOEC	-	lowest observed effect concentration
MATC	-	maximum acceptable toxicant concentration
NOEC	-	no observed effect concentration
NWR	-	National Wildlife Refuge
NWRS	-	National Wildlife Refuge System
RSWQT	-	refuge-specific water quality target
SMAV	-	species mean acute value
SMCV	-	species mean chronic value
TAN	-	total ammonia nitrogen
TRAP	-	Toxicity Relationship Analysis Program
WQT	-	water quality target

1.0 Introduction

The Environmental Protection Agency (EPA) establishes acute and chronic national ambient water quality criteria (AWQC) for the protection of aquatic life in U.S. waters. The EPA AWQC are developed by evaluating relationships between the concentrations of contaminants in water and their effects on aquatic organisms and are used by federal, state, tribal, and other agencies to create water quality standards and control releases of pollutants to the environment. These national criteria are developed based on the assumption that aquatic ecosystems can withstand some stress and tolerate occasional adverse effects (Stephan *et al.* 1985). By design, the national criteria are intended to protect 95% of tested taxa (Stephan *et al.*1985). While this level of protection is considered to be adequate for most water bodies, it may not be adequate for certain National Wildlife Refuges (NWRs) that may require an enhanced level of environmental protection to achieve conservation, management, and restoration goals for fish, wildlife, and plant resources. In addition, aquatic habitats on NWRs may support sensitive, threatened, and/or endangered species, which could require a higher level of protection than is afforded by the EPA AWQC.

This appendix provides an evaluation of the freshwater nationally recommended AWQC that have been established for ammonia (USEPA 2013) and cadmium (USEPA 2001). While EPA AWQC exist for approximately 150 substances, ammonia and cadmium have been identified by refuge staff and FWS Contaminants Specialists as contaminants of interest due to their presence on NWRs (Fish and Wildlife Service [FWS] workshop in Arlington, VA in February, 2013). Hence, these substances were selected to determine if the EPA AWQC provide an adequate level of protection for taxa of concern on NWRs.

1.1 Overview of Environmental Protection Agency Ambient Water Quality Criteria

The EPA AWQC are derived using data generated from standard toxicity tests and the methodology described in Stephan *et al.* (1985). Stephan *et al.* (1985) describes the steps required for compiling and evaluating toxicity data, and calculating the final acute and chronic numerical criteria for the protection of aquatic organisms. First, all of the available data generated on the toxicity and bioaccumulation of the substance to aquatic organisms should be compiled. These data must be accompanied by sufficient information to allow the reviewer to evaluate acceptability of test procedures and conclude that the data are reliable and useable. In order to help ensure that species representative of the aquatic community are included in the dataset, Stephan *et al.* (1985) established minimum data requirements for the derivation of EPA AWQC. Numerical criteria are not developed for substances for which the minimum data requirements are not met. The acute and chronic EPA AWQC have unique derivation methods. The procedures for deriving acute and chronic EPA AWQC are briefly described separately in the following sections.

1.1.1 Derivation of Acute Environmental Protection Agency Ambient Water Quality Criteria

The acute EPA AWQC (i.e., criterion maximum concentration; CMC) is defined as the 1-hour average concentration of a substance in water that should not be exceeded within a three-year period in order to protect against adverse effects on aquatic life. To derive the CMC, data generated from acute toxicity tests, including LC_{50}s (i.e., concentration lethal to 50% of the tested organisms) and/or EC_{50}s (i.e., concentration affecting 50% of the tested organisms), are required for a minimum of eight diverse taxonomic groups (see Stephan *et al*. [1985] for further details). These data must meet the usability criteria outlined in Stephan *et al.* (1985; e.g., tests conducted using procedures outlined in ASTM methods

documents, acceptable control mortality, total organic carbon in dilution water < 5 mg/L). A species mean acute value (SMAV) is determined for each species, calculated as the geometric mean of the effect concentrations (i.e., LC_{50}/EC_{50}) from short-term (i.e., $\leq$ 96-hours) toxicity tests performed under flow-through conditions (with the exception that static-renewal is acceptable for daphnids) in which the concentration of the test analyte was measured at appropriate intervals. If no studies meet these test conditions, the SMAV is calculated using all available test results (i.e., using the results from static or static-renewal tests, and results in which nominal concentrations [i.e., concentrations of the test analyte were not measured] were presented). A genus mean acute value (GMAV) is then determined for each genus, calculated as the geometric mean of the SMAVs. The GMAVs are ranked from lowest to highest, and the four GMAVs closest to the 5^{th} percentile are used to determine the final acute value (FAV). The FAV is then divided by two to obtain the CMC.

1.1.2 Derivation of Chronic Environmental Protection Agency Ambient Water Quality Criteria

The chronic EPA AWQC (i.e., criterion continuous concentration; CCC) is typically defined as the 4-day average concentration of a substance in water that should not be exceeded within a three-year period in order to protect against sub-lethal effects on aquatic organisms. To derive the CCC, low-effect thresholds generated from longer-term toxicity tests (i.e., > 96-hours), including EC_{15-25} and maximum allowable toxicant concentrations (MATCs; also known as chronic values; i.e., defined as the geometric mean of no observed effect concentrations [NOEC] and lowest observed effect concentrations [LOEC]) are used. The terms MATC and chronic value are used interchangeably in this appendix. The chronic dataset should include data from toxicity tests that demonstrate a reduction in survival, growth, or reproduction. The method used to calculate the chronic criterion is dependent on the number of taxa represented in the chronic dataset. If sufficient chronic data are available to meet the minimum eight diverse taxonomic

groups listed in Stephan *et al*. (1985), the final chronic value (FCV) is determined by calculating the species mean chronic values (SMCVs) for each tested species, calculated as the geometric mean of the low-effect concentrations from toxicity tests that meet the data usability criteria. A genus mean chronic value (GMCV) is then determined for each genus, calculated as the geometric mean of the SMCVs. The GMCVs are ranked from lowest to highest, and the four GMCVs closest to the 5th percentile are used to determine the FCV. Otherwise, the FCV can be derived by dividing the FAV by the acute-chronic ratio (ACR), using data from a minimum of three taxa (see Stephan *et al.* [1985] for methods for calculating the ACR). The FCV is used directly as the CCC.

1.2 Environmental Protection Agency Ambient Water Quality Criteria for Ammonia

The EPA ammonia criteria for the protection of aquatic life have undergone four revisions (in 1985, 1999, 2009, and 2013) since the guidelines were first published in 1976. Updated versions have incorporated additional data and toxicity test methodologies, re-examined temperature and pH relationships, and moved from developing the chronic criterion using an ACR to calculating the criterion from a chronic toxicity dataset. Data used in the development of the 1999 criteria indicated that juvenile and adult fish were the most sensitive to ammonia during short-term (i.e., $\leq$ 96-hour) exposures, whereas benthic invertebrates and the early-life-stages (ELS) of fish were the most sensitive during long-term (i.e., chronic) exposures. In response to rising concerns over the sensitivity of freshwater mussels and snails to ammonia, EPA published updated draft criteria in 2009 that incorporated recent toxicity data generated for invertebrates and fish exposed to ammonia under acute and chronic conditions (USEPA 2009). The revised FAV was based on four mussel and clam genera, while three of four GMCVs used to define the FCV were for mussel and clam genera. The latest EPA AWQC revision (2013) for ammonia includes additional data (including some of the most recent toxicity data for mussels) and re-analyzed data that were compiled for the 1999

and 2009 documents. A summary of water quality criteria developed by EPA and other jurisdictions for ammonia is presented in Table A6.1.

For the 2013 update of the EPA AWQC for ammonia, acceptable acute and chronic toxicity data were converted (when necessary) to total ammonia nitrogen (TAN), then normalized to pH 7.0 (for all species) and 20°C (for invertebrate species only) using the procedures described in USEPA (2013). In general, freshwater mollusks make up the most sensitive taxonomic group in the acute dataset, and the four most sensitive genera are mussel species. The four most sensitive genera in the chronic exposure dataset consist of three mollusk genera (i.e., clams and mussels) and the sunfish genus (*Lepomis*). The chronic exposure dataset consists of estimates of the EC_{20}, calculated using EPA's Toxicity Relationship Analysis Program (TRAP) from acceptable survival and growth tests (28-day) with juvenile freshwater mussels and snails. However, the growth data for mussels (i.e., Wang *et al.* 2007a; Wang *et al.* 2011) were excluded from the chronic dataset due to uncertainty in the method of measurement for the growth endpoint (USEPA 2013).

USEPA (2013) has recommended an acute freshwater criterion (i.e., CMC) of 17 mg TAN/L at pH of 7 and temperature of 20°C, which is the maximum one-hour average that should not be exceeded more than once in a three-year period. The chronic criterion (i.e., CCC), 1.9 mg TAN/L, is a threshold that the 30-day rolling average should not exceed more than once within a three-year period. In addition, the rolling 4-day average should not exceed 2.5 times the CCC.

1.3 Environmental Protection Agency Ambient Water Quality Criteria for Cadmium

The EPA cadmium criteria for the protection of aquatic life have undergone a number of revisions since the guidelines were first published in 1976. Prior to the most recent EPA AWQC for cadmium (i.e., USEPA 2001), criteria were updated

in 1980, 1985, 1996, and 1999. In general, subsequent versions have incorporated additional toxicity data than were presented in previous versions. In early versions of the criteria document, cadmium was expressed as total recoverable cadmium (e.g., USEPA 1980; 1996). In the 1985 update, EPA also expressed the criteria as acid-soluble cadmium (USEPA 1985). The EPA has since recommended using dissolved metal concentrations for setting water quality standards (USEPA 1994). Updated cadmium criteria in the 1999 compendium of over 150 substances were not derived using an updated toxicity dataset or methodology; rather, the previous cadmium criteria (i.e., USEPA 1996) were recalculated using a conversion factor to express the criteria as a dissolved concentration.

The 2001 EPA AWQC derivation for cadmium included acute exposure data for 39 species of invertebrates, 24 species of fish, and two amphibian species, as well as chronic exposure data for seven species of invertebrates and 14 species of fish. Newly generated toxicity data included effects concentrations for threatened and endangered species that were not previously available (USEPA 2001). In addition, a re-analysis of the relationship between water hardness and toxicity was conducted. The 2001 update presented more stringent criteria than had been published previously. The acute criterion (i.e., CMC) decreased from 2.0 µg/L at 50 mg/L $CaCO_3$ (USEPA 1999) to 1.0 µg/L at 50 mg/L $CaCO_3$, whereas the updated chronic criteria (i.e., CCC) decreased from 1.3 µg/L at 50 mg/L $CaCO_3$ (USEPA 1999) to 0.15 µg/L at 50 mg/L $CaCO_3$. For the updated 2001 acute criterion, the FAV decreased from 2.76 µg/L at 50 mg/L $CaCO_3$ to 2.11 µg/L at 50 mg/L $CaCO_3$ (i.e., the SMAV for rainbow trout [*Oncorhynchus mykiss*]) to protect rainbow trout, a commercially important species; the FAV was then divided by two and converted from total to dissolved cadmium to derive the CMC.

The 2001 acute exposure dataset is comprised of estimates of the LC_{50}/EC_{50}, whereas all chronic data are presented as chronic values, defined as the geometric mean of the NOEC and LOEC. All toxicity data presented in Appendix 2 (and mentioned herein) were normalized to a total hardness of 50 mg/L $CaCO_3$. USEPA (2001) presents the toxicity datasets in total cadmium concentrations; after

the derivation of the CMC and CCC, hardness-dependent conversion factors were applied to convert the criteria to dissolved cadmium concentrations.

In the 2001 EPA AWQC for cadmium, SMAVs were available for species in 55 genera and ranged from 13.4 µg/L (*Daphnia magna*) to 96,900 µg/L (*Chironomus riparius*) for invertebrates, and 1.61 µg/L (brown trout; *Salmo trutta*) to 10,700 µg/L (Mozambique tilapia; *Oreochromis mossambicus*) for fish. In general, fish are the most sensitive group to cadmium during acute exposure with three of the four most sensitive genera being salmonids. SMCVs were presented for species representing 16 genera and ranged from 0.275 µg/L (*Hyalella azteca*) to 27.2 µg/L (*Ceriodaphnia dubia*) for invertebrates, and 1.31 µg/L (*O. mykiss*) to >23.6 µg/L (blue tilapia; *O. aurea)* for fish. Three of the four most sensitive genera to cadmium during chronic exposure are invertebrates (i.e., amphipods, cladocerans, and the aquatic life-stage of insects).

USEPA (2001) recommended an acute criterion (i.e., CMC) of 1.0 µg/L (dissolved cadmium at a total hardness of 50 mg/L $CaCO_3$), which is the maximum 24-hour average dissolved concentration that should not be exceeded more than once in a three-year period. The chronic criterion (i.e., CCC), 0.15 µg/L (dissolved cadmium at a total hardness of 50 mg/L $CaCO_3$), is the four-day average dissolved concentration that should not be exceeded more than once in a three-year period. Criteria values for various water-hardness concentrations (as well as equations for calculating the criteria at any water hardness) are presented in Table A6.2.

2.0 Methods

A step-wise approach was used to determine if the EPA AWQC for ammonia (USEPA 2013) and cadmium (USEPA 2001) provide an adequate level of

protection for sensitive aquatic organisms and/or threatened and endangered species. These steps included:

- Compilation and verification of data used to develop the current EPA AWQC;
- Acquisition, screening, and compilation of additional candidate toxicity datasets to develop the *recalculation* and *evaluation datasets*;
- Normalization of additional toxicity data to standard pH and water temperature for ammonia data and to standard hardness for cadmium data;
- Selection of additional toxicity data for the recalculation of species and genus mean values (i.e., SMAVs, GMAVs, SMCVs, and GMCVs) and for evaluation of the EPA AWQC;
- Recalculation of species and genus mean values (i.e., SMAVs, GMAVs, SMCVs, and GMCVs); and,
- Evaluation of the EPA AWQC by:
    - Comparing the criteria to the distribution of recalculated genus mean values, species mean values, and effects concentrations from individual studies; and,
    - Evaluating the nature, frequency, and magnitude of toxicity at concentrations of ammonia and cadmium below the EPA AWQC for each of the selected taxa of concern using the results from individual studies.

Each of these steps is described in the following sections.

2.1 Compilation and Verification of Environmental Protection Agency Data

All acute and chronic exposure data presented in the most recent criteria documents for ammonia (USEPA 2013) and cadmium (USEPA 2001) were incorporated into a relational database in MS Access format. The species and genus mean values presented in the criteria documents were also imported into the project database and verified to ensure that any potential errors had not occurred during the translation process. Data verification involved confirmation of data in the database against data in the criteria reports using 10% number-for-number checks against the primary data source initially, and increasing to 100% number-for-number checks if significant errors were detected in the initial auditing step. In addition to the data translation and auditing steps, the data used to calculate SMAVs, GMAVs, SMCVs, and GMCVs derived in the criteria documents were checked for consistency with the described methods, and with the guidance and screening criteria in Stephan *et al.* (1985).

2.2 Acquisition, Screening, and Compilation of Additional Candidate Datasets

To facilitate evaluation of the EPA AWQC, additional toxicity data (i.e., data that were not used in the derivation of the most recent AWQC) were compiled for ammonia and cadmium. Since the most recent version of the EPA AWQC for ammonia was published just prior to this review, an extensive search for additional ammonia toxicity data was not conducted. Rather, key researchers were asked to identify datasets that were not included in USEPA (2013). Because studies conducted in recent years have highlighted the sensitivity of mollusks to the toxic effects of ammonia (USEPA 2013), data acquisition focused on studies involving mussels and snails. In addition, some studies that were included in the AWQC report (i.e., USEPA 2013) were reviewed to determine if additional data (e.g., test

results from more sensitive endpoints) could be used in the evaluation of the criteria.

Since the most recent AWQC for cadmium were published in 2001, compilation of more recent toxicity data was performed to augment the EPA dataset. Identification of candidate datasets involved reviewing scientific literature, sending inquiries to researchers, and reviewing water quality guideline documents from other jurisdictions (e.g., Canadian Council of Ministers of the Environment [CCME] and British Columbia Ministry of Environment [BCMOE]). In addition, studies that were included in the AWQC document (i.e., USEPA 2001) were further reviewed to determine if additional data could be extracted to support the recalculation of species and genus mean values and/or in the evaluation of the cadmium criteria.

All candidate datasets were acquired in electronic format. An evaluation of each dataset was conducted to determine if it included relevant data (e.g., selected media type, selected chemical of interest), and to determine if the study was deemed acceptable for inclusion in the EPA AWQC evaluation (by considering factors such as experimental design, control mortality, compliance with recognized toxicity testing methods, and relevant endpoints). If necessary, effects concentrations from each new dataset were normalized to standard conditions (i.e., temperature = 20°C, pH = 7.0, hardness = 50 mg/L $CaCO_3$) as described in the following section. For cadmium, chronic values were calculated as the geometric mean of the NOEC and LOEC from a single study. All acceptable and relevant toxicity data were compiled in the project database and were subject to verification and auditing procedures as described in Section 2.1.

2.3 Normalization of Additional Toxicity Data

When there are factors (i.e., physical or chemical properties in the water) known to modify the toxicity of a substance, those factors must be taken into account to

derive the EPA AWQC. Therefore, additional toxicity data were normalized to the same standard conditions as were used to normalize the data used in the criteria documents.

For ammonia, temperature and pH are the primary factors known to modify toxicity (USEPA 2013). Prior to incorporating additional ammonia data into the project database, each new dataset was reviewed to determine if the effect concentrations had been normalized (i.e., adjusted to standard conditions of water temperature and pH). The EPA dataset presented toxic effect concentrations as TAN, normalized to pH 7.0 (for all species) and 20°C (for invertebrate species only). Therefore, the additional ammonia data compiled for this evaluation, which included only invertebrate species, were normalized to pH 7.0 according to the method outlined in USEPA (2013). All tests were performed at 20°C and results were reported as TAN.

The toxicity of cadmium is influenced by water hardness, which is typically the primary factor used to modify estimates of cadmium toxicity (e.g., USEPA 2001; CCME 2014). USEPA (2001) presents cadmium toxicity data normalized to a total hardness of 50 mg/L $CaCO_3$. Therefore, all additional toxicity data compiled for this evaluation were normalized to a hardness of 50 mg/L $CaCO_3$ using the pooled slopes presented in USEPA (2001; i.e., 1.0166 for acute exposure data and 0.7409 for chronic exposure data). All species and genus mean values were calculated using data normalized to a hardness of 50 mg/L $CaCO_3$.

2.4 Selection of Additional Toxicity Data

Subsequent to the incorporation of additional normalized toxicity data into the project database, data were selected for use in the recalculation and evaluation analyses. The methodology used to create the supplemental datasets is described below.

For each chemical of interest (i.e., ammonia and cadmium), two datasets were created from the toxicity data compiled in the project database, a *recalculation dataset* and an *evaluation dataset*. Additional data generated from toxicity tests that met all of the acceptable criteria outlined in Stephan *et al*. (1985), but were not included in the calculation of the AWQC by USEPA, were combined with the USEPA datasets (i.e., the datasets used to derive the most recent AWQC) to create the *recalculation dataset* for each analyte (i.e., ammonia and cadmium). Data from the *recalculation datasets* were used to recalculate species and genus mean values by generally following the acceptance criteria and methodology outlined in Stephan *et al.* (1985) and the AWQC documents (USEPA 2001; 2013).

Specifically, the *recalculation dataset* included data from standard toxicity tests that were conducted using acceptable methods and procedures, showed acceptable control mortality, and were conducted under typical conditions (i.e., using appropriate test durations and life stages). Effects concentrations (i.e., EC_{50}/LC_{50}) for appropriate endpoints (e.g., immobility, survival) were obtained to supplement the acute exposure data, whereas EC_{20} or similar (for ammonia) and chronic values or similar (for cadmium) for appropriate endpoints (e.g., reproduction, growth) were obtained to supplement the chronic exposure data. Also consistent with the guidance provided in Stephan *et al.* (1985), the agreement of results within and between species was reviewed for the *recalculation dataset*, and more resistant life stages were excluded if data showed that another life stage was at least a factor of two more sensitive for the same species. However, some deviations from the guidance were followed. These deviations included:

- Unbounded values (i.e., results reported as less- or greater-than values) were excluded from the *recalculation dataset*, except in cases where it was the only value available for the species or genus;

- For cadmium, USEPA (2001) excluded early-life-stage (ELS) tests from chronic mean value calculations if data from life-cycle tests were available; these ELS results were included in the *recalculation dataset* and used to recalculate species mean values; and,

- Stephan *et al.* (1985) recommended using test durations of 48- or 96-hours for embryos and larvae of bivalve mussels, and a test duration of 96-hours for older life stages. However, more recent guidance on conducting laboratory toxicity tests with freshwater mussels (e.g., ASTM 2006) recommends 24- to 48-hour tests for glochidia and 48- to 96-hour tests for juvenile mussels. Hence, the results from 48-hour tests with older life stage mussels were included in the acute *recalculation dataset* for cadmium.

A second dataset (i.e., the *evaluation dataset*) was then created for each analyte and was used to evaluate the criteria by comparing results from individual toxicity tests to the AWQC. The *evaluation datasets* included the results from acceptable toxicity tests used to recalculate species and genus mean values, plus a wider variety of data not typically used in the derivation of AWQC. For example, acceptable static-renewal tests and flow-through tests that reported nominal concentrations that USEPA had excluded from mean value calculations (because flow-through tests with measured concentrations were available for the same species) were included in the evaluation of the acute AWQC. In addition, effects concentrations other than those typically used to derive acute AWQC (i.e., the EC_{50}/LC_{50}), or effects concentrations other than those typically used to derive chronic WQC (i.e., EC_{20}/IC_{20}/chronic values), and additional endpoints beyond survival, growth, and reproduction (e.g., behavioral endpoints) were included in the *evaluation datasets*.

2.5 Recalculation of Species and Genus Acute and Chronic Mean Values

Following incorporation and refinement of additional toxicity data into the project database, species and genus mean values (i.e., SMAVs, GMAVs, SMCVs, and GMCVs) were recalculated for each analyte (ammonia and cadmium) using the *recalculation datasets*. Mean values were recalculated according to the

methodology provided in Stephan *et al.* (1985) and USEPA (2001; 2013), with the exception of the procedures for selecting data (as described in Section 2.4).

2.6 Evaluation of the Ambient Water Quality Criteria

Evaluation of the national recommended AWQC for ammonia and cadmium involved a total of four steps:

- Comparing the acute and chronic criteria to the recalculated genus mean acute and chronic values (i.e., GMAVs and GMCVs calculated with the *recalculation datasets*);
- Comparing the acute and chronic criteria to the recalculated species mean acute and chronic values (i.e., SMAVs and SMCVs calculated with the *recalculation datasets*);
- Comparing the acute and chronic criteria to the effect concentrations obtained from individual toxicity tests (i.e., the toxicity data that were included in the *evaluation datasets*); and,
- Evaluating the nature, frequency, and magnitude of toxicity at concentrations of ammonia and cadmium below the EPA AWQC for each of the selected taxa of concern using the results from individual studies.

Visual analysis of the species sensitivity distributions generated using the *recalculation datasets* and *evaluation datasets* was conducted to provide an evaluation of the EPA AWQC for ammonia and cadmium. In addition, EPA AWQC were also compared to toxicity data for selected taxa of concern to determine whether the EPA AWQC are protective of these potentially more sensitive species. To facilitate identification of taxa of concern on NWRs, FWS convened a workshop in Arlington, VA in February, 2013. Workshop participants were charged with the task of identifying the ecological receptors that use aquatic

habitats within the National Wildlife Refuge System (NWRS). Based on the Arlington workshop results, the taxa of concern on NWRs are likely to include aquatic-dependent mammals, migratory birds, amphibians, reptiles, fish, aquatic invertebrates, and aquatic plants. The evaluation of the EPA AWQC for ammonia and cadmium included an analysis of the nature, frequency, and magnitude of toxicity at concentrations below the EPA AWQC for aquatic organisms, including amphibians, fish, aquatic invertebrates, and/or aquatic plants (as available data permitted).

3.0 Results

3.1 Ammonia

3.1.1 Description of the Recalculation and Evaluation Datasets

Since the most recent version of the EPA AWQC for ammonia (USEPA 2013) was published just prior to this review, an extensive search for additional data was not performed. Rather, additional candidate data were identified for some of the more sensitive genera (i.e., mussels and snails). Additional data were selected for the *recalculation* and *evaluation datasets* from Wang *et al.* (2007a; 2011), Miao *et al.* (2010), and Besser *et al.* (2013). The data presented in Besser *et al.* (2013) were not included in the 2013 criteria document; however, a subset of the toxicity data from Wang *et al.* (2007a, 2011) and Miao (2010) were included in the dataset used to derive the EPA AWQC. The data added to the *recalculation dataset* from those studies included additional endpoints (e.g., growth data) and effects concentrations (e.g., IC_{25}, the concentration that causes a 25% inhibition in tested organisms) during chronic exposure. In addition, other studies (Blahm 1978; Calamari *et al.* 1981; Reinbold and Pescitelli 1982; Bader and Grizzle 1992; Diamond *et al.* 1993; Hickey and Vickers 1994; Buhl 2002; Wang *et al.* 2007b) in the USEPA (2013) dataset contained data that met the screening criteria outlined here, but were excluded from mean value calculations presented in the 2013 criteria document because these tests were conducted as static-renewal tests or with concentrations

only described nominally (and flow-through tests with measured concentrations for the same species existed for USEPA [2013] to use in the mean value calculations). These data were included in the *evaluation dataset*, but not in the recalculation of mean values. Data used in the recalculation of mean values and evaluation of the EPA AWQC are summarized in Appendix 1 in Table A1.1 (for acute exposure) and Table A1.2 (for chronic exposure).

The original and recalculated SMAVs and GMAVs for ammonia are presented in Table A6.3. Overall, SMAVs and GMAVs were recalculated for only two genera, *Lampsilis* (mussels) and *Fluminicola* (snails). In both cases, consideration of the additional toxicity data resulted in SMAVs that differed by less than 10% compared to the SMAVs used to generate the USEPA (2013) acute criteria. Similarly, the recalculated GMAVs were similar to the original GMAVs (i.e., within 10%).

The original and recalculated SMCVs and GMCVs for ammonia are presented in Table A6.4. The addition of new toxicity data to the *recalculation dataset* resulted in recalculated SMCVs for four species, including three freshwater mussel species (i.e., *Lampsilis fasciola*, *Lampsilis siliquoidea*, and *Villosa iris*) and one snail species (*Fluminicola* sp.). In one case, consideration of the additional data resulted in nearly a three-fold reduction in the SMCVs. The GMCVs were recalculated for three genera, including two mussels and one snail. Inclusion of the additional data resulted in a reduction of the GMCV for *Lampsilis* by more than 40%; the other GMCVs were reduced by 2 to 30%. Hence, the new data provide important information on the toxicity of ammonia to mollusks. While no new data were included for rainbow trout (*O. mykiss)*, a new SMCV was calculated for this species, and subsequently for the *Oncorhynchus* genus, due to the exclusion of unbounded values (i.e., less- or greater-than values) from the USEPA (2013) dataset.

3.1.2 Evaluation of the Acute Ambient Water Quality Criterion

The 2013 acute EPA AWQC for ammonia was evaluated to determine if it provides an adequate basis for protecting taxa of concern on NWRs. The results of the first method of evaluation (i.e., comparing the criterion to the recalculated GMAVs) indicate that adverse effects (based on exceedance of the genus mean LC_{50}/EC_{50}) would not be predicted at ammonia concentrations at or below the acute criterion (Figure A6.1). The results of the second evaluation method (i.e., comparing the criterion to the recalculated SMAVs) also indicate that adverse effects would not be predicted at or below the acute criterion (based on exceedance of the species mean LC_{50}/EC_{50}; Figure A6.2). Based on the available data, the species most sensitive to ammonia in acute exposures is the ellipse mussel (*Venustaconcha ellipsiformis*; lifestage: glochidia; USEPA 2013). The SMAV and GMAV for this species is 23.1 mg TAN/L, which is higher than the acute criterion of 17 mg TAN/L (Table A6.3). Mussels make up the eleven most sensitive species and seven most sensitive genera in the enhanced acute dataset (Table A6.3).

The third evaluation method involved comparing the criterion to the toxicity thresholds obtained from individual toxicity tests. The results of this evaluation show that a number of effects concentrations fall below the acute criterion (17 mg TAN/L; Figure A6.3), indicating that there is substantial variability in the estimates of the effect concentration for a species. This variability may arise from grouping of different life-stages together to estimate the SMAVs, variability in organism sensitivity, or variability in test conditions. Effects data from toxicity tests with the guppy (*Poecilia reticulata*; 10.8 mg TAN/L, Kumar and Krishnamoorthi 1983), rainbow mussel (*V. iris*; 12.6 mg TAN/L, Scheller 1997; 15.2 mg TAN/L, Mummert *et al.* 2003), and pink mucket (*L. abrupta*; 14.7 mg TAN/L, Wang *et al*. 2007b) fell below the acute criterion. Two other mussel species, the oyster mussel (*Epioblasma capsaeformis*; Wang *et al.* 2007b) and paper pondshell mussel (*Utterbackia imbecillis*; Black 2001), had effects values that just exceeded the criterion (i.e., 17.8 mg TAN/L and 17.9 mg TAN/L, respectively). All of these tests were included in mean value calculations used to derive the acute criterion (USEPA 2013), except for a static-renewal test with pink

mucket from Wang *et al*. (2007b), which was excluded because results from a flow-through test were available for the species (Table A1.1).

3.1.3 Evaluation of the Chronic Ambient Water Quality Criterion

The 2013 chronic EPA AWQC for ammonia was also evaluated using the recalculated GMCVs/SMCVs and the entire toxicological dataset. The results of the comparisons of the chronic criterion to the recalculated GMCVs and SMCVs indicate that the chronic criterion of 1.9 mg TAN/L will not be fully protective against chronic effects to mussels (Figures A6.4 and A6.5). Additional SMCVs for the wavy-rayed lampmussel (1.29 mg TAN/L) and the fatmucket (1.17 mg TAN/L) resulted in the recalculation of the GMCV for the *Lampsilis* genus, which decreased from 2.13 mg TAN/L (USEPA 2013) to 1.23 mg TAN/L (Table A6.4). In addition, the recalculated SMCV/GMCV for the rainbow mussel (*Villosa iris*) of 2.41 mg TAN/L was lower than the SMCV/GMCV calculated by USEPA (2013; i.e., 3.50 mg TAN/L; Table A6.4). Mussels make up the three most sensitive species in the chronic *recalculation dataset*, followed by two fish species: the bluegill sunfish (*L. macrochirus*; lifestage: ELS) and rainbow trout (*O. mykiss*; lifestage: ELS). The two most sensitive genera based on the available data in the *recalculation dataset* are mussels (*Lampsilis* and *Villosa*), followed by the sunfish (*Lepomis*), clams of the genus *Musculium*, and snails of the genus *Fluminicola*.

The third method of evaluating the chronic criterion involved comparison of the criterion to the results from individual toxicity tests. The results of this evaluation show that a number of effects concentrations fall below the chronic criterion, indicating that some organisms may experience deleterious effects at concentrations of ammonia below the chronic criterion (Figure A6.6). Twelve tests conducted with various mussel species fall below the criterion, including the fatmucket (Wang *et al.* 2007a; 2011; n = 8), wavy-rayed lampmussel (Wang *et al.* 2007a; n = 3), and the rainbow mussel (Wang *et al.* 2007a; n = 1). Measured endpoints included survival (n = 5) and growth (n = 7). All data were included in the *recalculation dataset*, except for one test with the wavy-rayed lampmussel

from Wang *et al.* (2007a; endpoint: survival). Growth responses for mussels were not included in the USEPA (2013) chronic dataset; USEPA (2013) cited the uncertainty of assessing the growth endpoint, test variability, and the need for additional research and method development as reasons for not including growth data for mussels.

3.1.4 Evaluation of the Protectiveness of Acute and Chronic Water Quality Criteria for Sensitive Taxa of Concern

3.1.4.1 Acute Exposure to Ammonia

The *evaluation dataset* includes acute toxicity data for three taxa of concern identified for NWRs: amphibians, fish, and aquatic invertebrates. Acute toxicity data for one fish species and two invertebrate species include effect concentrations that fall below the acute criterion for ammonia, while effect concentrations for two additional invertebrate species are just above the criterion.

Based on the data compiled in the *evaluation dataset*, 44 species of fish were included in the acute exposure dataset. The results of one of the four toxicity tests with the guppy (*P. reticulata*) showed lethal toxicity to ammonia at a concentration below the EPA AWQC. In the derivation of the acute EPA AWQC for ammonia, USEPA (2013) included a 4-day EC/LC_{50} of 10.8 mg TAN/L from Kumar and Krishnamoorthi (1983), which is 36% lower than the acute criterion. Generally, fish species are expected to be protected by the acute EPA AWQC.

Based on the data compiled in the *evaluation dataset*, ammonia concentrations below the acute EPA AWQC (i.e., CMC) may be toxic to two freshwater mussel species. Of the 52 invertebrate species included in the acute dataset (including 17 mussel species), the rainbow mussel (*V. iris*) and pink mucket (*L. abrupta*) exhibited lethal effects at concentrations of ammonia below the EPA AWQC. Therefore, 96% of the tested invertebrate species (and 88% of the tested mussel species) are expected to be protected by the CMC against adverse effects. For the rainbow mussel, two of ten lethal effects concentrations included in the criteria

document for the calculation of mean values fell below the acute criterion, including:

- A 24-hour EC/LC_{50} of 12.6 mg TAN/L in acute exposures with glochidia (Scheller 1997), which is 26% lower than the acute criterion; and,
- A 96-hour EC/LC_{50} of 15.2 mg TAN/L in acute exposures with 2- to 5-day old juvenile mussels (Mummert *et al.* 2003), which is 11% lower than the acute criterion.

For the pink mucket (*L. abrupta*), one of two lethal effects concentrations in the *evaluation dataset* fell below the CMC: an effect concentration of 14.7 mg TAN/L from a 96-hour test conducted with 2-month old juvenile mussels (Wang *et al.* 2007b), which is 14% lower than the acute criterion. Toxicity tests with two other mussel species showed toxicity at concentrations just above the EPA AWQC. Wang *et al.* (2007b) reported a 6-hour EC/LC_{50} of 17.8 mg TAN/L in exposures with oyster mussel (*E. capsaeformis*) glochidia, and Black (2001) reported a 96-hour EC/LC_{50} of 17.9 mg TAN/L in a test with <2-day old juvenile paper pondshell mussels (*U. imbecillis*). For both of these tests, effects concentrations of no more than 5% above the acute criterion were reported.

USEPA (2013) included data from 96-hour toxicity tests conducted with four species of amphibians. The lethal effects concentrations ranged from 33.4 to 406 mg TAN/L in 96-hour exposures with embryo- or developmental-stage frogs and toads. These values are all higher than the acute criterion, indicating that the current acute EPA AWQC should be protective of amphibian species in these life stages.

Based on the data compiled to support this evaluation, it is likely that the CMC for ammonia may not be low enough to prevent adverse effects (i.e., lethal effects) to some fish and invertebrate species, particularly mussel species, under certain conditions. Therefore, a lower water quality target (WQT) is required to protect

sensitive fish and invertebrate species against acute toxicity on NWRs. USEPA (2013) did not include an assessment of toxicity data for plants, as the available data (as reported in the 1985 EPA AWQC document) indicate that effects concentrations for aquatic plant species are two orders of magnitude higher than the effects concentrations for animal species (USEPA 2013). In addition, no data have been compiled on the toxicity of ammonia to aquatic-dependent wildlife (e.g., birds and mammals). Typically, aquatic life represents the most sensitive group to non-bioaccumulative substances, such as ammonia. Therefore, it is likely that the CMC would be protective of adverse effects to these receptor groups (i.e., aquatic-dependent wildlife).

3.1.4.2 Chronic Exposure to Ammonia

The *evaluation dataset* includes toxicity data from chronic exposures for two taxa of concern identified for NWRs, fish and aquatic invertebrates. While all tested fish species showed no effects below the CCC, three of the tested invertebrate species (all mussels) showed effects below the CCC during chronic exposures to elevated levels of ammonia. Overall, 70% of the tested invertebrate species (but none of the mussel species) are expected to be protected by the chronic EPA AWQC. Normalized effect concentrations for the species for which some of the effects thresholds fell below the chronic EPA AWQC include:

- Fatmucket (*L. siliquoidiea*):
    - Chronic values: six of six values are below the criterion (1.22 and 1.31 mg TAN/L [the same value is repeated for multiple endpoints], which are an average of 33% lower than the chronic criterion);
    - IC_{25}: two of two values are below the criterion (1.06 and 1.45 mg TAN/L, which are an average of 34% lower than the chronic criterion); and,
    - EC_{20}: zero of two values are below the criterion;

- Wavy-rayed lampmussel (*L. fasciola*):
    - Chronic values: zero of two values are below the criterion;
    - IC_{25}: two of two values are below the criterion (1.29 and 1.88 mg TAN/L, which are an average of 17% lower than the chronic criterion); and,
    - EC_{20}: one of one value is below the criterion (1.41 mg TAN/L, which is 26% lower than the chronic criterion);
- Rainbow mussel (*V. iris*):
    - Chronic values : one of two values is below the criterion (1.32 mg TAN/L, which is 31% lower than the chronic criterion);
    - IC_{25}: zero of two values are below the criterion; and,
    - EC_{20}: zero of one value is below the criterion.

The mussel data below the chronic criterion were reported from tests associated with a variety of endpoints, including survival, growth, and biomass (i.e., based on the compiled data, no single endpoint appears to be more sensitive than the others). Based on the data compiled to support this evaluation, the CCC for ammonia is not likely to fully protect against lethal and sub-lethal effects to sensitive invertebrate species (i.e., mussels). Therefore, a lower WQT is required to protect invertebrates, particularly mussel species, against adverse effects associated with exposure to ammonia on NWRs.

The dataset compiled to evaluate chronic toxicity to aquatic life does not contain any data from tests conducted with amphibians. While the data compiled to evaluate the CMC indicate this taxa of concern will be protected during acute exposures to ammonia, more information is required to determine if the chronic criterion would protect against lethal and sub-lethal effects to amphibians in long-term exposures. Although USEPA (2013) did not include an assessment of toxicity data for plants, it is assumed that aquatic plants would be protected by the

chronic EPA AWQC because the toxicity data for aquatic plants (as reported in the 1985 EPA AWQC document) indicated that criteria designed to protect aquatic animals will also be protective of aquatic vegetation (USEPA 2013). In addition, the dataset compiled to evaluate chronic toxicity does not contain data for aquatic-dependent mammals, migratory birds, or reptiles. Typically, aquatic life represents the most sensitive group to non-bioaccumulative substances, such as ammonia. Therefore, it is likely that the CCC would be protective against lethal and sub-lethal effects to these other receptor groups in long-term exposures.

3.2 Cadmium

3.2.1 Description of the Recalculation and Evaluation Datasets

Data were compiled from a variety of sources (e.g., Mebane 2010) to augment the USEPA (2001) dataset (including data from more recent studies). Identification of candidate datasets involved reviewing scientific literature, sending inquiries to researchers, and reviewing water quality guideline documents generated in other jurisdictions (e.g., CCME 2014 and BCMOE 2014). In addition, some studies that were included in the criteria document (i.e., USEPA 2001) were reviewed to determine if additional data could be extracted and used in the recalculation and/or evaluation of the criteria.

Additional data selected for inclusion in the *recalculation and evaluation datasets* were compiled from 40 studies published between 1972 and 2013. These data are summarized in Appendix 2 in Table A2.1 (for acute exposure) and Table A2.2 (for chronic exposure). The *recalculation dataset* includes lethal effects concentrations for five additional fish species and ten additional invertebrate species, allowing the calculation of GMAVs for three fish genera and four invertebrate genera that were not presented in USEPA (2001). For fish, the additional species include the white sturgeon (*Acipenser transmontanus*; Ingersoll and Mebane 2014), the mottled sculpin (*Cottus bairdi*; Besser *et al.* 2007), the shorthead sculpin (*Cottus confusus*; Mebane *et al.* 2012), and the mountain whitefish *(Prosopium williamsoni*;

Brinkman and Vieira 2008). Toxicity data for westslope cutthroat trout (*Oncorhynchus clarkii lewisi*; Mebane *et al.* 2012) were also included in the dataset compiled to evaluate acute exposure to cadmium, which contributed to the recalculation of the GMAV for the genus *Oncorhynchus*. Additional data for fish species already presented in the EPA dataset included effect concentrations for rainbow/steelhead trout (*O. mykiss;* Cusimano *et al.* 1986; Davies *et al.* 1993; Hansen *et al.* 2002a; Besser *et al.* 2007; Mebane *et al.* 2012; Ingersoll and Mebane 2014), brown trout (*Salmo trutta;* Brinkman and Hansen 2007), and bull trout (*Salvelinus confluentus*; Hansen *et al.* 2002a). All additional acute toxicity data for fish used in the recalculation of SMAVs/GMAVs were lethal effects concentrations (i.e., LC_{50}), except for three mortality/behavior (i.e., immobilization and loss of equilibrium) effects concentrations (at the EC_{50} level) for the white sturgeon *(A. transmontanus*) and the rainbow trout (*O. mykiss*) from Ingersoll and Mebane (2014).

Additional data compiled for the acute *recalculation dataset* include ten additional invertebrate species, which supported the calculation of GMAVs for two genera of mayfly (*Baetis* and *Rhithrogena*; Brinkman and Johnston 2008; Mebane *et al.* 2012), the amphipod genus *Hyalella* (Suedel *et al.* 1997), and the mussel genus *Lasmigona* (Black 2001), none of which were presented in USEPA (2001). Other additional data added to the *recalculation dataset* include lethal effects concentrations for the midge, *Chironomus tentans* (now known as *Chironomus dilutus*; Suedel *et al.* 1997; Watts and Pascoe 2000), the amphipod, *Gammarus pulex* (McCahon and Pascoe 1988; Felten *et al.* 2008), and three mussel species, including: *Lampsilis. rafinesqueana* (Wang *et al.* 2010), *L. siliquoidea* (Wang *et al.* 2010), and *Lampsilis ventricosa* (Lasee 1991). Additional data for species already presented in the EPA toxicity dataset include effects concentrations for the midge (*C. riparius*; Pascoe *et al.* 1990; Watts and Pascoe 2000), two cladocerans, *C. dubia* (Suedel *et al.* 1997) and *D. magna* (Schuytema *et al.* 1984; Suedel *et al.* 1997), and the paper pondshell mussel (*U. imbecillis*; Black 2001). These additions resulted in updated species and genus mean values for those invertebrate species. The USEPA (2001) and recalculated species and genus mean values for acute exposures are listed in Table A6.5.

Toxicity data from acute exposures included in the *evaluation dataset* are comprised of a broader suite of effect levels than were used for the recalculation of mean values, including EC_{10}, EC_{20}, and mean acute values (i.e., the geometric mean of the NOEC and LOEC). Endpoints in the *evaluation dataset* are primarily associated with mortality, although six values for the white sturgeon (*A. transmontanus*) and rainbow trout (*O. mykiss*) include a combination of mortality and behavior (i.e., immobilization and loss of equilibrium; Ingersoll and Mebane 2014), and one behavioral endpoint (i.e., dominance ability; Sloman *et al.* 2003) was included as well.

Additional chronic toxicity data were compiled in the *recalculation dataset* and include effect concentrations for four additional fish species, six additional invertebrate species, and one amphibian species. The GMCVs were recalculated for three fish genera, four invertebrate genera, and one genus of amphibian that were not presented in the criteria document. For fish, these additional data include sub-lethal effects concentrations for white sturgeon (*A. transmontanus*; Vardy *et al.* 2011; Ingersoll and Mebane 2014), mottled sculpin *(C. bairdii;* Besser *et al.* 2007), and mountain whitefish (*P. williamsoni*; Brinkman and Vieira 2008). Effects data for the bull trout (*S. confluentus*; Hansen *et al.* 2002b) were not included in USEPA (2001); the new data were incorporated into the dataset to support the recalculation of the GMCV for the genus *Salvelinus*. Additional data for species already presented in the EPA toxicity dataset include sub-lethal effects concentrations for fathead minnow (*Pimephales promelas*; Pickering and Gast 1972; Spehar and Fiandt 1986; Suedel *et al.* 1997; Castillo and Longley 2001), coho salmon (*Oncorhynchus kisutch*; Eaton *et al.* 1978), chinook salmon (*Oncorhynchus tshawytscha*; Chapman 1982), rainbow trout (*O. mykiss*; Davies *et al.* 1993; Hollis *et al.* 1999; Scott *et al.* 2003; Besser *et al.* 2007; Mebane *et al.* 2008; Ingersoll and Mebane 2014), brown trout (*S. trutta*; Eaton *et al.* 1978; Brinkman and Hansen 2007), brook trout (*Salvelinus fontinalis*; Sauter *et al.* 1976; Eaton *et al.* 1978), and lake trout (*Salvelinus namaycush*; Eaton *et al.* 1978). Incorporation of these data resulted in recalculated SMCVs/GMCVs for these fish species.

All additional fish data added to the chronic toxicity dataset used to recalculate SMCVs/GMCVs are chronic values (or MATCs; i.e., the geometric mean of the NOEC and LOEC), except for one LC_{20} for white sturgeon (*A. transmontanus*) from Vardy *et al.* (2011). Endpoints for fish reflected in the *recalculation dataset* included survival, growth, biomass, and reproduction. In addition, one value associated with a behavioral endpoint was included in the dataset: a 7-day chronic value for predator avoidance of 0.523 µg/L (normalized to a hardness of 50 mg/L $CaCO_3$) for rainbow trout (Scott *et al.* 2003). Although this behavioral endpoint is the most sensitive value for rainbow trout in the chronic *recalculation dataset*, it is comparable to other values for this species. For example, Davies *et al.* (1993) reported a 50 mg/L $CaCO_3$ hardness-normalized 100-day chronic value for mortality in rainbow trout of 0.750 µg/L, and Besser *et al.* (2007) reported a 50 mg/L $CaCO_3$ hardness-normalized 28-day chronic value for mortality in rainbow trout of 1.10 µg/L.

Additional data in the chronic *recalculation dataset* include six additional invertebrate species, including: the mayfly genus *Rhithrogena* (Brinkman and Johnston 2008), the amphipod genus *Gammarus* (Felten *et al.* 2008), the genus *Hydra* (Holdway *et al.* 2001), and the mussel genus *Lampsilis* (Lasee 1991; Wang *et al.* 2010), all of which were not presented in the criteria document (USEPA 2001). Incorporation of data for an additional species, the cladoceran *Ceriodaphnia reticulata* (Elnabarawy *et al.* 1986), resulted in an updated GMCV for that genus. Additional data for species already presented in the EPA dataset include sub-lethal effects concentrations for the midge *C. dilutus* (Ingersoll and Kemble 2001), the amphipod *H. azteca* (Suedel *et al.* 1997; Chadwick Ecological Consultants, Inc. 2004), and the cladocerans *C. dubia* (Suedel *et al.* 1997), *D. magna* (Elnabarawy *et al.* 1986; Suedel *et al.* 1997; Chadwick Ecological Consultants, Inc. 2004), and *Daphnia pulex* (Ingersoll and Winner 1982; Elnabarawy *et al.* 1986). All additional chronic toxicity data for invertebrates, used in the recalculation of SMCVs/GMCVs, were chronic values (i.e., MATCs) with survival, growth, biomass, and reproductive endpoints. The USEPA (2001) and recalculated species and genus mean values for chronic exposures are listed in Table A6.6.

Chronic toxicity data included in the *evaluation dataset* are comprised of a broader suite of effect levels, including low-effect thresholds (e.g., EC_{10-25}) and severe effects thresholds (e.g., EC_{50}) for the survival, growth, biomass, and reproduction endpoints than were used in the recalculation of species and genus mean values. Exceptions include one behavioral endpoint (feeding rate for the amphipod *Gammarus pulex*; Felten *et al.* 2008) and one developmental endpoint (molting for the mayfly *Rhithrogena hageni*; Brinkman and Johnston 2008).

Toxicity data from Gerhardt (1992) were not included in USEPA (2001) because the study was conducted with the mayfly species *Baetis rhodani* and *Leptophlebia marginata*, which are not resident in North America. However, data from this study are included in the *evaluation dataset* because these species are known to occur in regions with climates similar to those found in North America (e.g., the United Kingdom), and members of the same families are known to occur in North America. Similarly, an acute study with the amphipod *G. pulex* (McCahon and Pascoe 1988) was excluded by USEPA (2001) because *G. pulex* is a non-resident species. This species, which is commonly found in Europe, was included in the *recalculation* and *evaluation datasets* (for acute and chronic data) because *G. pulex* can be considered a surrogate species for other amphipods in the genus *Gammarus*, which has many species residing in North America.

3.2.2 Evaluation of the Acute Ambient Water Quality Criterion

The 2001 acute EPA AWQC for cadmium was evaluated to determine if it provides adequate protection for aquatic organisms utilizing habitats on NWRs. The results of the first evaluation method (i.e., comparing the criterion to the recalculated GMAVs) indicate that adverse effects (based on exceedance of the genus mean LC_{50}/EC_{50}) would not be predicted at cadmium concentrations below the acute criterion (Figure A6.7). The genus most sensitive to cadmium in the *recalculation dataset* is the salmonid *Salvelinus*. The GMAV for this genus is 2.01 µg/L, which is above the acute criterion of 1.0 µg/L. The second evaluation method compared the criterion to the recalculated SMAVs. The results of this

analysis also indicate that adverse effects (based on exceedance of the species mean LC_{50}/EC_{50}) would not be predicted at cadmium concentrations at or below the criterion (Figure A6.8). Although the lowest SMAV/GMAV (i.e., for brown trout) increased with the additional data, fish still appear to be the most sensitive group to cadmium in short-term exposures, based on information in the *recalculation dataset*. Fish make up the seven most sensitive genera in the *recalculation dataset* and the four most sensitive species (based on SMAVs) are salmonids.

Although no SMAVs or GMAVs fell below the acute EPA AWQC, the criterion may not be sufficiently protective of rainbow trout (*O. mykiss*) under certain conditions. The SMAV for rainbow trout decreased from 2.11 µg/L to 1.62 µg/L with the incorporation of additional data from recent toxicity tests. USEPA (2001) included 13 effects concentrations in the calculation of the SMAV for rainbow trout (*O. mykiss*), ranging from 0.634 µg/L to 9.03 µg/L; the 25 additional values included in the recalculation of the SMAV range from 0.572 µg/L to 3.91 µg/L (normalized to a hardness of 50 mg/L $CaCO_3$). For the 2001 acute criterion, the FAV decreased from 2.76 µg/L to 2.11 µg/L (i.e., the SMAV for rainbow trout) to protect rainbow trout, a commercially important species (the FAV was then divided by two and converted to dissolved concentration using a conversion factor of 0.973). Following the methodology used in USEPA (2001; i.e., lowering the FAV to the SMAV of a commercially important species, but using the updated SMAV for rainbow trout of 1.62 µg/L), the addition of these new data would lower the CMC from 1.0 µg/L to 0.79 µg/L (dissolved cadmium at a hardness of 50 mg/L $CaCO_3$).

The third evaluation method involved comparing the criterion to the results of individual toxicity tests. The results of this analysis indicate that lethal effects could occur for some fish species under certain conditions. Specifically, the results of a number of toxicity tests provide evidence that toxic effects can occur during acute exposure to cadmium at concentrations below the acute criterion (Figure A6.9). Hansen *et al.* (2002a) reported 120-hour LC_{50}s for rainbow trout fry ranging from 0.572 µg/L to 0.870 µg/L (normalized to a hardness of 50 mg/L

$CaCO_3$) in exposures run with water hardness of about 30 mg/L $CaCO_3$. In addition, Davies *et al.* (1993) and Mebane *et al.* (2012) reported a similar 50 mg/L $CaCO_3$ hardness-normalized LC_{50} of 0.677 µg/L (test run with water hardness of 422 mg/L $CaCO_3$) and 0.821 µg/L (test run with water hardness of 21 mg/L $CaCO_3$) respectively, in 96-hour exposures with rainbow trout fry. A mean acute value (i.e., the geometric mean of the NOEC and LOEC) of 0.520 µg/L (normalized to a hardness of 50 mg/L $CaCO_3$) was calculated with data from Sloman *et al.* (2003), who reported NOEC and LOEC values for dominance ability in 24-hour tests run at 120 mg/L $CaCO_3$ water hardness. Finally, Ingersoll and Mebane (2014) reported EC_{10}, EC_{20}, and mean acute values for mortality and mortality combined with behavior (i.e., immobilization and loss of equilibrium) ranging from 0.388 µg/L to 0.926 µg/L (normalized to a hardness of 50 mg/L $CaCO_3$) in exposures run with water hardness of about 100 mg/L $CaCO_3$. Even if the criterion was lowered to 0.79 µg/L (at a hardness of 50 mg/L $CaCO_3$) to protect rainbow trout (*O. mykiss*), a number of the effects concentrations reported from these toxicity tests would fall below the acute criterion.

Adverse effects concentrations from short-term exposure to cadmium in aquatic invertebrates vary greatly between the taxonomic groups. Crustaceans (e.g., cladocerans and amphipods) are among the most sensitive groups (e.g., Baird *et al.* 1991; Suedel *et al.* 1997), along with various mussel species (e.g., Keller and Zam 1991; Black 2001; Wang *et al.* 2010), while the aquatic life-stages of various insects including the midges and mayflies are more tolerant during short-term cadmium exposure (e.g., Williams *et al.* 1985; Pascoe *et al.* 1990; Suedel *et al.* 1997; Watts and Pascoe 2000; Brinkman and Johnston 2008).

In the *evaluation dataset*, the cladoceran *D. magna* and the amphipod *H. azteca* were found to be the most sensitive invertebrate species to short-term cadmium exposures. For example, Baird *et al.* (1991) reported LC_{50} estimates ranging from 1.04 to 33.4 µg/L for *D. magna*, and Guilhermino *et al.* (1996) reported an LC_{50} of 2.74 µg/L (all values have been normalized to a hardness of 50 mg/L $CaCO_3$; tests were run at a hardness of 170 mg/L $CaCO_3$). Suedel *et al.* (1997) reported a 96-hour LC_{50} of 8.38 µg/L and a 48-hour LC_{50} of 16.8 µg/L (normalized to a hardness

of 50 mg/L $CaCO_3$; tests were run at a hardness of 17 mg/L $CaCO_3$) for *H. azteca*. Estimates of the LC_{50}s for a number of species included in the acute dataset are near the acute criterion, indicating that the EPA AWQC of 1.0 µg/L (at a hardness of 50 mg/L $CaCO_3$) may not be sufficiently protective of all invertebrate species, particularly cladocerans.

3.2.3 Evaluation of the Chronic Ambient Water Quality Criterion

The 2001 chronic EPA AWQC for cadmium was also evaluated to determine if it is likely to be adequately protective of aquatic organisms. The first two evaluation methods involved comparing the chronic criterion to the recalculated GMCVs and SMCVs. The results of these evaluations indicate that the criterion of 0.15 µg/L (at a hardness of 50 mg/L $CaCO_3$) will protect against chronic effects for all tested genera (Figure A6.10) and tested species (Figure A6.11) included in the *recalculation dataset*. The species most sensitive to cadmium under chronic exposure are the amphipod *H. azteca* and the mottled sculpin, which have SMCVs/GMCVs of 0.356 µg/L and 0.757 µg/L, respectively.

Recalculation of mean chronic values resulted in higher GMCVs for *Hyalella* and *Daphnia*, the two most sensitive genera in USEPA (2001). USEPA (2001) included only one effect concentration for *H. azteca*, a life cycle test from Ingersoll and Kemble (2001). Although the addition of three results for *H. azteca* from Chadwick Ecological Consultants, Inc. (2004) and Suedel *et al.* (1997) increased the GMCV slightly from 0.275 µg/L to 0.356 µg/L, *Hyalella* remains the most sensitive genus in the *recalculation dataset*. Mean values calculated for the mottled sculpin, hydra, and mountain whitefish, which are additional species to the *recalculation dataset*, make up the other three most sensitive genera in the chronic dataset. The GMCVs for the four most sensitive genera ranged from 0.275 µg/L to 2.80 µg/L in USEPA (2001), whereas the four most sensitive genera in the *recalculation dataset* had effects concentrations that ranged from 0.356 µg/L to 2.08 µg/L.

The third evaluation method involved comparing the chronic criterion to the results from individual toxicity tests. The results of this evaluation revealed that sub-lethal effects concentrations from six toxicity tests fall below the chronic criterion, indicating that under certain conditions some invertebrates (i.e., amphipods and cladocerans) may experience sub-lethal effects at cadmium concentrations below the criterion (Figure A6.12). Three of the tests used in the *evaluation dataset* were included in the calculation of GMCVs used to derive the chronic criterion. The two lowest effect concentrations in the *evaluation dataset* are for the cladocerans *C. reticulata* and *D. pulex* (Elnabarawy *et al.* 1986). Only acute data from this study were included in USEPA (2001); however, data from the chronic portion of this study were considered acceptable according to the methodology presented in Stephan *et al.* (1985) and USEPA (2001). Elnabarawy *et al.* (1986) reported a 7-day EC_{16} for reproduction of 0.2 µg/L (normalized to 0.06 µg/L at a hardness of 50 mg/L $CaCO_3$) for *C. reticulata* in exposures run with a water hardness of 240 mg/L $CaCO_3$. In the same study, the 14-d EC_{16} for reproduction for *D. pulex* was also reported as 0.2 µg/L. However, these estimates are considered less reliable due to limitations of the study design and statistical analyses. Ingersoll and Kemble (2001) reported an IC_{25} for *H. azteca* biomass of 0.51 µg/L (normalized to 0.14 µg/L at a hardness of 50 mg/L $CaCO_3$) on day 28 of exposures with a water hardness of 280 mg/L $CaCO_3$, which is the fourth lowest effect concentration in the *evaluation dataset*. However, a clear dose-response relationship was not observed in the underlying data. These results indicate that concentrations of cadmium below the CCC in aquatic habitats may have adverse effects on aquatic invertebrates.

3.2.4 Evaluation of the Protectiveness of Acute and Chronic Water Quality Criteria for Sensitive Taxa of Concern

3.2.4.1 Acute Exposure to Cadmium

The *evaluation dataset* includes toxicity data for three taxa of concern identified for NWRs: amphibians, fish, and aquatic invertebrates. The only effects concentrations in the *evaluation dataset* that are below the acute criterion are for

fish. Of the 29 species of fish (including eight salmonid species) included in the acute dataset, only rainbow trout exhibited acute toxicity to cadmium at concentrations below the EPA AWQC. Therefore, 97% of the tested fish species and 88% of the tested salmonid species are expected to be protected by the acute EPA AWQC. Normalized to a hardness of 50 mg/L $CaCO_3$, the effect concentrations for rainbow trout that are below the acute EPA AWQC include:

- EC_{10}: two of six values are below the criterion (0.388 and 0.622 µg/L, which are an average of 51% lower than the criterion);
- EC_{20}: two of six values are below the criterion (0.581 and 0.869 µg/L, which are an average of 30% lower than the criterion);
- EC/LC_{50}: nine of 37 values are below the criterion (0.572 to 0.870 µg/L, which are an average of 31% lower than the criterion); and,
- Mean acute values: three of six values are below the criterion (0.520 to 0.926 µg/L, which are an average of 25% lower than the criterion).

In addition, a total of 23 of 37 estimates of the EC/LC_{50} (i.e., 62%) for rainbow trout in the *evaluation dataset* are less than the FAV (i.e., 2.11 µg/L for total cadmium). While a safety factor of two is applied to the FAV to derive the acute criterion, the data show that the current acute EPA AWQC may not be low enough to protect the most sensitive species in the acute dataset, rainbow trout. As discussed in Section 3.2.2, rainbow trout is a commercially important species identified by USEPA (2001). Therefore, a lower acute WQT may be required to protect all taxa of concern on NWRs.

While none of the effects concentrations for invertebrates in the *evaluation dataset* fell below the acute EPA AWQC, a number of results are just above the criterion. In total, 49 invertebrate species, including seven cladoceran species, were tested. The cladoceran *D. magna* was found to be the most sensitive species to cadmium toxicity during acute exposures; studies reported a total of 32 estimates of the $EC/LC_{50,}$ ranging from 1.04 to 125 µg/L (normalized to a hardness of 50 mg/L

$CaCO_3$). Two of the estimates of the LC_{50} are less than the FAV. Therefore, there is some uncertainty in the level of protection for *D. magna* based on the data compiled in the acute toxicity dataset, and a lower acute WQT may be required to protect more sensitive invertebrate species on NWRs.

The results of two toxicity tests with amphibians were compiled in the *evaluation dataset*. The lowest normalized LC/EC_{50} in the dataset was 521 µg/L from a toxicity test conducted with 3-month old Northwestern salamander (*Ambystoma gracile*) larvae in a water hardness of 45 mg/L $CaCO_3$ (Nebeker *et al.* 1995). This value is substantially higher than the acute criterion, indicating that the CMC should protect against lethal effects to amphibian species. However, more toxicity data are required to decrease uncertainty that amphibian species of all life stages will be protected by the EPA AWQC.

USEPA (2001) presented 33 acute and chronic effects concentrations for several species of plants, which were not included in the calculation of mean values or derivation of the EPA AWQC. Normalized (to a hardness of 50 mg/L $CaCO_3$) effects concentrations ranged from 2 to 20,000 µg/L in exposures lasting from 96 hours to 28 days. The reported effects concentrations are within the range of acute effects concentrations for fish and invertebrate species presented in USEPA (2001), and some values are within the range of reported chronic values (USEPA 2001). Since the lowest effects concentrations for plants presented in USEPA (2001) are higher than the lowest concentrations for fish and invertebrate species in the EPA acute and chronic datasets, USEPA (2001) concluded that the criteria, which are designed to protect fish and invertebrate species, should also protect plant species.

There have been relatively few studies conducted to evaluate the toxicity of cadmium to algae and aquatic plants since the publication of the last EPA AWQC for cadmium. Drost *et al.* (2007) studied the toxicity of selected metals to duckweed (*Lemna minor*) with two exposure durations. In 72-hour exposures, an EC_{50} for growth rate of 116 µg/L of cadmium (at a hardness of 50 mg/L $CaCO_3$)

was reported. A 7-day EC_{50} of 88.0 µg/L was reported from a longer toxicity test (at a hardness of 50 mg/L $CaCO_3$; both experiments were run at a water hardness of 166 mg/L $CaCO_3$). Although the growth rate of duckweed recovered to that observed in control exposures after being removed from the treatment for an additional 72-hours, the concentration of cadmium in the tissues of the plant did not decrease (i.e., there was no depuration of the cadmium; Drost *et al.* [2007]). In a study conducted by Källqvist (2009) with the green alga, *Pseudokirchneriella subcapitata*, the reported 72-hour EC_{50} for growth ranged from 135 to 242 µg/L (at a hardness of 50 mg/L $CaCO_3$). Other effects concentrations for growth rate reported in this study included estimates of the 72-hour EC_{20} ranging from 23.8 to 107 µg/L, and the 72-hour EC_{10} ranging from 6.50 to 62.6 µg/L (all values reported here were normalized to a hardness of 50 mg/L $CaCO_3$). The tests were conducted over an increasing range of water hardness (i.e., 3.4 to 46.2 mg/L $CaCO_3$). Since none of the more recent effects concentrations compiled for aquatic plants were found to be lower than the acute and chronic EPA AWQC, it is assumed that the current acute criterion will be protective of aquatic plants.

In addition, no data have been compiled on the toxicity of cadmium to aquatic-dependent wildlife (i.e., birds and mammals). Typically, aquatic life represent the most sensitive group to non-bioaccumulative or slightly bioaccumulative substances. Therefore, it is likely that the CMC would be protective of lethal effects to these receptor groups.

3.2.4.2 Chronic Exposure to Cadmium

The *evaluation dataset* includes chronic toxicity data for amphibians, fish, and aquatic invertebrates, all of which were identified as taxa of concern for NWRs. Sub-lethal effects concentrations in the *evaluation dataset* that are below the chronic criterion are all for invertebrate species. Of the 17 invertebrate species included in the *evaluation dataset*, the cladocerans *C. reticulata*, *D. pulex*, and *D. magna* and the amphipod *H. azteca* showed effects at concentrations of cadmium below the EPA AWQC. Therefore, 76% of the tested invertebrate species are

expected to be protected by the chronic EPA AWQC. Effect concentrations for the species that fall below the chronic EPA AWQC include:

- Elnabarawy *et al.* (1986) reported a 7-day EC_{16} for reproduction of 0.2 µg/L for *C. reticulata* in exposures run with water hardness of 240 mg/L $CaCO_3$ (0.06 µg/L when normalized to a hardness of 50 mg/L $CaCO_3$). In the same study, the 14-d EC_{16} for reproduction for *D. pulex* was also reported as 0.2 µg/L at a water hardness of 240 mg/L $CaCO_3$. Both effect concentrations are 59% lower than the chronic criterion. However, these estimates are considered less reliable due to limitations of the study design and statistical analyses.
- Ingersoll and Kemble (2001) reported an IC_{25} for biomass of 0.51 µg/L on day 28 of exposures with *H. azteca* run with water hardness of 280 mg/L $CaCO_3$ (0.14 µg/L when normalized to a hardness of 50 mg/L $CaCO_3$). The IC_{25} reported for this test is 6.6% lower than the chronic criterion. However, a clear dose-response relationship was not observed in the underlying data.
- Three 21-day chronic values for reproduction of 0.124, 0.146, and 0.152 µg/L (normalized to a hardness of 50 mg/L $CaCO_3$) were reported by Chapman *et al.* (1980) for *D. magna* in exposures run with water hardness ranging from 53 to 209 mg/L $CaCO_3$. The chronic values reported for this study are 18%, 3.9%, and < 1% lower than the chronic criterion. A total of 19 values from chronic tests are available for *D. magna* in the *evaluation dataset* (i.e., 16% of the chronic values for *D. magna* in the *evaluation dataset* are below the chronic criterion).

Based on the data compiled in the *evaluation dataset*, the current chronic EPA AWQC for cadmium is not low enough to protect some of the more sensitive invertebrate species (i.e., cladocerans and amphipods). Therefore, a lower chronic WQT would be required to ensure protection of these sensitive invertebrate species on NWRs.

For chronic exposures with fish, the lowest effect concentration in the *evaluation dataset* is a 62-day MATC for growth of 0.237 µg/L (normalized to a hardness of 50 mg/L $CaCO_3$) from an ELS test with rainbow trout run with water hardness of about 30 mg/L $CaCO_3$ (Mebane *et al.* 2008). Therefore, the chronic criterion should be protective of fish species.

Only one study involving an amphibian species is included in the *evaluation dataset*, and it was not included in USEPA (2001). The lowest effect concentration is a 24-day chronic value for growth (weight and length) of 105 µg/L (normalized to a hardness of 50 mg/L $CaCO_3$) in exposures with 3-month old Northwestern salamander (*A. gracile*) larvae run at a water hardness of 45 mg/L $CaCO_3$ (Nebeker *et al.* 1995). This value is much higher than the chronic criterion, indicating that the current chronic EPA AWQC should be protective of amphibian species. However, additional data are required to decrease uncertainty in effects thresholds for amphibian species to ensure that all life stages will be protected by the EPA AWQC. The *evaluation dataset* does not contain toxicity data for aquatic-dependent mammals, migratory birds, or reptiles. Typically, aquatic life represent the most sensitive group to non-bioaccumulative or slightly bioaccumulative substances. Therefore, it is likely that the CCC would be protective of lethal and sub-lethal effects to these receptor groups.

4.0 Discussion

The results of the evaluation of the EPA AWQC for ammonia and cadmium indicate that the criteria may not be protective of all taxa of concern on NWRs. Based on the data compiled for ammonia, the acute EPA AWQC (i.e., CMC) is not low enough to protect the most sensitive fish species tested (guppy), and both the acute and chronic criteria may not be low enough to protect the tested sensitive invertebrate species (i.e., mussels). For cadmium, the acute EPA AWQC is not sufficiently protective against effects in rainbow trout, the most sensitive species tested in the cadmium effects dataset. In addition, the chronic criterion may not be

low enough to protect some of the more sensitive invertebrate species (i.e., cladocerans and amphipods) from the chronic effects of cadmium exposure. The evaluation of the EPA AWQC for ammonia and cadmium with respect to each of the evaluation methods (i.e., comparing the criteria to the recalculated genus/species mean values, comparing the criteria to the results from individual toxicity tests, and evaluating the toxicity of cadmium and ammonia at concentrations below the EPA AWQC for each of the selected taxa of concern) is discussed below. Comments are also provided on the methodology used by EPA to derive the AWQC.

For the first two evaluation methods, comparisons of recalculated species and genus mean values to the acute and chronic criteria generally indicated that the EPA AWQC will be protective of all of the species and genera represented in the ammonia and cadmium datasets (i.e., except for the SMCV/GMCV for ammonia, discussed in Section 3.1.3). However, averaging of effect concentrations within species and genera inherently results in the loss of the full range of results (i.e, effect values), including data from the more sensitive end of the distribution. In addition, effects concentrations from multiple life-stages may be grouped together in the calculation of species or genus mean values. Furthermore, the methods used to select what concentrations are used in the calculation of mean values can result in the exclusion of important data points. For example, guidance provided in Stephan *et al.* (1985) dictates that for species where more than one value is available for a species, the geometric mean is calculated from the results of tests performed under flow-through conditions (with the exception that static-renewal is acceptable for daphnids) in which the concentrations of the test analyte were measured. However, if no studies meet those test conditions, the geometric mean is calculated using all available values (i.e., the results of tests performed under static or static-renewal test conditions, and tests in which the concentrations of the test analyte were not measured). Using this methodology, acceptable results from toxicity tests performed under static or static-renewal conditions may be excluded based solely on the availability of data collected under more preferred test conditions. While flow-through tests with measured concentrations provide the

most reliable results, toxicity tests in which test water is renewed every 24 hours in the study can result in acceptable data. In addition, Stephan *et al.* (1985) state that if measured concentrations are not available, nominal concentrations are acceptable for most test materials.

Excluding results collected under certain test conditions for some species while including them for others (based solely on the availability of other data) may bias the mean values calculated for derivation of the EPA AWQC. For example, in the USEPA (2013) acute dataset for ammonia, most static-renewal and static tests from Wang *et al.* (2007b) were included in mean value calculations, while three *Lampsilis* static-renewal tests were removed (i.e., because flow-through tests were available for the same species, following the rules in Stephan *et al.* [1985]). One of the excluded tests reported an effect concentration of 14.7 mg TAN/L in 96-hour exposures with juvenile pink mucket mussels, which is below the acute criterion. Inclusion of such results in the derivation of the acute criterion may have resulted in a CMC that provides more adequate protection of these sensitive mussel species.

For cadmium, comparisons of species and genus mean acute values to the acute criterion indicate that the EPA AWQC will likely protect all species/genera represented in the *recalculation dataset*. According to the methodology used to derive the most recent EPA AWQC for cadmium (i.e., USEPA 2001; Stephan *et al.* 1985), if the SMAV for a commercially important species is lower than the FAV, the SMAV should replace the FAV (which is then divided by two to derive the CMC). Therefore, if a new EPA AWQC was to be derived from the acute *recalculation dataset*, the CMC would be lowered from 1.0 µg/L to 0.79 µg/L (dissolved cadmium at a hardness of 50 mg/L $CaCO_3$) to protect rainbow trout.

As mentioned above, the full range of effects concentrations is reduced when toxicity data are averaged within species and genera, including values from the more sensitive end of the distribution. The third evaluation method compared the results of individual toxicity tests against the EPA AWQC, which involved more

test results and a wider variety of data than were used in the recalculation of mean values (i.e., the *evaluation datasets*). For example, while only one endpoint (e.g., survival) from an individual toxicity test was included in the recalculation of SMAVs/GMAVs/SMCVs/GMCVs, multiple endpoints (e.g., survival, growth, reproduction) from a single test were considered for comparison to the EPA AWQC. The datasets used for this evaluation also included acceptable test results other than estimates of the EC_{50}/LC_{50} (for acute data), and estimates of the EC_{20}/chronic values (for chronic data), and endpoints besides survival, reproduction, and growth (e.g., behavioral endpoints). Although many of the effects concentrations included in this portion of the evaluation are not typically used by EPA in the derivation of AWQC, some of these types of values are considered acceptable for inclusion in guideline derivation in other jurisdictions.

A number of individual toxicity test results from the *evaluation datasets* were found to fall below the EPA AWQC for ammonia and cadmium, indicating that sensitive organisms may experience deleterious effects at concentrations below the criteria. For ammonia, studies conducted with the pink mucket (Wang *et al.* 2007b), the guppy (Kumar and Krishnamoorthi 1983), and rainbow mussels (Scheller 1997; Mummert *et al.* 2003) reported effects concentrations below the acute criterion. While the mussel and guppy tests were included in the calculation of the species and genus mean values in USEPA (2013), the observed variability in the estimates of effects concentrations is not considered. Twelve estimates of effects concentrations from longer-term tests fall below the chronic criterion for ammonia. These results were from tests conducted with the fatmucket, the rainbow mussel, and the wavy-rayed lampmussel; all results except those from one test were additional data not included in USEPA (2013). The chronic *evaluation dataset* includes a variety of mussel toxicity test results from Wang *et al.* (2007a), including an IC_{25} estimate and chronic values for survival and growth. Growth responses for mussels were not included in the USEPA (2013) chronic dataset; EPA cited the uncertainty of assessing the growth endpoint, test variability, and the need for additional research and method development as reasons for not including growth data for mussels (USEPA 2013). However, results from subsequent

analyses of data from toxicity tests with mussels confirm that the growth data reported in Wang *et al.* (2007a; e.g., Wang *et al.* 2010; 2011) are reliable.

For cadmium, the comparison of individual toxicity test results to the EPA AWQC revealed that a number of results from tests conducted with rainbow trout fell below the acute criterion. Three of the tests were included in the calculation of mean values in USEPA (2001). For the chronic *evaluation dataset* for cadmium, six effect concentrations fell below the chronic criterion. These effect concentrations were generated for invertebrate species, specifically three cladoceran species (*C. reticulata*, *D. pulex*, and *D. magna*), and the amphipod *H. azteca*. Three of the tests were included in mean value calculations used to derive the EPA AWQC. The additional tests reported effects concentrations for growth and reproductive endpoints, indicating that sub-lethal effects at concentrations below the CCC could be expected in aquatic habitats.

The evaluation of the EPA AWQC for ammonia and cadmium indicates that the criteria may not be low enough to protect all taxa of concern on NWRs. Data available on the toxicity of ammonia to taxa of concern indicate that the acute criterion should protect 98% of tested fish species, 96% of tested invertebrate species (but 88% of tested mussel species), and the tested amphibian species. For chronic exposure data, the results indicate that the criterion should protect all of the tested fish species and 70% of tested invertebrate species (although none of the tested mussel species). Therefore, lower acute and chronic criteria for ammonia may be required to protect sensitive fish and invertebrate species (particularly mussel species) on NWRs. It is expected that the current EPA AWQC are low enough to protect the other taxa of concern identified on NWRs (i.e., aquatic-dependent mammals, migratory birds, reptiles, and aquatic plants) from the toxic effects of ammonia. However, more data are required to ensure that the criteria are low enough to protect amphibians.

Data available on the toxicity of cadmium to taxa of concern indicate that the acute criterion should protect 97% of tested fish species (but only 88% of tested

salmonid species) and all of the tested invertebrate species. In chronic exposures, the results indicate the criterion should protect all of the tested fish species, but only 76% of tested invertebrate species. Therefore, lower acute and chronic criteria for cadmium may be required to protect sensitive fish and invertebrate species on NWRs. Although the available toxicity data indicate that the acute and chronic criteria will protect the tested amphibian species, more data are required to decrease uncertainty in estimates of the effects thresholds. It is expected that the current EPA AWQC are low enough to protect the other taxa of concern identified on NWRs (i.e., aquatic-dependent mammals, migratory birds, reptiles, and aquatic plants) from the toxic effects of cadmium.

NWRs may provide habitat for sensitive, threatened, and/or endangered species, which may require a higher level of environmental protection than may be afforded by national or state-wide guidelines. EPA guidance for deriving AWQC (i.e., Stephan *et al.* 1985) allows for an override of the FAV if the SMAV for a commercially or recreationally important species is lower than the calculated FAV (i.e., the SMAV replaces the calculated FAV to provide protection for the important species; Stephan *et al.* 1985). Although this override can, in certain cases, allow for a criterion to be generated that is more protective than the CMC (e.g., as was done for rainbow trout in USEPA [2001] for cadmium), it does not ensure the protection of more sensitive species that may not be considered commercially or recreationally important, nor the protection of prey species that may support the viability of these species. In order to provide adequate and appropriate protection for taxa of concern or threatened and endangered species inhabiting NWRs, it is recommended that refuge-specific water quality targets (RSWQTs) be developed.

5.0 Summary and Conclusions

For waters on NWRs that support sensitive species or taxa of concern, the primary management goal is the protection of all life stages of sensitive species and taxa of concern, as well as the occupied habitats upon which they depend, from any adverse effects associated with exposure to a contaminant or a contaminant mixture for an indefinite period of time. The evaluation of the EPA AWQC for ammonia and cadmium provided herein suggests that these criteria may not always provide the level of protection required on NWRs. While the EPA AWQC provide a consistent basis for evaluating water quality conditions, they may not provide adequate protection for threatened or endangered species, sensitive species, or taxa of concern using aquatic habitats on NWRs. For this reason, refuge staff require consistent procedures for establishing RSWQTs that will provide a basis for protecting biological resources on NWRs.

6.0 References

ASTM International. 2013. Standard guide for conducting laboratory toxicity tests with freshwater mussels. ASTM E2455-06(2013). Annual Book of ASTM Standards Volume 11.06. West Conshohocken, Pennsylvania.

Bader, J.A. and J.M. Grizzle. 1992. Effects of ammonia on growth and survival of recently hatched channel catfish. Journal of Aquatic Animal Health 4(1): 17-23. (As cited in USEPA 2013).

Baird, D.J., I. Barber, M. Bradley, A.M.V.M. Soares and P. Calow. 1991. A comparative study of genotype sensitivity to acute toxic stress using clones of *Daphnia magna* Straus. Ecotoxicological and Environmental Safety 21: 257-265. (As cited in USEPA 2001).

BCMOE (British Columbia Ministry of Environment). 2014. Ambient water quality guidelines for cadmium - technical report. Prepared by J.A. Sinclair, A. Schein, M.E. Wainwright, H.J. Prencipe, D.D. MacDonald, and M.L., Haines at MacDonald Environmental Sciences Ltd. and C. Meays at the Water Protection & Sustainability Branch, Environmental Sustainability and Strategic Policy Division, BC Ministry of Environment. ISBN 978-0-7726-6741-0.

Besser, J.M., C.A. Mebane, D.R. Mount, C.D. Ivey, J.L. Kunz, I.E. Greer, T.W. May and C.G. Ingersoll. 2007. Sensitivity of mottled sculpins (*Cottus bairdi*) and rainbow trout (*Oncorhynchus mykiss*) to acute and chronic toxicity of cadmium, copper, and zinc. Environmental Toxicology and Chemistry 26:1657-1665.

Besser, J., R. Warbritton, and C. Ingersoll. 2013. Data Summary for Project, 'Development of Methods for Propagation of ESA-Listed and Surrogate Species of Freshwater Snails for use in Toxicity Testing.' Draft. Columbia Environmental Research Center, United States Geological Survey, Columbia, MO.

Black, M.C. 2001. Water quality standards for North Carolina's endangered mussels. Final Report. Department of Health Science, University of Georgia, Athens, GA.

Blahm, T.H. 1978. Toxicity of chemical fire retardants to juvenile coho salmon and rainbow trout. Ph.D. Thesis, University of Idaho, Moscow, ID. Available from: Dissertation Abstracts International B Sciences and Engineering 39(9):4115. (As cited in USEPA 2013).

Brinkman, S.F. and D.L. Hansen. 2007. Toxicity of cadmium to early life stages of brown trout (*Salmo trutta*) at multiple water hardnesses. Environmental Toxicology and Chemistry 26:1666-1671.

Brinkman, S.F. and W.D. Johnston. 2008. Acute toxicity of aqueous copper, cadmium and zinc to the mayfly *Rhithrogena hageni*. Archives of Environmental Contamination and Toxicology 54:466-472.

Brinkman, S. and N. Vieira. 2008. Water pollution studies: federal aid project F-243-R15. 38 pp.

Buhl, K.J. 2002. The relative toxicity of waterborne inorganic contaminants to the Rio Grande silvery minnow (*Hybognathus amarus*) and fathead minnow (*Pimephales promelas*) in a water quality simulating that in the Rio Grande, Albuquerque, NM. Final Report to the U.S. Fish and Wildlife Service, New Mexico Ecological Services Field Office, Albuquerque, New Mexico. (As cited in USEPA 2013).

Calamari, D., R. Marchetti and G. Vailati. 1977. Effect of prolonged treatments with ammonia on stages of development of *Salmo gairdneri*. Nuovi annali d'igiene e microbiologia 28(5): 333-345. (As cited in USEPA 2013).

Calamari, D., R. Marchetti and G. Vailati. 1981. Effects of long-term exposure to ammonia on the developmental stages of rainbow trout (*Salmo gairdneri*). Rapports et procès-verbaux des réunions / Conseil permanent international pour l'exploration de la mer 178:81-86. (As cited in USEPA 2013).

Castillo, V., III and G. Longley. 2001. Comparison of EPA target toxicity aquatic test organisms to the fountain darter: 7 day chronic toxicity test using cadmium chloride, performed 11/12/99-3/6/00 (5 parts). Federal Assistance Agreement No. X-986345-01.

CCME (Canadian Council of Ministers of the Environment). 2007. A protocol for the derivation of water quality guidelines for the protection of aquatic life 2007. In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg, Manitoba.

CCME (Canadian Council of Ministers of the Environment). 2014. Canadian Water Quality Guidelines: Cadmium. Scientific Criteria Document. Winnipeg, Manitoba. Accessed 19 March 2014 from: http://www.ccme.ca/files/Resources/supporting_scientific_documents/pn_1515_cwqg_cadmium_scd.pdf

Chadwick Ecological Consultants Inc. 2004. Chronic toxicity of cadmium to freshwater crustaceans at different water hardness concentrations. Chadwick Ecological Consultants, Incorporated 1-64.

Chapman, G.A. 1982. Chinook salmon early life stage tests with cadmium, copper, and zinc. Letter of December 6, 1982 to Charles Stephan, U.S. Environmental Protection Agency Environmental Research Laboratory, Duluth, Corvallis, Oregon. 4 pp.

Chapman, G.A., S. Ota and F. Recht. 1980. Effects of water hardness on the toxicity of metals to *Daphnia magna* (Status report - January 1980).

Cusimano, R.F., D.F. Brakke and G.A. Chapman. 1986. Effects of pH on the toxicities of cadmium, copper, and zinc to steelhead trout (*Salmo gairdneri*). Canadian Journal of Fisheries and Aquatic Sciences 43:1497-1503.

Davies, P.H., W.C. Gorman, C.A. Carlson and S.F. Brinkman. 1993. Effect of hardness on bioavailablity and toxicity of cadmium to rainbow trout. Chemical Speciation and Bioavailability 5(2):67-77.

Diamond, J.M., D.G. Mackler, W.J. Rasnake and D. Gruber. 1993. Derivation of site-specific ammonia criteria for an effluent-dominated headwater stream. Environmental Toxicology and Chemistry 12(4): 649-658. (As cited in USEPA 2013).

Drost, W., M. Matzke, and T. Backhaus. 2007. Heavy metal toxicity to *Lemna minor*: Studies on the time dependence of growth inhibition and the recovery after exposure. Chemosphere 67:36-43.

Elnabarawy, M.T., A.N. Welter and R.R. Robideau. 1986. Relative sensitivity of three daphnid species to selected organic and inorganic chemicals. Environmental Toxicology and Chemistry 5(393):393-398.

Felten, V., G. Charmantier, R. Mons, A. Geffard, P. Rousselle, and M. Coquery. 2008. Physiological and behavioural responses of *Gammarus pulex* (Crustacea Amphipoda) exposed to cadmium. Aquatic Toxicology 86:413-425.

Gerhardt, A. 1992. Acute toxicity of Cd in stream invertebrates in relation to pH and test design. Hydrobiologia 239:93-100.

Hansen, J. A., P.G. Welsh, J. Lipton, D. Cacela and A.D. Dailey. 2002a. Relative sensitivity of bull trout (*Salvelinus confluentus*) and rainbow trout (*Oncorhynchus mykiss*) to acute exposures of cadmium and zinc. Environmental Toxicology and Chemistry 21:67-75.

Hansen, J.A., P.G. Welsh, J. Lipton, and M.J. Suedkamp. 2002b. The effects of long-term cadmium exposure on the growth and survival of juvenile bull trout (*Salvelinus confluentus*). Aquatic Toxicology 58:165-174.

Hickey, C.W. and M.L. Vickers. 1994. Toxicity of ammonia to nine native New Zealand freshwater invertebrate species. Archives of Environmental Contamination and Toxicology 26(3):292-298. (As cited in USEPA 2013).

Holdway, D.A., K. Lok and M. Semaan. 2001. The acute and chronic toxicity of cadmium and zinc to two Hydra species. Environmental Toxicology 16:557-565.

Hollis, L., J.C. McGeer, D.G. McDonald and C.M. Wood. 1999. Cadmium accumulation, gill Cd binding, acclimation, and physiological effects during long-term sublethal Cd exposure in rainbow trout. Aquatic Toxicology 46:101-119.

Ingersoll, C. and N. Kemble. 2001. Revised description of toxicity data on cadmium: Chronic water-only exposures with the amphipod *Hyalella azteca* and the midge *Chironomus tentans*. Memo from United States Department of the Interior, U.S. Geological Survey, to Cindy Roberts, U.S. Environmental Protection Agency, Health and Ecological Criteria Division. 11 January 2001.

Ingersoll, C.G. and C.A. Mebane (Eds.). 2014. Acute and chronic sensitivity of white sturgeon (*Acipenser transmontanus*) and rainbow trout (*Oncorhynchus mykiss*) to cadmium, copper, lead, or zinc in laboratory water-only exposures. U.S. Geological Survey Scientific Investigations Report 2013-5204. 70 p., plus appendices. Available at http://dx.doi.org/10.3133/sir20135204.

Ingersoll, C.G. and R.W. Winner. 1982. Effect on *Daphnia pulex* (de Geer) of daily pulse exposures to copper and cadmium. Environmental Toxicology and Chemistry 1:321-327.

Källqvist, T. 2009. Effect of water hardness on the toxicity of cadmium to the green alga *Pseudokirchneriella subcapitata* in an artificial growth medium and nutrient-spiked natural lake waters. Journal of Toxicology and Environmental Health, Part A 72:277-283.

Keller, A.E. and S.G. Zam. 1991. The acute toxicity of selected metals to the freshwater mussel, *Anodonta imbecilis.* Environmental Toxicology and Chemistry 10: 539-546. (As cited in USEPA 2001).

Lasee, B.A. 1991. Histological and ultrastructural studies of larval and juvenile *Lampsilis* (Bivalva) from the Upper Mississippi River. PhD Dissertation. 145 pp.

Little, E.E. 2002. Behavioral measures of injuries to fish and aquatic organisms: regulatory considerations, p. 411-431 in Giacomo Dell'Omo editor, Behavioral Ecotoxicology. John Wiley and Sons, Ltd. (As cited in Ingersoll and Mebane 2014.)

McCahon, C.P. and D. Pascoe. 1988. Increased sensitivity to cadmium of the freshwater amphipod *Gammarus pulex* (L.) during the reproductive period. Aquatic Toxicology 13:183-194.

Mebane, C.A. 2010. Cadmium risks to freshwater life: derivation and validation of low-effect criteria values using laboratory and field studies. Scientific Investigations Report 2006-5245. Version 1.2. 130 99.

Mebane, C.A., D.P. Hennessy, and F.S. Dillon. 2008. Developing acute-to-chronic toxicity ratios for lead, cadmium, and zinc using rainbow trout, a mayfly, and a midge. Water, Air, and Soil Pollution 188:41-66.

Mebane, C.A., F.S. Dillon and D.O. Hennessy. 2012. Acute toxicity of cadmium, lead, zinc, and their mixtures to stream-resident fish and invertebrates. Environmental Toxicology and Chemistry 31:1334-1348.

Miao, J., M.C. Barnhart, E.L. Brunson, D.K. Hardesty, C.G. Ingersoll, and N. Wang. 2010. An evaluation of the influence of substrate on the response of juvenile freshwater mussels (fatmucket, *Lampsilis siliquoidea*) in acute water exposures to ammonia. Environmental Toxicology and Chemistry 29: 2112-2116.

Nebeker, A.V., G.S. Schuytema and S.L. Ott. 1995a. Effects of cadmium on growth and bioaccumulation in the Northwestern salamander *Ambystoma gracile*. Archives of Environmental Contamination and Toxicology 29:492-499. (As cited in USEPA 2001).

Nebeker, A.V., G.S. Schuytema and S.L. Ott. 1995b. Effects of cadmium on growth and bioaccumulation in the Northwestern salamander *Ambystoma gracile*. Archives of Environmental Contamination and Toxicology 29:492-499.

Pascoe, D., A.F. Brown, B.M.J. Evans and C. McKavanagh. 1990. Effects and fate of cadmium during toxicity tests with Chironomus riparius - the influence of food and artificial sediment. Archives of Environmental Contamination and Toxicology 19: 872-877. (As cited in USEPA 2001).

Pickering, Q.H. and M.H. Gast. 1972. Acute and chronic toxicity of cadmium to fathead minnow (*Pimephales promelas*). Journal of the Fisheries Research Board of Canada 29(8):1099-1106.

Reinbold, K.A. and S.M. Pescitelli. 1982. Effects of exposure to ammonia on sensitive life stages of aquatic organisms. Project Report, Contract No. 68-01-5832. Illinois Natural History Survey, Champaign, Illinois. (As cited in USEPA 2013).

Sauter, S., K. S. Buxton, K. J. Macek and S. R. Petrocelli. 1976. Effects of exposure to heavy metals on selected fresh water fish: Toxicity of copper, cadmium, chromium and lead to eggs and fry of seven fish species. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency. EPA-600/3-76-105.

Schuytema, G. S., P. O. Nelson, K. W. Malueg, A. V. Nebeker, D. F. Krawczyk, A. K. Ratcliff and J.H. Gakstatter. 1984. Toxicity of cadmium in water and sediment slurries to *Daphnia magna*. Environmental Toxicology and Chemistry 3:293-308.

Scott, G.R., K.A. Sloman, C. Rouleau and C.M. Wood. 2003. Cadmium disrupts behavioural and physiological responses to alarm substance in juvenile rainbow trout (*Oncorhynchus mykiss*). Journal of Experimental Biology 206:1779-1790.

Sloman, K.A., G.R. Scott, Z. Diao, C. Rouleau, C.M. Wood and D.G. McDonald. 2003. Cadmium affects the social behaviour of rainbow trout, *Oncorhynchus mykiss*. Aquatic Toxicology 65:171-185.

Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman, and W.A. Brungs. 1985. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. PB85-227049. United States Environmental Protection Agency. Washington, District of Columbia.

Stratus Consulting, Inc. 1999. Sensitivity of bull trout (*Salvelinus confluentus*) to cadmium and zinc in water characteristic of the Coeur D'Alene River Basin: acute toxicity report. Final Report to U.S. Environmental Protection Agency Region X. 55 pp. (As cited in USEPA 2001).

Suedel, B.C., J.H. Rodgers Jr. and E. Deaver. 1997. Experimental factors that may affect toxicity of cadmium to freshwater organisms. Archives of Environmental Contamination and Toxicology 33:188-193.

USEPA (United States Environmental Protection Agency). 1980. Ambient water quality criteria for cadmium. EPA-440/5-80-025. Office of Water Regulation and Standards, Criteria and Standards Division. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 1985. Ambient water quality criteria for cadmium. EPA-440/5-84-032 (Revised late 1984). National Technical Information Service. Springfield, Virginia. (As cited in USEPA 2001).

USEPA (United States Environmental Protection Agency). 1986. 1995 Updates: Water quality criteria documents for the protection of aquatic life in water. EPA-820-B-96-001. Office of Water. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 1994. Water quality standards handbook, second ed. EPA-823-B-94-005b. Office of Water. Washington, District of Columbia. (As cited in USEPA 2001).

USEPA (United States Environmental Protection Agency). 1999. National Recommended Water Quality Criteria - Correction. EPA-822-Z-99-001. Office of Water. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 2001. 2001 Update of ambient water quality criteria for cadmium. EPA-822-R-01-001. Office of Water, Office of Science and Technology. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 2009. Draft 2009 update: aquatic life ambient water quality criteria for ammonia - freshwater. EPA-822-D-09-001. Office of Water, Office of Science and Technology. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 2013. Aquatic life ambient water quality criteria for ammonia - freshwater 2013. EPA-822-R-13-001. Office of Water, Office of Science and Technology. Washington, District of Columbia.

Vardy, D.W., A.R. Tompsett, J. L. Sigurdson, J.A. Doering, X. Zhang, J.P. Giesy and M. Hecker. 2011. Effects of sub-chronic exposure of early life stages of white sturgeon (*Acipenser transmontanus*) to copper, cadmium, and zinc. Environmental Toxicology and Chemistry 30:2497-2505.

Wang, N., C.G. Ingersoll, D.K. Hardesty, I.E. Greer, D.J. Hardesty, C.D. Ivey, J.L. Kunz, W.G. Brumbaugh, F.J. Dwyer, A.D. Roberts, J.T. Augspurger, C.M. Kane, R.J. Neves and M.C. Barnhart. 2007a. Contaminant sensitivity of freshwater mussels: Chronic toxicity of copper and ammonia to juvenile freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10):2048-2056.

Wang, N., C.G. Ingersoll , D.K. Hardesty, C.D. Ivey, J.L. Kunz, T.W. May, F.J. Dwyer, A.D. Roberts, T. Augspurger, C.M. Kane, R.J. Neves and M.C. Barnhart. 2007b. Contaminant sensitivity of freshwater mussels: Acute toxicity of copper, ammonia, and chlorine to glochidia and juveniles of freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10):2036-2047. (As cited in USEPA 2013).

Wang, N., C.G. Ingersoll, C.D. Ivey, D.K. Hardesty and T.W. May. 2010. Sensitivity of early life stages of freshwater mussels (Unionidae) to acute and chronic toxicity of lead, cadmium and zinc in water. Environmental Toxicology and Chemistry 29(9):2053-2063.

Wang, N., R.A. Consbrock, C.G. Ingersoll, and M.C. Barnhart. 2011. Evaluation of influence of sediment on the sensitivity of a unionid mussel (*Lampsilis siliquoidea*) to ammonia in 28-day water exposures. Environmental Toxicology and Chemistry 30: 2270-2276.

Watts, M.M. and D. Pascoe. 2000. A comparative study of *Chironomus riparius* Meigen and *Chironomus tentans* Fabricius (Diptera: Chironomidae) in aquatic toxicity tests. Archives of Environmental Contamination and Toxicology 39:299-306.

Williams, K.A., D.W.J. Green and D. Pascoe. 1985. Studies on the acute toxicity of pollutants to freshwater macroinvertebrates; 1: Cadmium. Archiv für Hydrobiologie 102(4): 461-471. (As cited in USEPA 2001).

Tables

Table A6.1. Comparison of water quality criteria and guidelines for ammonia from selected jurisdictions[1].

Exposure Type	USEPA 1999 AWQC (mg TAN/L)[2,3]	USEPA 2009 Draft AWQC (mg TAN/L)[2,3,4]	USEPA 2013 AWQC (mg TAN/L)[3]	CCME WQG (mg TAN/L)[3]	BCMOE WQG (mg TAN/L)[3]
Acute[5]	24 [7]	19	17 [7]	NG	19.2
Chronic[6]	4.5	0.91	1.9	3.96	1.22

AWQC = ambient water quality criteria; BCMOE = British Columbia Ministry of Environment; CCME = Canadian Council of Ministers of the Environment; N = nitrogen; NG = no guideline; TAN = total ammonia nitrogen; USEPA = U.S. Environmental Protection Agency; WQG = water quality guideline.

[1] Criteria and guidelines for the protection of aquatic life.

[2] Reported in USEPA (2013).

[3] Applicable at pH 7.0 and a water temperature of 20°C.

[4] For waters where mussels are present.

[5] Application of acute thresholds: USEPA AWQC = 1-hour average, not to be exceeded more than once in three years on average; BCMOE WQG = maximum not to be exceeded.

[6] Application of chronic thresholds: USEPA AWQC = 30-day rolling average not to be exceeded more than once in three years on average, and not to exceed 2.5 times the criteria as a 4-day average within the 30-days, more than once in three years on average; BCMOE WQG = average of 5 samples collected in 30 days; CCME WQG = maximum concentration, not to be exceeded.

[7] For waters where salmonids are present.

Table A6.2. Comparison of water quality criteria and guidelines for cadmium from selected jurisdictions[1].

Exposure Type	USEPA 1999 AWQC (µg Cd/L)[2,3]	USEPA 2001 AWQC (µg Cd/L)[4]	CCME WQG (µg Cd/L)[5]	BCMOE WQG (µg Cd/L)[6,7]
Acute[8]				
50 mg/L hardness	2.0	1.0	1.0	NG
100 mg/L hardness	4.3	2.0	2.1	NG
200 mg/L hardness	9.0	3.9	4.2	NG
Chronic[9]				
50 mg/L hardness	1.3	0.15	0.09	0.018
100 mg/L hardness	2.2	0.25	0.16	0.033
200 mg/L hardness	3.7	0.40	0.28	0.060

AWQC = ambient water quality criteria; BCMOE = British Columbia Ministry of Environment; CCME = Canadian Council of Ministers of the Environment; USEPA = U.S. Environmental Protection Agency; WQG = water quality guideline.

[1] Criteria and guidelines for the protection of aquatic life. All values are for dissolved cadmium.

[2] Based on cadmium data compiled in USEPA (1996)

[3] Acute equation: $e^{(1.128[\ln(\text{hardness})]-3.6867)} * (1.136672-[\ln(\text{hardness})(0.041838)])$; Chronic equation: $e^{(0.7852[\ln(\text{hardness})]-2.715)} * (1.101672-[\ln(\text{hardness})(0.041838)])$

[4] Acute equation: $e^{(1.0166[\ln(\text{hardness})]-3.924)} * (1.136672-[\ln(\text{hardness})(0.041838)])$; Chronic equation: $e^{(0.7409[\ln(\text{hardness})]-4.719)} * (1.101672-[\ln(\text{hardness})(0.041838)])$

[5] Acute equation: $10^{(1.016(\log[\text{hardness}]) - 1.71)}$, valid for hardnesses between 5.3 and 360 mg $CaCO_3$/L. At hardness < 5.3 mg $CaCO_3$/L the WQG = 0.11 µg/L. At hardness > 360 mg $CaCO_3$/L the WQG = 7.7 µg/L; Chronic equation: $10^{(0.83(\log[\text{hardness}]) - 2.46)}$, valid for hardnesses between 17 and 280 mg $CaCO_3$/L. At hardness < 17 mg $CaCO_3$/L the WQG = 0.04 µg/L. At hardness > 280 mg $CaCO_3$/L the WQG = 0.37 µg/L.

[6] Working WQG (Nagpal *et al.* 2006). Draft WQG is currently under review.

[7] Chronic equation: $10^{\wedge[0.86 * \log(\text{hardness}) - 3.2]}$

[8] Application of acute thresholds: USEPA AWQC = 24-hr average, not to be exceeded more than once every three years on average; BCMOE WQG = maximum not to be exceeded; CCME WQG = estimate of severe effects.

[9] Application of chronic thresholds: USEPA AWQC = four-day average, not to be exceeded more than once every three years on average; BCMOE WQG = average of 5 samples collected in 30 days; CCME WQG = estimate of threshold for protection of aquatic life under indefinite exposure.

Table A6.3. Species and genus mean acute values used in the derivation and recalculation of the ambient water quality criteria for ammonia (USEPA 2013).

Receptor Group / Scientific Name	Common Name	USEPA (2013) Values		Recalculated Values[1]	
		SMAV (mg TAN/L)	GMAV (mg TAN/L)	SMAV (mg TAN/L)	GMAV (mg TAN/L)
Amphibian					
Pseudacris crucifer	Spring peeper	61.18		61.18	
Pseudacris regilla	Pacific tree frog	83.71	71.56	83.71	71.56
Rana pipiens	Leopard frog	96.38	96.38	96.38	96.38
Xenopus laevis	Clawed toad	122.5	122.5	122.5	122.5
Fish					
Acipenser brevirostrum	Shortnose sturgeon	156.7	156.7	156.7	156.7
Campostoma anomalum	Central stoneroller	115.9	115.9	115.9	115.9
Catostomus commersonii	White sucker	157.5		157.5	
Catostomus platyrhynchus	Mountain sucker	136.2	146.5	136.2	146.5
Chasmistes brevirostris	Shortnose sucker	69.36	69.36	69.36	69.36
Cottus bairdii	Mottled sculpin	222.2	222.2	222.2	222.2
Cyprinella lutrensis	Rainbow dace	196.1		196.1	
Cyprinella spiloptera	Spotfin shiner	83.8		83.8	
Cyprinella whipplei	Steelcolor shiner	80.94	110	80.94	110
Cyprinus carpio	Common carp	106.3	106.3	106.3	106.3
Deltistes luxatus	Lost River sucker	56.62	56.62	56.62	56.62
Etheostoma nigrum	Johnny darter	71.45		71.45	
Etheostoma spectabile	Orangethroat darter	77.17	74.25	77.17	74.25
Gambusia affinis	Western mosquitofish	219.3	219.3	219.3	219.3
Gasterosteus aculeatus	Threespine stickleback	281.5	281.5	281.5	281.5
Hybognathus amarus	Rio Grande silvery minnow	72.55	72.55	72.55	72.55
Ictalurus punctatus	Channel catfish	142.4	142.4	142.4	142.4
Lepomis cyanellus	Green sunfish	150.8		150.8	
Lepomis gibbosus	Pumpkinseed	77.53		77.53	
Lepomis macrochirus	Bluegill sunfish	104.5	106.9	104.5	106.9
Micropterus dolomieu	Smallmouth bass	150.6		150.6	
Micropterus salmoides	Largemouth bass	86.02		86.02	
Micropterus treculii	Guadalupe bass	54.52	89.06	54.52	89.06
Morone americana	White perch	132.7		132.7	
Morone chrysops	White bass	144		144	
Morone saxatilis	Striped bass	246.2		246.2	
Morone saxatilis x chrysops	Sunshine bass	70.22	134.8	70.22	134.8
Notemigonus crysoleucas	Golden shiner	63.02	63.02	63.02	63.02
Notropis topeka	Topeka shiner	96.72	96.72	96.72	96.72
Oreochromis mossambicus	Mozambique tilapia	185.2	185.2	185.2	185.2
Pimephales promelas	Fathead minnow	159.2	159.2	159.2	159.2
Poecilia reticulata	Guppy	74.66	74.66	74.66	74.66
Sander vitreus	Walleye	117.1	117.1	117.1	117.1
Fish - Salmonid					
Oncorhynchus aguabonita	Golden trout	112.1		112.1	
Oncorhynchus clarkii	Cutthroat trout	78.92		78.92	
Oncorhynchus gorbuscha	Pink salmon	180.7		180.7	

Table A6.3. Species and genus mean acute values used in the derivation and recalculation of the ambient water quality criteria for ammonia (USEPA 2013).

Receptor Group / Scientific Name	Common Name	USEPA (2013) Values		Recalculated Values[1]	
		SMAV (mg TAN/L)	GMAV (mg TAN/L)	SMAV (mg TAN/L)	GMAV (mg TAN/L)
Fish - Salmonid (cont.)					
Oncorhynchus kisutch	Coho salmon	87.05		87.05	
Oncorhynchus mykiss	Rainbow trout	82.88		82.88	
Oncorhynchus tshawytscha	Chinook salmon	82.39	99.15	82.39	99.15
Prosopium williamsoni	Mountain whitefish	51.93	51.93	51.93	51.93
Salmo salar	Atlantic salmon	183.3		183.3	
Salmo trutta	Brown trout	102	136.7	102	136.7
Salvelinus fontinalis	Brook trout	156.3		156.3	
Salvelinus namaycush	Lake trout, siscowet	159.3	157.8	159.3	157.8
Invertebrate - ALS insect					
Callibaetis skokianus	Mayfly	364.6		364.6	
Callibaetis sp.	Mayfly	166.7	246.5	166.7	246.5
Chironomus riparius	Midge	1029		1029	
Chironomus tentans	Midge	451.8	681.8	451.8	681.8
Drunella grandis	Mayfly	442.4	442.4	442.4	442.4
Enallagma sp.	Damselfly	164	164	164	164
Erythromma najas	Insect	2515	2515	2515	2515
Pachydiplax longipennis	Dragonfly	233	233	233	233
Philarctus quaeris	Caddisfly	994.5	994.5	994.5	994.5
Skwala americana	Little golden stonefly	192.4	192.4	192.4	192.4
Stenelmis sexlineata	Beetle	735.9	735.9	735.9	735.9
Invertebrate - Amphipod					
Crangonyx pseudogracilis	Amphipod	270.5		270.5	
Crangonyx sp.	Amphipod	122.2	181.8	122.2	181.8
Hyalella azteca	Scud	192.6	192.6	192.6	192.6
Invertebrate - Cladoceran					
Ceriodaphnia acanthina	Water flea	154.3		154.3	
Ceriodaphnia dubia	Water flea	134.2	143.9	134.2	143.9
Chydorus sphaericus	Water flea	162.6	162.6	162.6	162.6
Daphnia magna	Water flea	157.7		157.7	
Daphnia pulicaria	Water flea	99.03	125	99.03	125
Simocephalus vetulus	Water flea	142.9	142.9	142.9	142.9
Invertebrate - Clam					
Musculium transversum	Long fingernailclam	89.36	89.36	89.36	89.36
Invertebrate - Decapod					
Orconectes immunis	Crayfish	1550		1550	
Orconectes nais	Crayfish	303.8	686.2	303.8	686.2
Procambarus clarkii	Red swamp crayfish	138	138	138	138

Table A6.3. Species and genus mean acute values used in the derivation and recalculation of the ambient water quality criteria for ammonia (USEPA 2013).

Receptor Group / Scientific Name	Common Name	USEPA (2013) Values		Recalculated Values[1]	
		SMAV (mg TAN/L)	GMAV (mg TAN/L)	SMAV (mg TAN/L)	GMAV (mg TAN/L)
Invertebrate - Isopod					
Asellus aquaticus	Isopod	378.2	378.2	378.2	378.2
Caecidotea racovitzai	Aquatic sowbug	387	387	387	387
Invertebrate - Mussel					
Actinonaias ligamentina	Mucket	63.89		63.89	
Actinonaias pectorosa	Pheasantshell	79.46	71.25	79.46	71.25
Alasmidonta heterodon	Dwarf wedgemussel	>109.0	>109.0	>109.0	>109.0
Epioblasma capsaeformis	Oyster mussel	31.14	31.14	31.14	31.14
Fusconaia masoni	Atlantic pigtoe	47.4	47.4	47.4	47.4
Lampsilis abrupta	Pink mucket	26.03		26.03	
Lampsilis cardium	Plain pocketbook	50.51		50.51	
Lampsilis fasciola	Wavy-rayed lampmussel	48.11		48.11	
Lampsilis higginsii	Higgin's eye	41.9		41.9	
Lampsilis rafinesqueana	Neosho mucket	69.97		69.97	
Lampsilis siliquoidea	Fatmucket	55.42	46.63	**49.78**	**45.80**
Lasmigona subviridis	Green floater	23.41	23.41	23.41	23.41
Potamilus ohiensis	Pink papershell	>109.0	>109.0	>109.0	>109.0
Pyganodon grandis	Giant floater mussel	70.73	70.73	70.73	70.73
Utterbackia imbecillis	Pondshell mussel	46.93	46.93	46.93	46.93
Venustaconcha ellipsiformis	Ellipse	23.12	23.12	23.12	23.12
Villosa iris	Rainbow mussel	34.23	34.23	34.23	34.23
Invertebrate - Snail					
Fluminicola sp.	Pebblesnail	>62.15	>62.15	**68.52**	**68.52**
Lymnaea stagnalis	Great pond snail	88.62	88.62	88.62	88.62
Physa gyrina	Pouch snail	164.5	164.5	164.5	164.5
Planorbella trivolvis	Marsh ramshorn snail	211.6	211.6	211.6	211.6
Pleurocera uncialis	Pagoda hornsnail	68.54	68.54	68.54	68.54
Invertebrate - Worm					
Dendrocoelum lacteum	Flatworm	119.5	119.5	119.5	119.5
Limnodrilus hoffmeisteri	Tubificid worm	170.2	170.2	170.2	170.2
Lumbriculus variegatus	Oligochaete worm	218.7	218.7	218.7	218.7
Tubifex tubifex	Tubificid worm	216.5	216.5	216.5	216.5

ALS = aquatic life stage; GMAV = genus mean acute value; SMAV = species mean acute value; TAN = total ammonia nitrogen; USEPA = United States Environmental Protection Agency.

[1] Bolded values indicate recalculated SMAVs/GMAVs (i.e., values are different than the values used in USEPA 2013).

Table A6.4. Species and genus mean chronic values used in the derivation and recalculation of the ambient water quality criteria for ammonia (USEPA 2013).

Receptor Group / Scientific Name	Common Name	USEPA (2013) Values		Recalculated Values[1]	
		SMCV (mg TAN/L)	GMCV (mg TAN/L)	SMCV (mg TAN/L)	GMCV (mg TAN/L)
Fish					
Catostomus commersonii	White sucker	>11.62	>11.62	>11.62	>11.62
Cyprinus carpio	Common carp	16.53	16.53	16.53	16.53
Esox lucius	Northern pike	20.38	20.38	20.38	20.38
Ictalurus punctatus	Channel catfish	21.36	21.36	21.36	21.36
Lepomis cyanellus	Green sunfish	14.63		14.63	
Lepomis macrochirus	Bluegill sunfish	3.273	6.92	3.273	6.92
Micropterus dolomieu	Smallmouth bass	11.07	11.07	11.07	11.07
Pimephales promelas	Fathead minnow	9.187	9.187	9.187	9.187
Fish - Salmonid					
Oncorhynchus clarkii henshawi	Lahontan cutthroat trout	25.83		25.83	
Oncorhynchus mykiss	Rainbow trout	6.663		**7.116**	
Oncorhynchus nerka	Sockeye salmon	<10.09	12.02	<10.09	**13.56**
Invertebrate - ALS insect					
Pteronarcella badia	Stonefly	73.74	73.74	73.74	73.74
Hyalella azteca	Amphipod	29.17	29.17	29.17	29.17
Invertebrate - Cladoceran					
Ceriodaphnia acanthina	Water flea	64.1		64.1	
Ceriodaphnia dubia	Water flea	45.08	53.75	45.08	53.75
Daphnia magna	Water flea	41.46	41.46	41.46	41.46
Invertebrate - Clam					
Musculium transversum	Long fingernailclam	7.547	7.547	7.547	7.547
Invertebrate - Mussel					
Lampsilis fasciola	Wavy-rayed lamp mussel	1.408		**1.285**	
Lampsilis siliquoidea	Fatmucket	3.211	2.126	**1.174**	**1.228**
Villosa iris	Rainbow mussel	3.501	3.501	**2.406**	**2.406**
Invertebrate - Snail					
Fluminicola sp.	Pebblesnail	7.828	7.828	**7.680**	**7.680**

ALS = aquatic life stage; GMCV = genus mean chronic value; SMCV = species mean chronic value; TAN = total ammonia nitrogen; USEPA = United States Environmental Protection Agency.

[1] Bolded values indicate recalculated SMCVs/GMCVs (i.e., values are different than the values used in USEPA 2013).

Table A6.5. Species and genus mean acute values used in the derivation and recalculation of the ambient water quality criteria for cadmium (USEPA 2001).

Receptor Group / Scientific Name	Common Name	USEPA (2001) Values		Recalculated Values[1]	
		SMAV (µg/L)	GMAV (µg/L)	SMAV (µg/L)	GMAV (µg/L)
Amphibian					
Ambystoma gracile	Salamander	521.4	521.4	521.4	521.4
Xenopus laevis	African clawed frog	1529	1529	1529	1529
Fish					
Acipenser transmontanus	White Sturgeon	ND		**11.25**	**11.25**
Carassius auratus	Goldfish	844	844	844	844
Catostomus commersonii	White sucker	3136	3136	3136	3136
Cottus bairdi	Mottled sculpin	ND		**2.296**	
Cottus confusus	Shorthead sculpin	ND		**2.246**	**2.271**
Cyprinus carpio	Common carp	4238	4238	4238	4238
Gambusia affinis	Mosquitofish	6499	6499	6499	6499
Gasterosteus aculeatus	Threespine stickleback	5439	5439	5439	5439
Gila elegans	Bonytail	38.72	38.72	38.72	38.72
Ictalurus punctatus	Channel catfish	5055	5055	5055	5055
Jordanella floridae	Flagfish	2847	2847	2847	2847
Lepomis cyanellus	Green sunfish	2965		2965	
Lepomis macrochirus	Bluegill sunfish	6028	4228	6028	4228
Morone saxatilis	Striped bass	2.925	2.925	2.925	2.925
Notropis lutrensis	Red shiner	3837	3837	3837	3837
Oreochromis mossambicus	Mozambique tilapia	10663	10663	10663	10663
Pimephales promelas	Fathead minnow	29.21	29.21	29.21	29.21
Poecilia reticulata	Guppy	2462	2462	2462	2462
Ptychocheilus lucius	Colorado squawfish	22.54 [2]		22.54 [2]	
Ptychocheilus oregonensis	Northern pikeminnow	2221 [2]	22.54	2221 [2]	22.54
Xyrauchen texanus	Razorback sucker	36.62	36.62	36.62	36.62
Fish - Salmonid					
Oncorhynchus clarkii lewisi	Westslope cutthroat trout	ND		**2.199**	
Oncorhynchus kisutch	Coho salmon	6.221		6.221	
Oncorhynchus mykiss	Rainbow trout	2.108		**1.624**	
Oncorhynchus tshawytscha	Chinook salmon	4.305	3.836	**3.901**	**3.051**
Prosopium williamsoni	Mountain Whitefish	ND		**4.92**	**4.92**
Salmo trutta	Brown trout	1.613	1.613	**2.384**	**2.384**
Salvelinus confluentus	Bull trout	2.152		**2.012**	
Salvelinus fontinalis	Brook trout	< 1.791	< 1.963	< 1.791	**2.012**
Invertebrate - ALS insect					
Baetis tricaudatus	Mayfly	ND		**49.16**	**49.16**
Chironomus riparius	Midge	96880	96880	**8258**	
Chironomus tentans	Midge	ND		**6382**	**7260**
Ephemerella grandis	Mayfly	2278	2278	2278	2278
Rhithrogena	Mayfly	ND		**317.6**	
Rhithrogena hageni	Mayfly	ND		**10940**	**1865**

Table A6.5. Species and genus mean acute values used in the derivation and recalculation of the ambient water quality criteria for cadmium (USEPA 2001).

Receptor Group / Scientific Name	Common Name	USEPA (2001) Values		Recalculated Values[1]	
		SMAV (µg/L)	GMAV (µg/L)	SMAV (µg/L)	GMAV (µg/L)
Invertebrate - Amphipod					
Crangonyx pseudogracilis	Amphipod	1700	1700	1700	1700
Gammarus pseudolimnaeus	Amphipod	78.69	78.69	78.69	
Gammarus pulex	Amphipod	ND		**35.88**	**53.13**
Hyalella azteca	Amphipod	ND		**11.86**	**11.86**
Invertebrate - Bryozoan					
Lophopodella carteri	Bryozoan	35.74	35.74	35.74	35.74
Pectinatella magnifica	Bryozoan	166.8	166.8	166.8	166.8
Plumatella emarginata	Bryozoan	259.7	259.7	259.7	259.7
Invertebrate - Cladoceran					
Alona affinis	Cladoceran	247.2	247.2	247.2	247.2
Ceriodaphnia dubia	Cladoceran	31.37		**49.44**	
Ceriodaphnia reticulata	Cladoceran	41.07	35.9	41.07	**45.06**
Daphnia magna	Cladoceran	13.41		**15.03**	
Daphnia pulex	Cladoceran	46.36	24.93	46.36	**26.4**
Moina macrocopa	Cladoceran	43.09	43.09	43.09	43.09
Simocephalus serrulatus	Cladoceran	30.21	30.21	30.21	30.21
Invertebrate - Copepod					
Cyclops varicans	Copepod	223.2	223.2	223.2	223.2
Invertebrate - Decapod					
Orconectes immunis	Crayfish	> 11509		> 11509	
Orconectes virilis	Crayfish	11859	> 11683	11859	**11860**
Procambarus clarkii	Crayfish	1748	1748	1748	1748
Invertebrate - Isopod					
Asellus bicrenata	Isopod	472.1	472.1	472.1	472.1
Lirceus alabamae	Isopod	48.44	48.44	48.44	48.44
Invertebrate - Mussel					
Actinonaias pectorosa	Mussel	33.80	33.8	33.80	33.8
Lampsilis rafinesqueana	Neosho Mucket	ND		**23.88**	
Lampsilis siliquoidea	Fatmucket	ND		**19.1**	
Lampsilis straminea claibornensis	Mussel	47.68		47.68	
Lampsilis teres	Mussel	23.90	33.76	23.90	
Lampsilis ventricosa	Mussel	ND		**27.78**	**27.03**
Lasmigona subviridis	Green floater	ND		**46.17**	**46.17**
Utterbackia imbecillis	Mussel	42.92	42.92	**33.77**	**33.77**
Villosa vibex	Mussel	35.18	35.18	35.18	35.18

Table A6.5. Species and genus mean acute values used in the derivation and recalculation of the ambient water quality criteria for cadmium (USEPA 2001).

Receptor Group / Scientific Name	Common Name	USEPA (2001) Values		Recalculated Values[1]	
		SMAV (µg/L)	GMAV (µg/L)	SMAV (µg/L)	GMAV (µg/L)
Invertebrate - Snail					
Aplexa hypnorum	Snail	103.9	103.9	103.9	103.9
Physa gyrina	Snail	100.2	100.2	100.2	100.2
Invertebrate - Worm					
Branchiura sowerbyi	Tubificid worm	2350	2350	2350	2350
Dendrocoelum lacteum	Planadan	14067	14067	14067	14067
Glossiponia complanta	Leech	192.5	192.5	192.5	192.5
Limnodrilus hoffmeisteri	Tubificid worm	775	775	775	775
Lumbriculus variegatus	Worm	130.6	130.6	130.6	130.6
Quistadrilus multisetosus	Tubificid worm	3133	3133	3133	3133
Rhyacodrilus montana	Tubificid worm	6169	6169	6169	6169
Spirosperma ferox	Tubificid worm	3427		3427	
Spirosperma nikolskyi	Tubificid worm	4406	3886	4406	3886
Stylodrilus heringianus	Tubificid worm	5386	5386	5386	5386
Tubifex tubifex	Tubificid worm	1361	1361	1361	1361
Varichaeta pacifica	Tubificid worm	3721	3721	3721	3721

ALS = aquatic life stage; GMAV = genus mean acute value; ND = no data; SMAV = species mean acute value; USEPA = United States Environmental Protection Agency.

[1] Bolded values indicate recalculated SMAVs/GMAVs (i.e., values are different than the values used in USEPA 2001).

[2] Species values are too divergent to use the geometric mean for the genus value; therefore, the most sensitive value was used.

Table A6.6. Species and genus mean chronic values used in the derivation and recalculation of the ambient water quality criteria for cadmium (USEPA 2001).

Receptor Group / Scientific Name	Common Name	USEPA (2001) Values		Recalculated Values[1]	
		SMCV (µg/L)	GMCV (µg/L)	SMCV (µg/L)	GMCV (µg/L)
Amphibian					
Ambystoma gracile	Salamander	ND		**132.9**	**132.9**
Fish					
Acipenser transmontanus	White Sturgeon	ND		**3.912**	**3.912**
Catostomus commersonii	White sucker	7.804	7.804	7.804	7.804
Cottus bairdi	Mottled sculpin	ND		**0.7568**	**0.7568**
Esox lucius	Northern pike	8.092	8.092	8.092	8.092
Jordanella floridae	Flagfish	5.318	5.318	5.318	5.318
Lepomis macrochirus	Bluegill sunfish	17.38	17.38	17.38	17.38
Micropterus dolomieu	Smallmouth bass	8.124	8.124	8.124	8.124
Oreochromis aurea	Blue tilapia	>23.63	>23.63	>23.63	>23.63
Pimephales promelas	Fathead minnow	16.38	16.38	**6.072**	**6.072**
Fish - Salmonid					
Oncorhynchus kisutch	Coho salmon (West Coast)	4.265		**5.202**	
Oncorhynchus mykiss	Rainbow trout	1.308		**1.765**	
Oncorhynchus tshawytscha	Chinook salmon	2.612	2.443	**2.602**	**2.88**
Prosopium williamsoni	Mountain Whitefish	ND		**2.08**	**2.08**
Salmo salar	Atlantic salmon	7.922		7.922	
Salmo trutta	Brown trout	5.004	6.296	**3.97**	**5.608**
Salvelinus confluentus	Bull trout	ND		**0.7764**	
Salvelinus fontinalis	Brook trout	2.643		**3.913**	
Salvelinus namaycush	Lake trout	8.088	4.624	**8.021**	**2.899**
Invertebrate - ALS insect					
Chironomus tentans	Midge	2.804	2.804	**2.762**	**2.762**
Rhithrogena hageni	Mayfly	ND		**2651**	**2651**
Invertebrate - Amphipod					
Gammarus pulex	Amphipod	ND		**3.22**	**3.22**
Hyalella azteca	Amphipod	0.2747	0.2747	**0.3559**	**0.3559**
Invertebrate - Cladoceran					
Ceriodaphnia dubia	Cladoceran	27.17	27.17	**6.993**	
Ceriodaphnia reticulata	Cladoceran	ND		**4.285**	**5.474**
Daphnia magna	Cladoceran	<0.3794 [2]		**1.189**	
Daphnia pulex	Cladoceran	6.167 [2]	<0.3794	**4.749**	**2.376**
Invertebrate - Hydra					
Hydra viridissima	Hydra (green)	ND		**1.136**	**1.136**
Invertebrate - Mussel					
Lampsilis siliquoidea	Fatmucket	ND		**6.282**	
Lampsilis ventricosa	Mussel	ND		**11.77**	**8.598**

Table A6.6. Species and genus mean chronic values used in the derivation and recalculation of the ambient water quality criteria for cadmium (USEPA 2001).

Receptor Group / Scientific Name	Common Name	USEPA (2001) Values		Recalculated Values[1]	
		SMCV (µg/L)	GMCV (µg/L)	SMCV (µg/L)	GMCV (µg/L)
Invertebrate - Snail					
Aplexa hypnorum	Snail	4.82	4.82	4.82	4.82
Invertebrate - Worm					
Aeolosoma headleyi	Oligochaete	20.74	20.74	20.74	20.74

ALS = aquatic life stage; GMCV = genus mean chronic value; ND = no data; SMCV = species mean chronic value; USEPA = United States Environmental Protection Agency.

[1] Bolded values indicate recalculated SMCVs/GMCVs (i.e., values are different than the values used in USEPA 2001).

[2] Species values are too divergent to use the geometric mean for the genus value; therefore, the most sensitive value was used.

Figures

Figure A6.1. Distribution of Genus Mean Acute Values (GMAVs) calculated from data used in the derivation of the nationally recommended acute water quality criterion for ammonia and additional data compiled from the scientific literature.

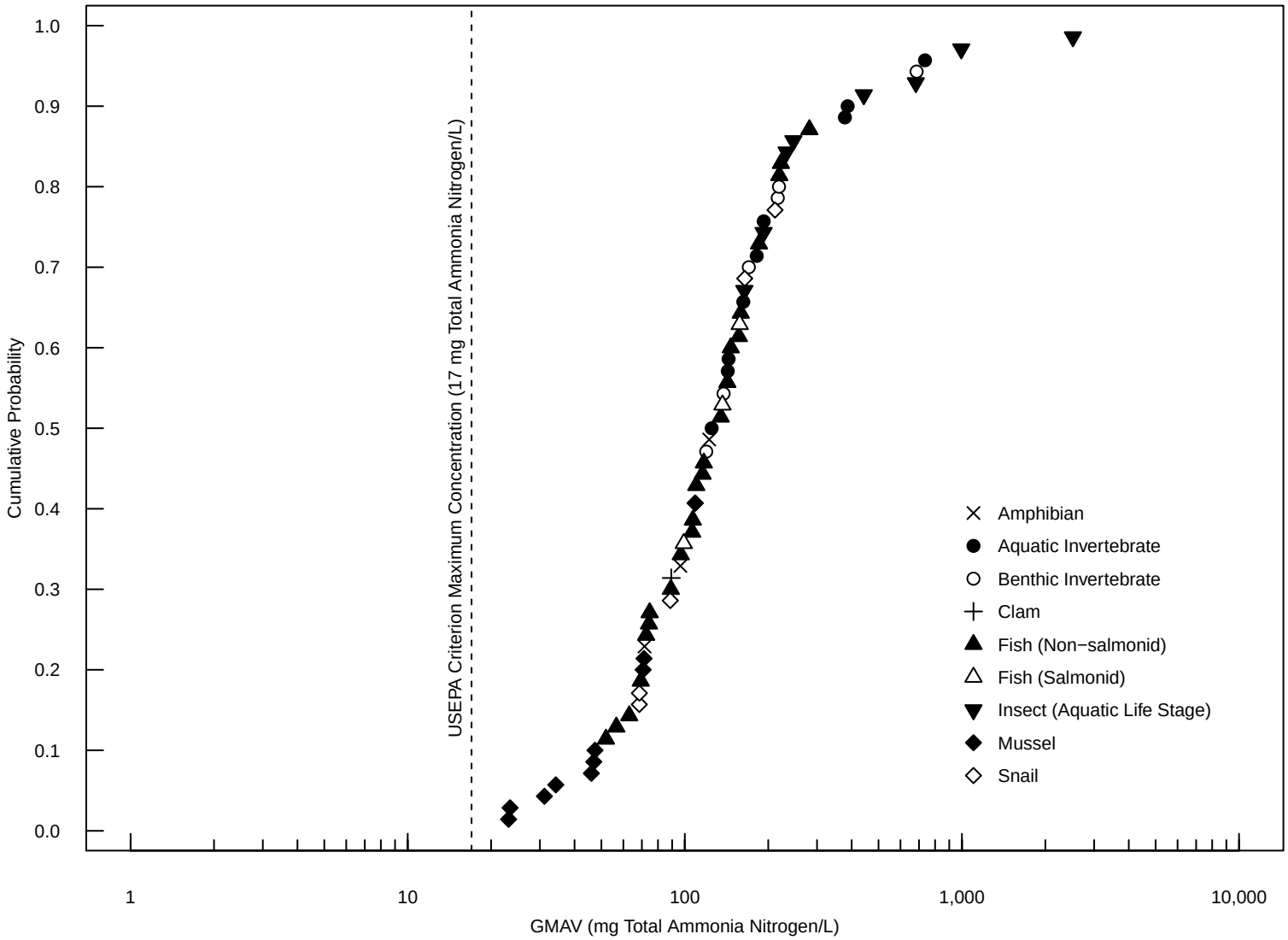


Figure A6.2. Distribution of Species Mean Acute Values (SMAVs) calculated from data used in the derivation of the nationally recommended acute water quality criterion for ammonia and additional data compiled from the scientific literature.

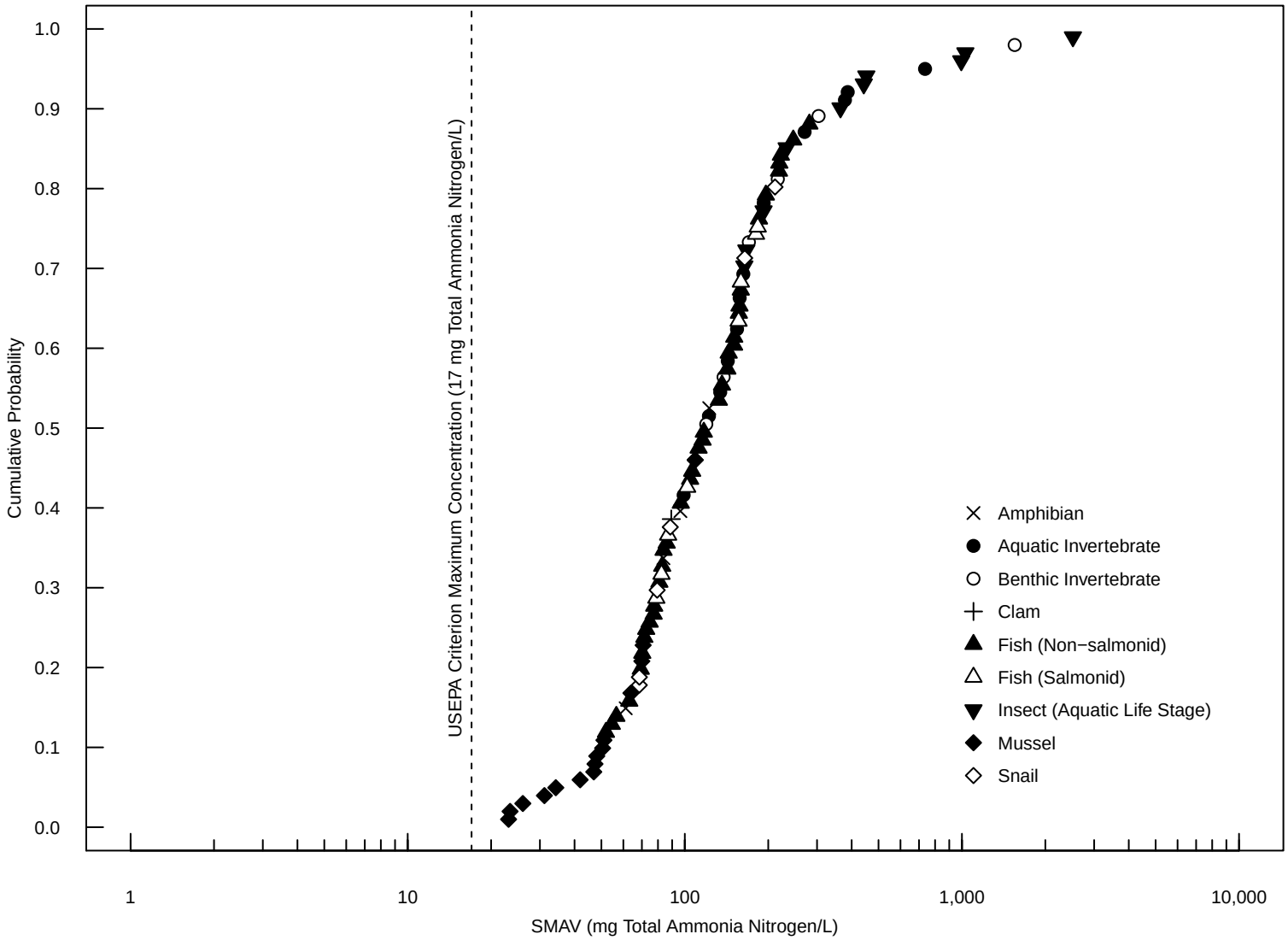


Figure A6.3. Distribution of normalized LC_{50} and EC_{50} values from individual toxicity tests used in the derivation of the nationally recommended acute water quality criterion for ammonia and additional data compiled from the scientific literature.

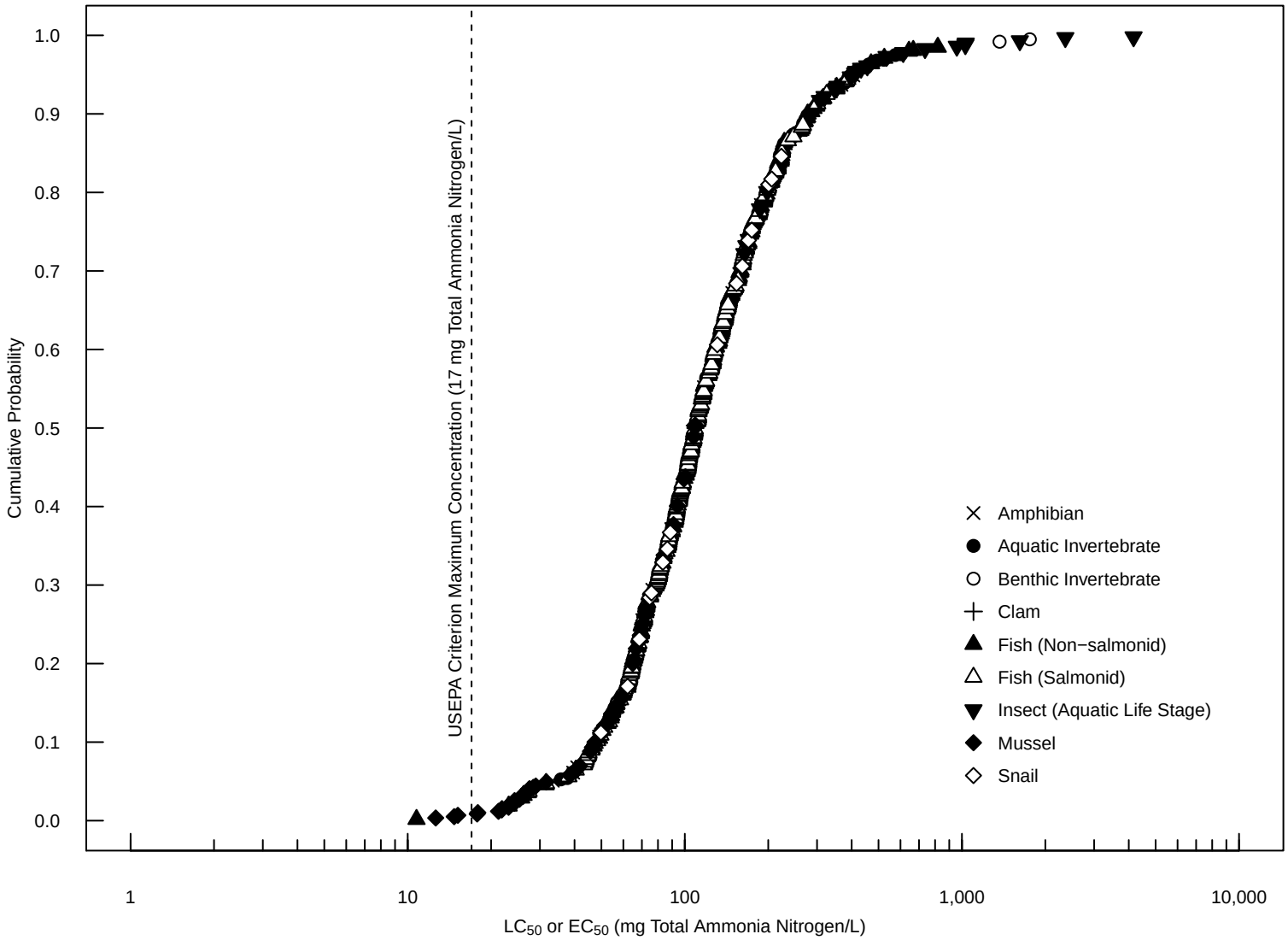


Figure A6.4. Distribution of Genus Mean Chronic Values (GMCVs) calculated from data used in the derivation of the nationally recommended chronic water quality criterion for ammonia and additional data compiled from the scientific literature.

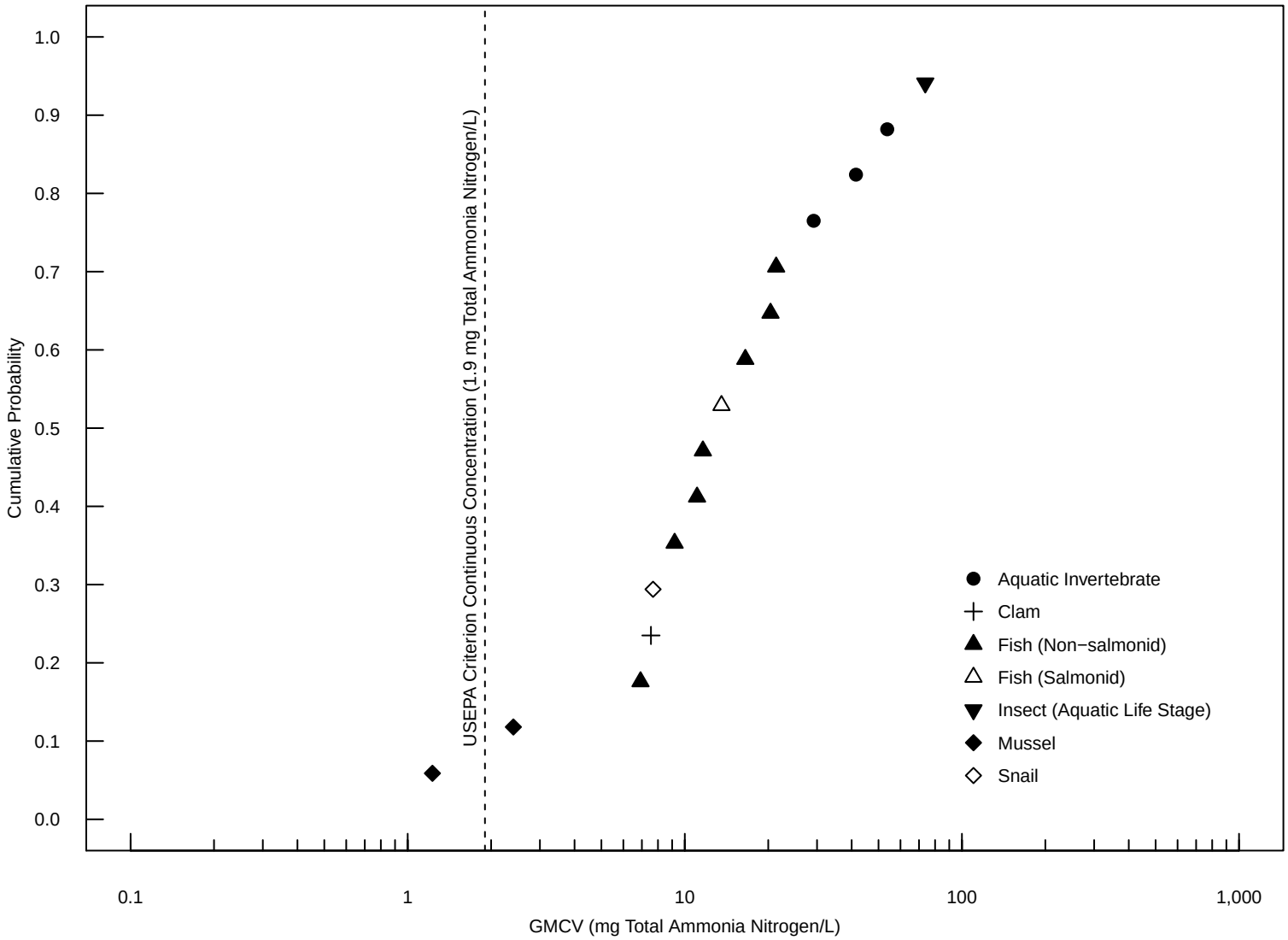


Figure A6.5. Distribution of Species Mean Chronic Values (SMCVs) calculated from data used in the derivation of the nationally recommended chronic water quality criterion for ammonia and additional data compiled from the scientific literature.

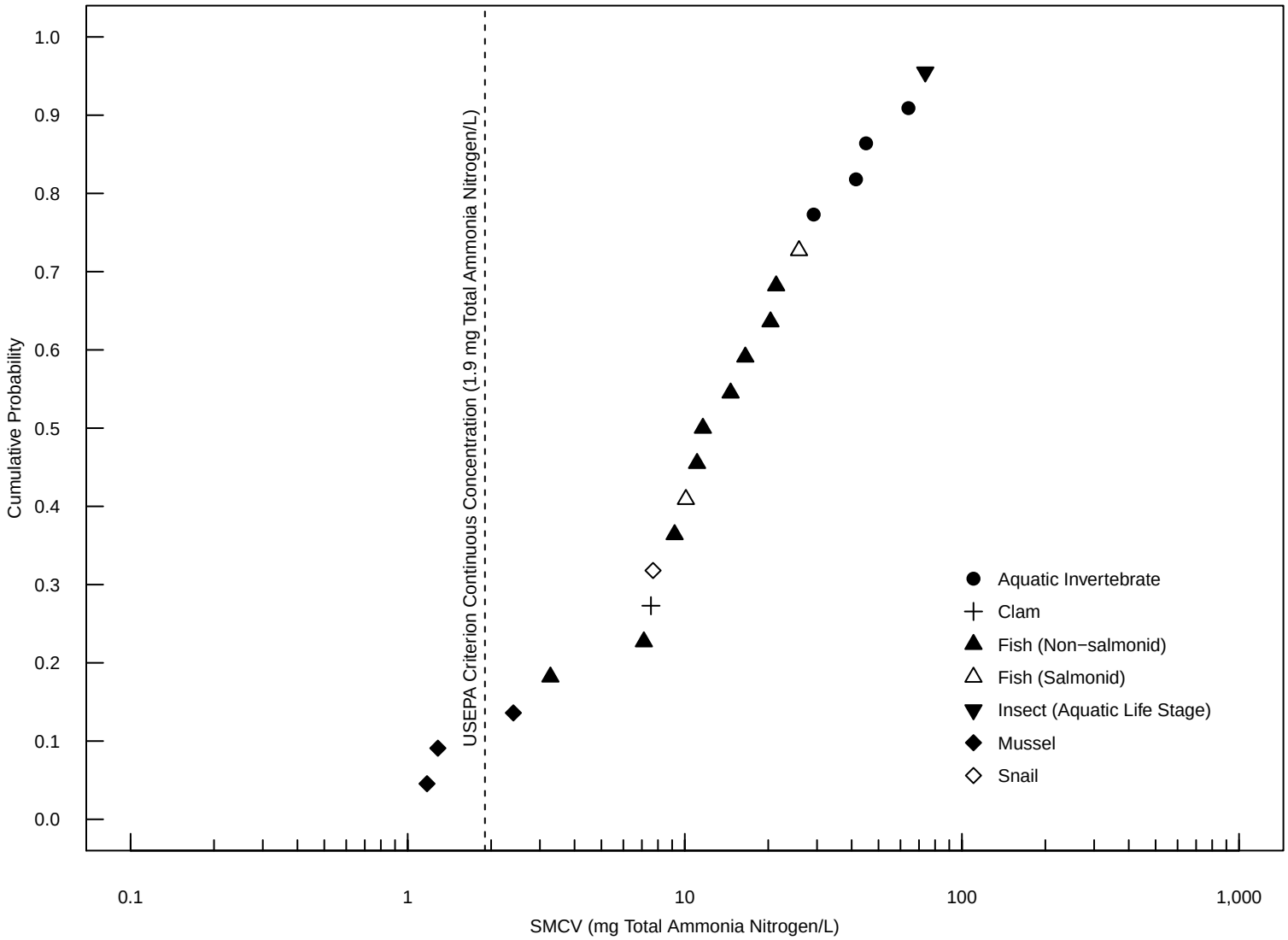


Figure A6.6. Distribution of normalized EC_{20} or similar effect levels from individual toxicity tests used in the derivation of the nationally recommended chronic water quality criterion for ammonia and additional data compiled from the scientific literature.

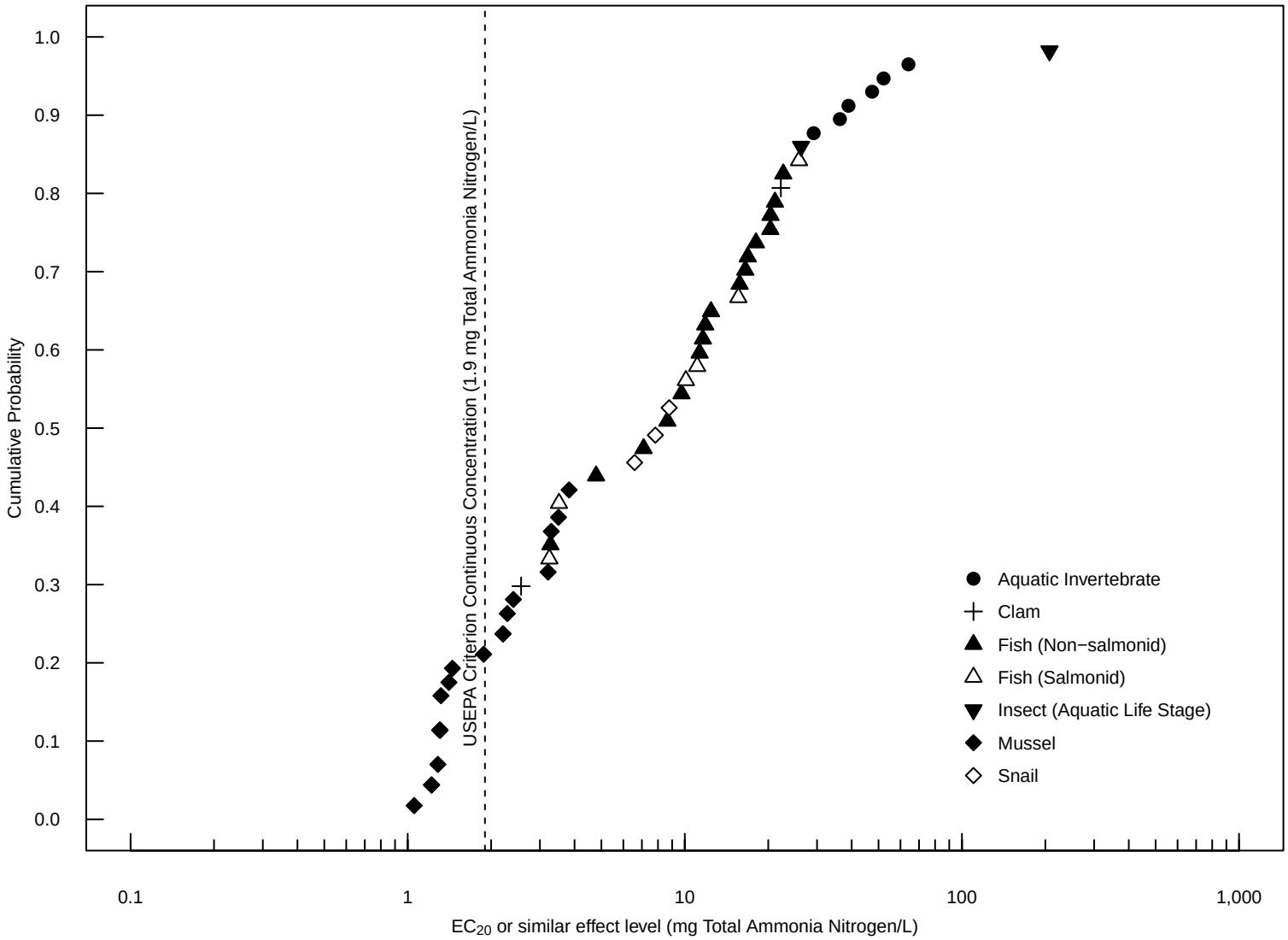


Figure A6.7. Distribution of Genus Mean Acute Values (GMAVs) calculated from data used in the derivation of the nationally recommended acute water quality criterion for cadmium and additional data compiled from the scientific literature.

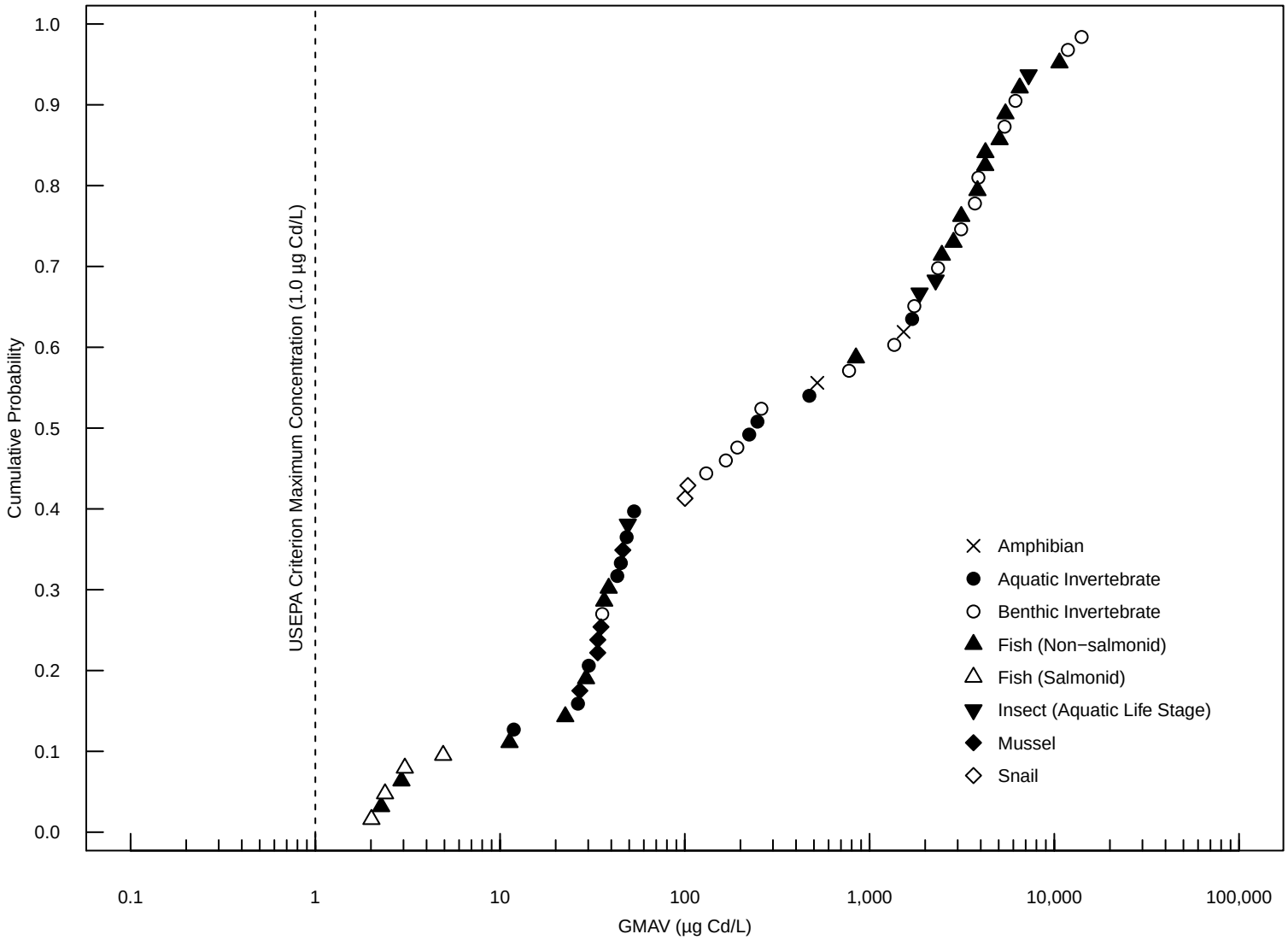


Figure A6.8. Distribution of Species Mean Acute Values (SMAVs) calculated from data used in the derivation of the nationally recommended acute water quality criterion for cadmium and additional data compiled from the scientific literature.

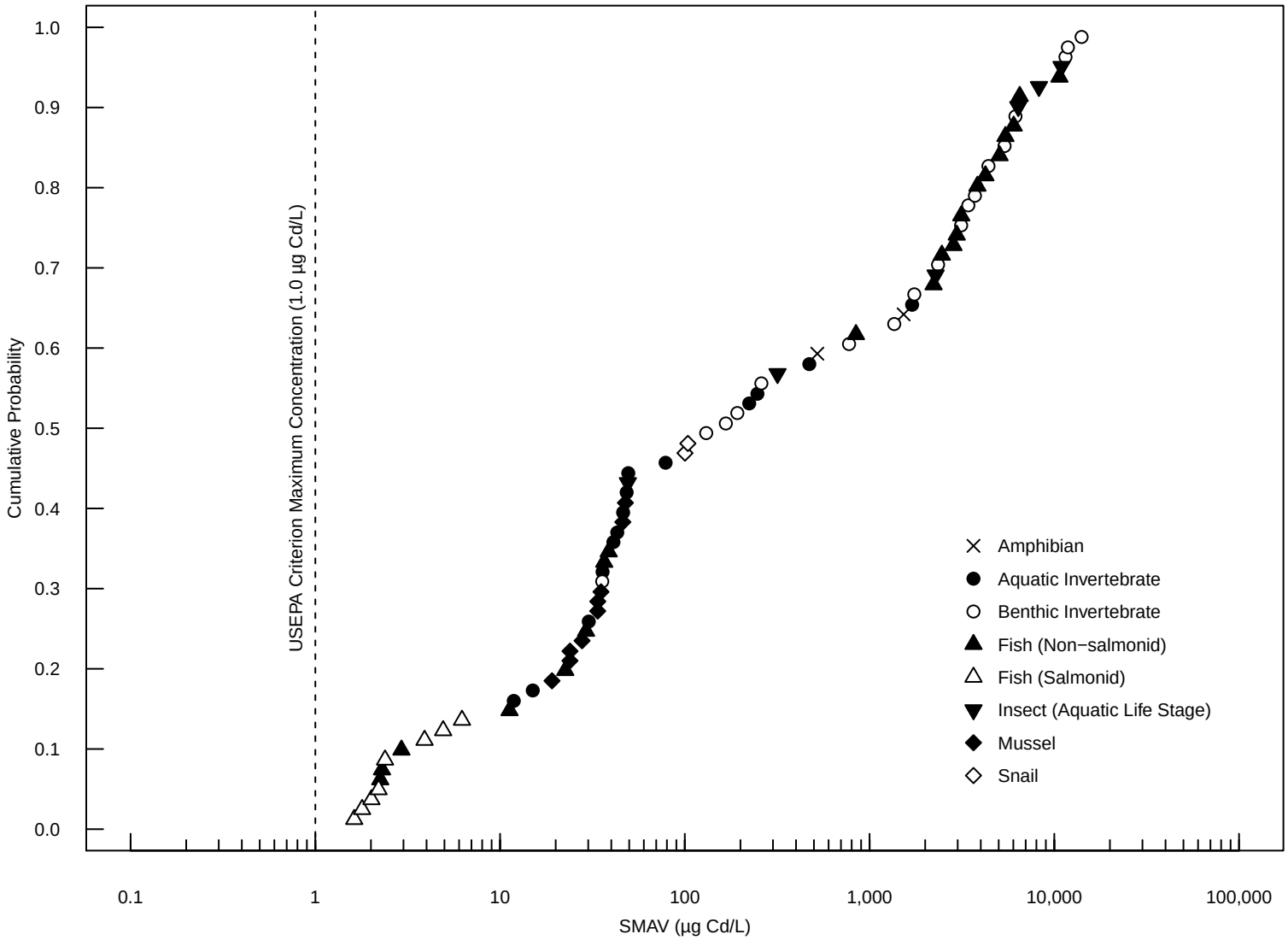


Figure A6.9. Distribution of normalized LC_{50} and EC_{50} values from individual toxicity tests used in the derivation of the nationally recommended acute water quality criterion for cadmium and additional data compiled from the scientific literature.

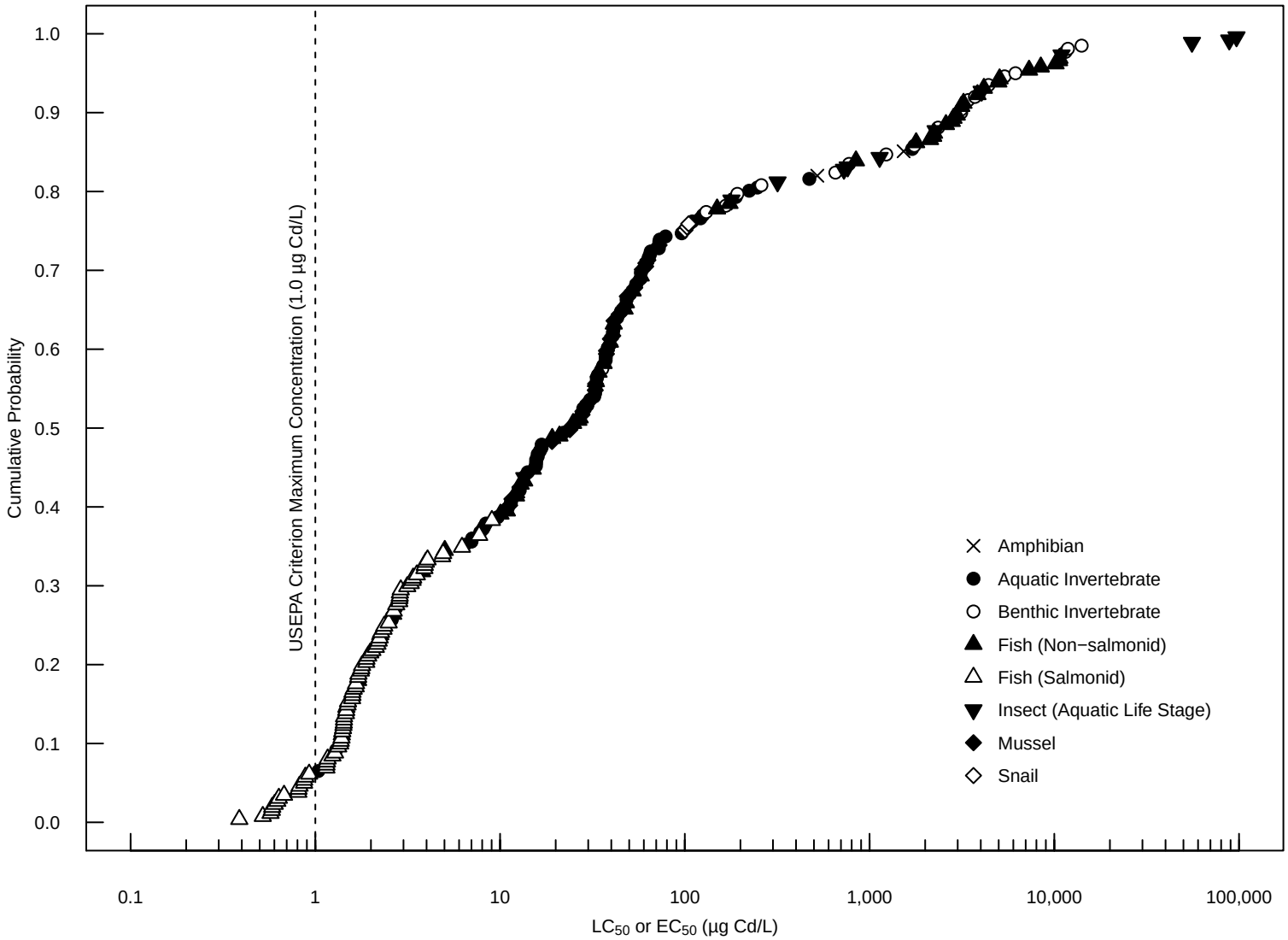


Figure A6.10. Distribution of Genus Mean Chronic Values (GMCVs) calculated from data used in the derivation of the nationally recommended chronic water quality criterion for cadmium and additional data compiled from the scientific literature.

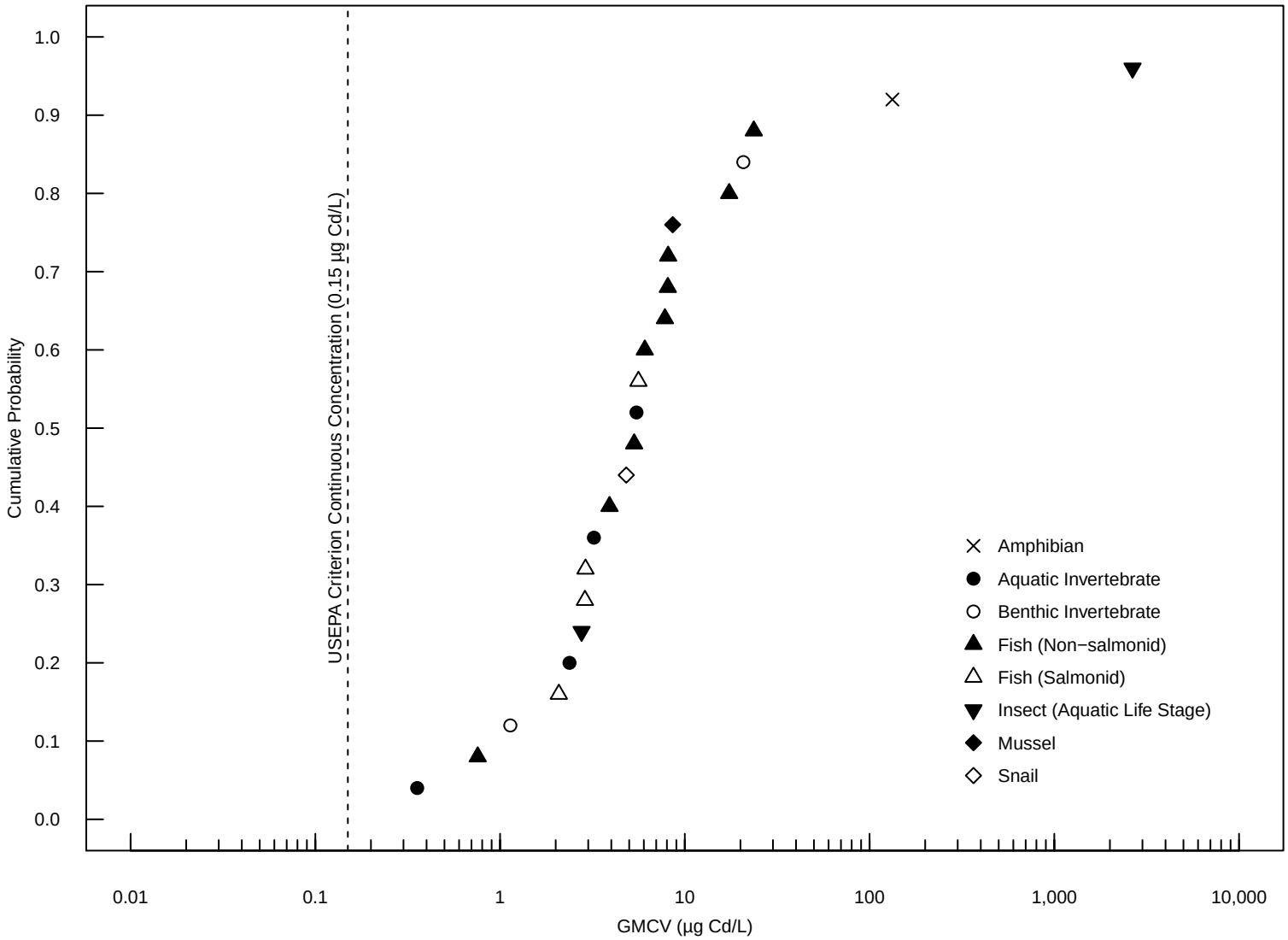


Figure A6.11. Distribution of Species Mean Chronic Values (SMCVs) calculated from data used in the derivation of the nationally recommended chronic water quality criterion for cadmium and additional data compiled from the scientific literature.

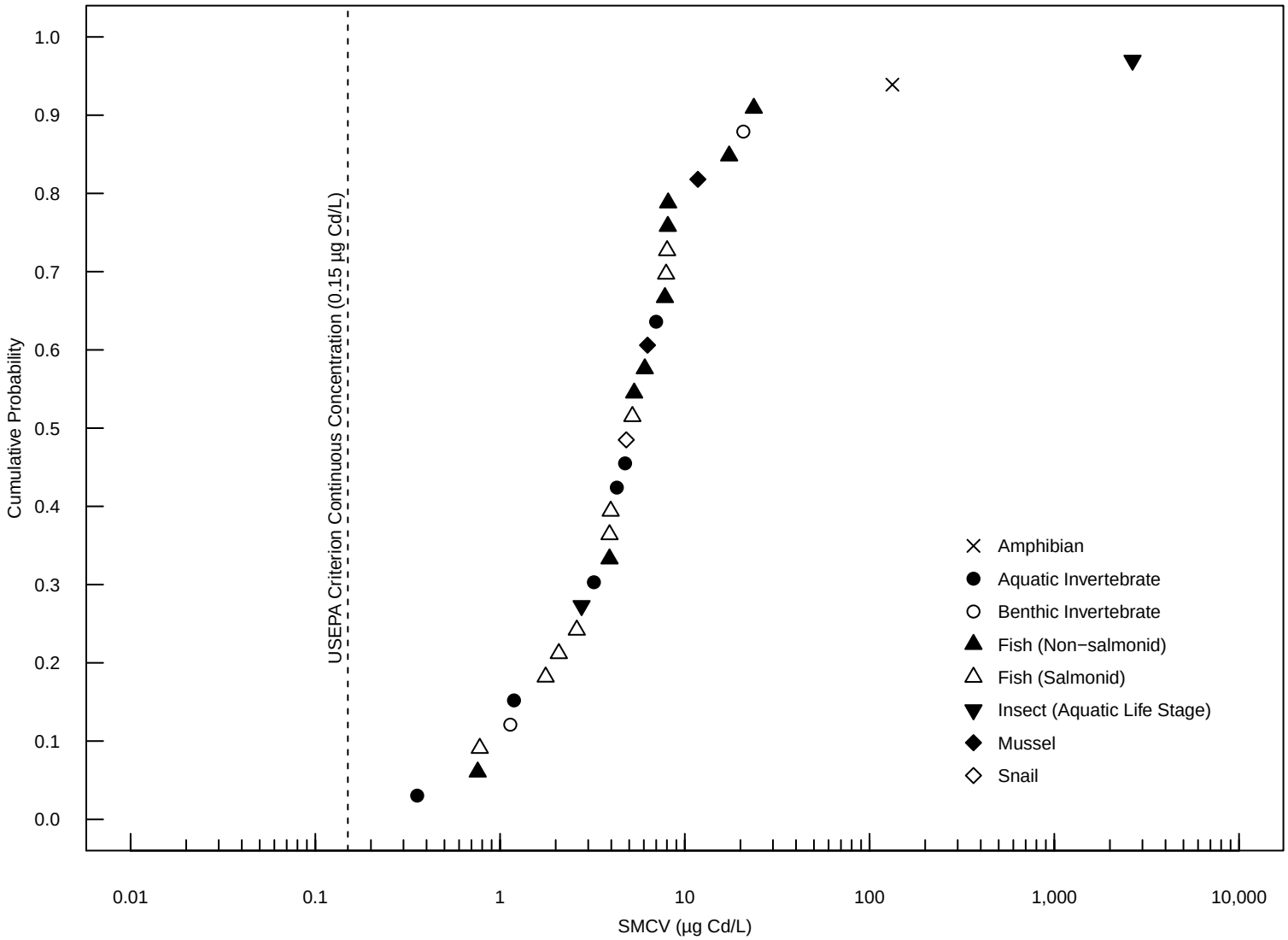
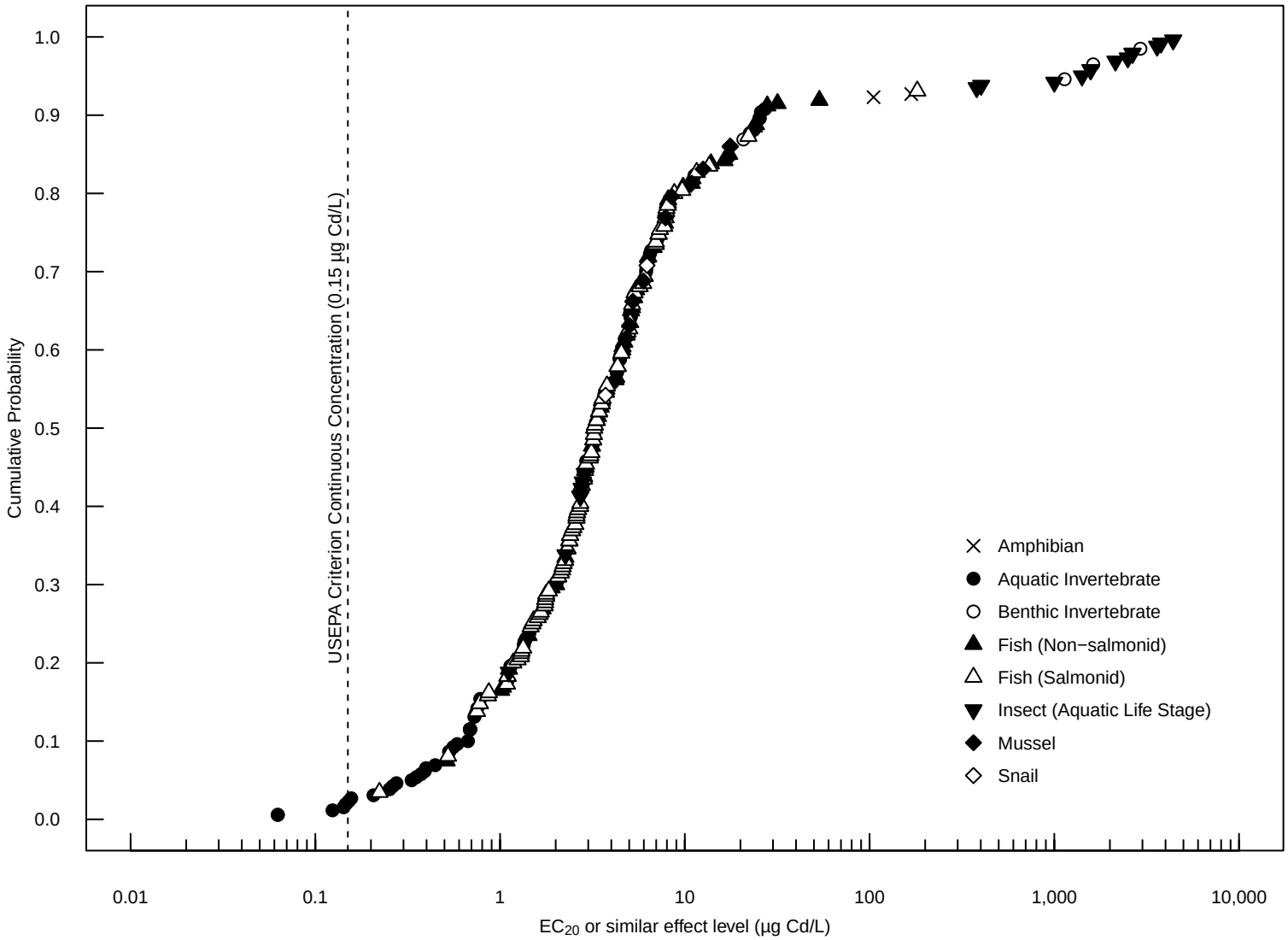


Figure A6.12. Distribution of normalized EC_{20} or similar effect levels from individual toxicity tests used in the derivation of the nationally recommended chronic water quality criterion for cadmium and additional data compiled from the scientific literature.



Appendix 7

Evaluation of Methods for Developing *de novo* Refuge-Specific Water Quality Targets for Ammonia for Sensitive Waters

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List of Acronyms

AWQC - ambient water quality criteria
BC - British Columbia
BCMOE - British Columbia Ministry of Environment
CCC - criterion continuous concentration
CCME - Canadian Council of Ministers of the Environment
CMC - criterion maximum concentration
DOI - Department of the Interior
EC_x - effective concentration affecting x% of the population
EPA - Environmental Protection Agency
FAV - final acute value
FCV - final chronic value
FWS - Fish and Wildlife Service
GMAV - genus mean acute value
GMCV - genus mean chronic value
IC_x - inhibitory concentration causing an x% inhibition in tested organisms
LC_x - lethal concentration affecting x% of the population
LOEC - lowest observed effect concentration
MATC - maximum acceptable toxicant concentration
NWR - National Wildlife Refuge
NWRS - National Wildlife Refuge System
NOEC - no observed effect concentration
RSWQT - refuge-specific water quality target
SMAV - species mean acute value
SMCV - species mean chronic value
SSD - species sensitivity distribution
TAN - total ammonia nitrogen
TRAP - Toxicity Relationship Analysis Program
WCS - water classification system
WQG - water quality guideline
WQS - water quality standard
WQT - water quality target

1.0 Introduction

The National Wildlife Refuge System (NWRS) is characterized by an abundance of freshwater habitats including a diversity of wetlands, streams, rivers, ponds, and lakes. Managing these diverse water resources represents a daunting challenge because each of these systems has unique characteristics that must be considered in decisions related to water resources management. In general, water quality management within the NWRS is focused on maintaining the highest possible quality of surface waters on each refuge. To assist refuge staff in attaining this goal, the Fish and Wildlife Service (FWS) has developed a water classification system (WCS) for the NWRS that provides a systematic basis for classifying receiving water bodies relative to their importance and sensitivity to disturbance. The three classes of surface waters defined by the WCS, and the associated narrative objectives that apply to each class of surface water, are described below:

- *Waters of Special Significance* - such waters meet the following characteristics:
    - Provide critical habitat for state or federally listed endangered species;
    - Support listed or endangered species with the potential for extinction;
    - Include habitats that support listed or endangered species through their entire life cycle;
    - Support aquatic-obligate listed or endangered species; or,
    - Include designated or proposed wilderness/natural areas.

  For these waters, a primary water management goal is to maintain and protect the quality of these special waters and the associated water uses (i.e., water quality conditions should not be degraded or impaired by human activities). Information on how to design baseline monitoring

programs in order to establish background conditions is provided in Appendix 5.

- *Sensitive Waters* - such waters support sensitive species or taxa of concern. For these waters, a primary water management goal is to protect all life stages of sensitive species or taxa of concern (which may include listed or endangered species with limited exposure to the water body of interest), as well as the occupied habitats upon which they depend, from adverse effects associated with exposure to a chemical or a chemical mixture for an indefinite period of time (i.e., entire life cycles). Ambient water quality criteria (AWQC) developed by the Environmental Protection Agency (EPA) may or may not offer the level of protection needed to protect sensitive species utilizing these waters (Appendix 6). This appendix (Appendix 7) describes in detail the rationale and methods for deriving refuge-specific water quality targets (RSWQTs) for Sensitive Waters.
- *Typical Waters* - such waters support other resources of concern. For these waters, a primary water management goal is to protect the designated uses of surface water resources, including protection of aquatic life and aquatic-dependent wildlife. An additional goal is the recovery of waters that have been degraded so that they are able to support designated uses, including the protection of aquatic life and aquatic-dependent wildlife.

Sensitive Waters support sensitive species or taxa of concern on National Wildlife Refuges (NWRs) and, thus, should be afforded enhanced protection (i.e., beyond the level of protection afforded by EPA AWQC, which are intended to protect 95% of tested aquatic species). The procedures for developing RSWQTs for Sensitive Waters are described in Section 5.2 of *Procedures for Deriving Refuge-Specific Water Quality Targets for the Protection of Natural Resources on National Wildlife Refuges.* In addition, preliminary RSWQTs are proposed for selected substances, determined by first compiling benchmarks from appropriate jurisdictions, and selecting the lowest benchmark for each substance. In some

cases (e.g., ammonia, cadmium), other ancillary information (e.g., pH, temperature, or water hardness) needs to be compiled in order to adjust the preliminary RSWQT to reflect site-specific conditions. However, if the preliminary RSWQT is not appropriate for the site (e.g., sensitive species may not be protected), generic benchmarks do not exist, or preliminary RSWQTs are not presented in Table 4 of the main report, then RSWQTs may be derived *de novo*, provided the requisite toxicity data are available.

The rationale for selecting the lowest of existing water quality benchmarks is explained in Section 2.0. Section 3.0 illustrates the recommended methods for developing *de novo* RSWQTs, with the goal of protecting sensitive species and/or taxa of concern on a NWR. Following this process will allow refuge staff, FWS Contaminants Specialists, and FWS Water Resource Branch staff to develop site-specific habitat management strategies to address water quality and quantity requirements for the NWR. While RSWQTs may be developed for any substance present on the NWR, the process described in this appendix is illustrated for ammonia.

2.0 Methods for Establishing Refuge-Specific Water Quality Targets for Sensitive Waters from Existing Water Quality Benchmarks

For waters of the NWRS that support sensitive species or taxa of concern (i.e., Sensitive Waters), the primary management goal is to protect all life stages of sensitive species and taxa of concern, and the occupied habitats upon which they depend, from adverse effects associated with exposure to a contaminant or a contaminant mixture for an indefinite period of exposure. As EPA AWQC may not be protective of sensitive species (see Appendix 6), alternate methods for defining suitable water quality conditions are warranted. Therefore, when developing RSWQTs for Sensitive Waters, water quality benchmarks from a variety of sources should be compiled, including, but not limited to, the EPA

AWQC, state water quality standards (WQSs) for the state in which the NWR is present, Canadian water quality guidelines (WQGs), and British Columbia (BC) WQGs. These benchmarks should be adjusted to account for site-specific water quality conditions if necessary (i.e., establish site-adapted water quality targets [WQTs]), using conservative estimates of the concentrations of the required ancillary water quality variables (e.g., using the 5th percentile for water hardness when deriving the site-adapted WQTs for certain metals). The lowest of these site-adapted WQTs should be selected as the preliminary RSWQT. Once the preliminary RSWQT has been selected, it should be compared to the background concentrations of the relevant substance in the NWR to ensure that it is applicable to the site. An evaluation of the sensitivity of the taxa of concern present on the NWR should be conducted to ensure that they are likely to be protected by the preliminary RSWQT. This step of the process is conducted by evaluating the toxicological data compiled during the derivation of the selected benchmark. The toxicological data are assessed to determine if the taxa of concern (or a closely related species) are present in the dataset. Next, the appropriate effects concentrations (i.e., IC_{10} [concentration causing a 10% inhibition in tested organisms]/EC_{10} [concentration affecting 10% of the population], or similar, for assessing chronic exposure, and LC_{50} [concentration lethal to 50% of the population], or similar, for assessing acute exposure) should be extracted. Subsequently, these values should be compared to the proposed RSWQT to determine if the RSWQT is expected to be protective of the species or taxa of concern. If the species of concern are not likely to be protected by the preliminary RSWQT, *de novo* RSWQTs for the NWR should be derived.

The process outlined recognizes that different methods are used for deriving water quality benchmarks within different jurisdictions (i.e., some are more protective of sensitive aquatic life than others). For example, the narrative intent of the Canadian WQGs is "to protect all forms of aquatic life and all aspects of the aquatic life cycles, including the most sensitive life stage of the most sensitive species over the long term, from the negative effects of anthropogenically altered environmental parameters (e.g., pH, temperature, and dissolved oxygen) or

exposures to substances via the water column" (CCME 2007). The Canadian Council of Ministers of the Environment (CCME) uses two approaches for deriving WQGs: Type A and Type B (CCME 2007). The distinction between these approaches depends on the adequacy of the available toxicity data. Type A long-term guidelines are based on statistical distributions (i.e., species sensitivity distribution [SSD]) of the available toxicity data that meet the acceptability requirements (CCME 2007). Each species is represented by only one point in the SSD, with the most sensitive effect/endpoint combination for a species, preferably a no-effect value, selected for inclusion in the SSD. If there is more than one comparable record for a life history stage and set of test conditions, the geometric mean of the effect concentrations is calculated and included in the SSD. If there are inadequate or insufficient toxicity data to model an SSD, yet the minimum number of toxicity studies are met, Type B guidelines should be derived (CCME 2007). For deriving either type of guideline, available toxicity data for a substance are first classified as primary, secondary, or unacceptable based on criteria that assess the reliability, suitability, and usefulness of the data. Primary studies are preferred, but secondary studies can also be used in the derivation of WQGs (CCME 2007).

Although CCME (2007) states that the WQGs are meant to protect the most sensitive life stage of the most sensitive species over the long term, the Type A guideline is defined as the estimated concentration corresponding to the 5th percentile of the evaluated species (based on the fitted SSD; CCME 2007). Therefore, by definition 5% of the species represented in the SSD may not be protected by the WQG. CCME (2007) acknowledges this issue, and attempts to compensate for it by including a *protection clause*. The *protection clause* can be invoked when there is a compelling reason to believe that the Type A long-term exposure guideline is not protecting all life stages of all species of aquatic life over an indefinite exposure period. For example, if a no-effect or low-effect endpoint for a species at risk is lower than the intercept of the 5th percentile to the fitted curve of the SSD, then that endpoint should become the WQG. If the endpoint is a lethality endpoint (LC_x) or has an effect level greater than 50% (i.e.,

EC_x or IC_x where x > 50), then a safety factor should be applied to the value to derive an appropriate guideline (CCME 2007). In addition, if there is an estimated LC_x where x > 15 for any species that falls below the proposed Type A guideline, then that value should become the recommended WQG (CCME 2007). Nonetheless, the *protection clause* does not protect ordinary species (i.e., species not listed as at risk) that have EC_x/IC_x values below the intercept of the 5th percentile to the fitted curve of the SSD. The minimum data requirements for Type A guidelines (see CCME [2007] for additional information) are:

- Three fish species, including at least one salmonid and one non-salmonid species;
- Three aquatic or semi-aquatic invertebrates (e.g., insects with an aquatic life stage), at least one of which must be a planktonic crustacean. For semi-aquatic invertebrates, the life stages tested must be aquatic; and,
- At least one study on a freshwater vascular plant or freshwater algal species (required for long-term guidelines, highly desirable but not necessary for short-term guidelines; CCME 2007).

When the minimum data requirements needed to derive a Type A guideline are not met, a Type B1 or B2 guideline should be derived. Type B1 and B2 guidelines follow the lowest endpoint derivation approach. A minimum number (i.e., same required data as the Type A procedure) of primary toxicity studies conducted with fish, invertebrates and plants is required to develop a Type B1 guideline (CCME 2007). From the available primary toxicity data, the lowest acceptable endpoint from a long-term exposure is used as the basis for the long-term guideline, while the lowest acceptable LC_{50} or equivalent from a short-term toxicity test is used as the basis for the short-term guideline. Both of these values are divided by a safety factor of 10 to obtain the recommended long-term and short-term guidelines, respectively (CCME 2007). By dividing the lowest acceptable toxicity endpoint by a safety factor, the Type B1 method should protect

the most sensitive species for which data are available. However, this method is only used when the Type A procedures cannot be used (CCME 2007).

If there are not enough primary data then a Type B2 guideline can be derived. The minimum data requirements can be met with primary and/or secondary data when deriving a Type B2 guideline and are:

- Two fish species, including at least one salmonid and one non-salmonid; and,
- Two aquatic or semi-aquatic invertebrates (e.g., insects with an aquatic life stage), at least one of which must be a planktonic crustacean. For semi-aquatic invertebrates, the life stages tested must be aquatic (CCME 2007).

The Type B2 guideline follows the same methodology as the Type B1 guideline, except either primary or secondary data can be selected as the lowest acceptable endpoint. As for a Type B1 guideline, a Type B2 short-term guideline is derived by dividing the lowest acceptable LC_{50} or equivalent from a short-term exposure by a safety factor of 10 (CCME 2007). The safety factors used to derive the guidelines attempt to account for uncertainty in the data, but a Type B2 guideline is, by design, the least reliable type of the CCME guidelines because it is based on a small number of acceptable quality studies.

While CCME WQGs are based on the lowest endpoint derivation approach only when a limited amount of acceptable data are available, the British Columbia Ministry of Environment (BCMOE) uses this type of approach as the default method when there is a robust set of good quality data (BCMOE 2012). Therefore, BCMOE WQGs are likely more conservative relative to CCME WQGs derived using an SSD. The BCMOE derives WQGs using a science-based approach that is intended to protect all forms of aquatic life and all aquatic stages of their life cycle during indefinite exposure (BCMOE 2012).

A minimum number of primary quality studies including fish, invertebrates, and plants is required to derive a BCMOE WQG:

- Three studies on three or more freshwater fish species resident in BC, including at least two cold-water species (e.g., trout);
- Two studies on two or more invertebrate species from different classes, one of which includes a planktonic species resident in BC (e.g., daphnid); and,
- One study on a freshwater vascular plant or freshwater algal species resident in BC (BCMOE 2012).

If limited data are available (meeting appropriate data requirements) then interim WQGs can be derived. From the primary studies, the lowest reliable low-effects threshold EC_x from a long-term study is selected as the basis of the long-term average WQG, while the lowest reliable LC_{50} or EC_{50} from a short-term test is selected as the basis for the short-term maximum WQG (BCMOE 2012). An appropriate uncertainty (i.e., safety) factor is then applied to the lowest reliable value to derive the long-term and short-term WQGs, respectively. An uncertainty factor between two and ten is generally used, and is decided on a case-by-case basis using scientific judgment (BCMOE 2012). The magnitude of the uncertainty factor depends on the quantity of the toxicity data (e.g., tests conducted with sensitive species, measuring multiple endpoints and effects), the quality of the toxicity data (e.g., met test acceptability criteria, measured concentrations at multiple times during the test), the severity of toxic effects, and the toxicity and bioaccumulation potential of the contaminant. The uncertainty factor helps to compensate for many sources of uncertainty, including differences in toxicity among species, between field and laboratory conditions, between life-cycle stages, and due to exposure to multiple chemicals at one time (BCMOE 2012). The order of preferred endpoints for deriving a long-term BCMOE guideline is the same as for CCME (2007) Type B1 and B2 guidelines and is as follows: most appropriate EC_x/IC_x representing a low-effects threshold >

EC_{15-25}/IC_{15-25} > lowest observed effect concentration (LOEC) > maximum acceptable toxicant concentration (MATC; also known as a chronic value) > EC_{26-49}/IC_{26-49} > non-lethal EC_{50}/IC_{50} > LC_{50} (BCMOE 2012). Regression-based toxicity estimates (e.g., EC_x) are preferred to hypothesis-based toxicity values (e.g., LOEC; BCMOE 2012). There are circumstances where it is not possible to derive a long-term and a short-term guideline due to the available data and the nature of the toxicity of the substance. See BCMOE (2012) for more details on the derivation of guidelines in these cases.

In summary, the derivation method influences the protectiveness of the resulting water quality benchmark. Therefore, compiling EPA AWQC, WQSs, and WQGs from multiple jurisdictions and selecting the lowest value as a RSWQT will likely result in a RSWQT that is more protective than if only EPA AWQC are considered. If the lowest of the available EPA AWQC, WQSs, and WQGs is not expected to be protective of sensitive species or taxa of concern on the NWR, then a *de novo* RSWQT should be derived for the NWR.

3.0 Evaluation of Methods for Deriving *de novo* Refuge-Specific Water Quality Targets

Candidate methods for deriving *de novo* RSWQTs for Sensitive Waters were evaluated by conducting an in-depth exploration of toxicity data from ammonia exposures. Ammonia was chosen as an example to illustrate the process for deriving *de novo* RSWQTs. This same process can be followed for other contaminants of interest to refuge staff. A step-wise approach was used to compile and evaluate the data from acute and chronic toxicity tests that were used to derive EPA AWQC for ammonia, data that were not used in the criteria derivation process, and more recent data that were developed from studies conducted after the criteria were derived. These steps included:

- Identification, acquisition, and screening of candidate datasets;

- Development of a relational project database;
- Verification and auditing of the project database;
- Calculation of genus mean acute values (GMAVs), species mean acute values (SMAVs), genus mean chronic values (GMCVs), and species mean chronic values (SMCVs); and,
- Evaluation of candidate methods for deriving RSWQTs.

Each of these steps is described in the following sections of this appendix.

3.1 Identification, Acquisition, and Screening of Candidate Datasets

Relevant data were compiled from acute and chronic toxicity tests with ammonia which meet the criteria for use in development of EPA AWQC (see Stephan *et al.* 1985). The toxicity data used in the development of the EPA AWQC for ammonia (USEPA 2013) became the primary dataset used for evaluating candidate procedures for deriving RSWQTs. Since the most recent version of the EPA AWQC for ammonia was published just prior to this review, an extensive search for additional ammonia toxicity data was not conducted to support this evaluation. Rather, key researchers in the field were asked to identify datasets that were not included in USEPA (2013). Because studies conducted in recent years have highlighted the sensitivity of mollusks to the toxic effects of ammonia (USEPA 2013), data acquisition focused on studies involving mussels and snails. In addition, some studies that were included in the AWQC report (i.e., USEPA 2013) were reviewed to determine if additional data (e.g., test results from more sensitive endpoints) could be used in the evaluation of the criteria. Additional data were obtained from Wang *et al.* (2007a; 2011), Miao *et al.* (2010), and Besser *et al.* (2013). The data presented in Besser *et al.* (2013) were not included in the 2013 criteria document; however, a subset of the toxicity data from Wang *et al.* (2007a, 2011) and Miao (2010) were included in the dataset used to derive

the EPA AWQC. The other data added from those studies included additional endpoints (e.g., growth data) and effects concentrations (e.g., IC_{25}) during chronic exposure. These additional data were combined with the data used in USEPA (2013) to form the *recalculation dataset* (i.e., the dataset used to recalculate species and genus mean values).

All of the candidate datasets that were identified were acquired electronically (i.e., through email or downloaded from a website). An evaluation of each candidate dataset was conducted to determine if it included the data required to support the evaluation. All relevant toxicity data (e.g., LC_{50}, EC_{20}, IC_{20}, SMAVs, and GMCVs) were compiled in the project database.

3.2 Data Compilation and Database Audit

Development of a project database represents an essential element of the data analysis process. Accordingly, the datasets that contained relevant toxicity data were incorporated into a relational database in MS Access format. To support this evaluation, three distinct datasets were created: the *USEPA (2013) dataset*, a *recalculation dataset* and an *evaluation dataset*. Toxicity data used in the 2013 update of the freshwater aquatic life EPA AWQC for ammonia were obtained from the final criteria report (USEPA 2013). All the data used in the calculation of SMAVs and SMCVs in the USEPA (2013) criteria document were considered the *USEPA (2013) dataset*. This dataset was supplemented in the database with toxicity results for different endpoints than those used in the EPA AWQC from the following studies: Wang *et al.* (2007a; 2011) and Miao *et al.* (2010). In addition, the results of toxicity tests from Besser *et al.* (2013; conducted after the EPA criteria were derived) were incorporated into the project database. Data from these four studies and the data used in USEPA (2013) formed the *recalculation dataset* and were used to recalculate species and genus means by following the methods outlined in Stephan *et al.* (1985) and the EPA AWQC report (USEPA 2013). Additional data not typically used in the derivation of AWQC were added to the *recalculation dataset* to form the *evaluation dataset*.

For example, acceptable static-renewal tests and flow-through tests that reported nominal concentrations that USEPA had excluded from mean value calculations (because flow-through tests with measured concentrations were available for the same species) were included in the *evaluation dataset*. All data underwent a series of quality assurance checks to ensure that the relevant information was compiled accurately. The information obtained from each dataset included test duration, species, life history stage, effect concentrations, endpoints, experimental design, and the ancillary parameters (i.e., water temperature and pH for ammonia) needed to normalize the effect concentrations from tests conducted under different water quality or laboratory conditions.

An audit of the project database was conducted to ensure that the underlying data were accurate and complete for use in the assessment. Following translation into the database, the data were verified to ensure that any potential translation errors had not occurred. Data verification involved an initial confirmation of data in the database against the original source. Auditing involved 10% number-for-number checks against the original source, increasing to 100% number-for-number checks if significant errors were detected in the initial auditing step. Similarly, a 100% number-for-number check was conducted on all datasets that were translated manually. Additional steps that were taken to verify the accuracy of the database included cross-checking the expected number of samples in the database against the original source, and checking consistency of units and chemical form (e.g., ammonia as nitrogen). The results of the data verification and auditing procedures indicated that the compiled information represented a reliable basis for evaluating the methods for deriving RSWQTs relative to the protection of Department of the Interior (DOI) priority resources of concern on NWRs. Additional information on the data compiled for this evaluation is presented in Appendix 6.

3.3 Normalization of Additional Toxicity Data

When there are factors (i.e., physical or chemical properties in the water) known to modify the toxicity of a substance, these factors must be taken into account before comparisons between the results of various studies can be made. Therefore, additional data were normalized to the same standard conditions as were the data used in the derivation of the EPA AWQC (USEPA 2013). For ammonia, temperature and pH are the primary factors known to modify toxicity. Prior to incorporating additional data into the project database, each new dataset was reviewed to determine if the effect concentrations had been normalized (i.e., adjusted to standard conditions of water temperature and pH). The *USEPA (2013) dataset* presented toxic effect concentrations as total ammonia nitrogen (TAN), normalized to pH 7.0 (for all species) and 20°C (for invertebrate species only). Therefore, the additional ammonia data compiled for this evaluation (from Wang *et al.* 2007a; 2011; Miao *et al.* 2010; Besser *et al.* 2013), which included only invertebrate species, were normalized to pH 7.0 according to the method outlined in USEPA (2013). All tests were performed at 20°C and results were reported as TAN.

3.4 Calculation of Genus and Species Mean Values

Genus and species mean values were recalculated using the *recalculation dataset* according to the methodology provided in Stephan *et al.* (1985) and USEPA (2013), except that no unbounded values (i.e., results reported as less- or greater-than values) were included, unless it was the only value available for a species or genus. Briefly, species mean values (i.e., SMAVs and SMCVs) were calculated by taking the geometric mean of acceptable effect values for a given species. Genus mean values (i.e., GMAVs and GMCVs) were calculated by taking the geometric mean of all SMAVs or SMCVs within a particular genus. For data from acute exposures, recalculated values included the SMAV for fatmucket mussel (*Lampsilis siliquoidea*), the GMAV for *Lampsilis*, and the SMAV/GMAV for the pebblesnail (*Fluminicola* sp.). For the chronic exposure

dataset, SMCVs for the wavy-rayed lampmussel (*Lampsilis fasciola*) and fatmucket were calculated. As a result, the GMCV for *Lampsilis* was recalculated; new SMCVs/GMCVs were also calculated for rainbow mussel (*Villosa iris*) and pebblesnail. While no new data were included for rainbow trout (*Oncorhynchus mykiss*), a new SMCV was calculated for this species, and subsequently the genus (*Oncorhynchus*), due to the exclusion of unbounded values (i.e., less- or greater-than values) from the *USEPA (2013) dataset*.

Additional data for evaluation of the candidate methods for deriving RSWQTs were added to the data used in the recalculation of species and genus mean values (i.e., forming the *evaluation dataset*). This dataset included data that USEPA (2013) had excluded from SMAV/SMCV calculations but that still met data acceptability requirements (i.e., static-renewal tests with measured concentrations or flow-through tests with nominal concentrations). These data were used in the evaluation of the EPA AWQC and candidate RSWQTs but were not used to recalculate mean values (data were from Blahm 1978; Calamari *et al.* 1981; Reinbold and Pescitelli 1982; Bader and Grizzle 1992; Diamond *et al.* 1993; Hickey and Vickers 1994; Buhl 2002; Wang *et al.* 2007b). These data were excluded from mean value calculations in USEPA (2013) because flow-through tests with measured concentrations were available for the same species as were tested in these exposures (Stephan *et al.* 1985). The *evaluation dataset* also included multiple endpoints and effect concentrations from Wang *et al.* (2007a; 2011), Miao *et al.* (2010), and Besser *et al.* (2013) that were not all included in the *recalculation dataset*.

3.5 Evaluation of Candidate Methods for Deriving *de novo* Numerical Refuge-Specific Water Quality Targets

For waters of the NWRS that support sensitive species or taxa of concern, the primary water management goal is to protect all life stages of sensitive species or taxa of concern, as well as the occupied habitats upon which they depend, from adverse effects associated with indefinite exposure to a chemical or a chemical

mixture. To that end, refuge staff, FWS Contaminants Specialists, and FWS Water Resource Branch staff require consistent procedures for establishing RSWQTs that will provide a basis for protecting essential biological resources. To facilitate the development of guidance for deriving *de novo* numerical RSWQTs, four candidate methods of deriving numerical RSWQTs were evaluated. The numerical RSWQTs described below were all developed using data compiled for the derivation of EPA AWQC as well as additional data on sensitive species, taxa of concern, and additional endpoints that were not considered in the derivation of the EPA AWQC (as described in Sections 3.1 and 3.2). The four methods included:

- Genus Mean Value 5th Percentile Approach: calculation of numerical RSWQTs using methods similar to Stephan *et al.* (1985) using the GMAVs/GMCVs calculated from the *recalculation dataset*;
- Species Mean Value 5th Percentile Approach: calculation of numerical RSWQTs using methods similar to Stephan *et al.* (1985) using the SMAVs/SMCVs calculated from the *USEPA (2013) dataset* and the *recalculation dataset*;
- Toxicity Test 5th Percentile Approach: calculation of numerical RSWQTs using methods similar to Stephan *et al*. (1985) using the results of individual toxicity tests from the *USEPA (2013) dataset* and the *recalculation dataset*; and,
- Modified BCMOE WQG Approach: calculation of numerical RSWQTs using methods described in BCMOE (2012) using the results of individual toxicity tests from the *USEPA (2013) dataset* and the *recalculation dataset*.

Again, the *USEPA (2013) dataset* included only the data that were used to derive the USEPA (2013) AWQC for ammonia. By comparison, the *recalculation dataset* included some additional data from Wang *et al.* (2007a; 2011), Miao *et al.* (2010), and Besser *et al.* (2013), as well as data in the *USEPA (2013) dataset*. The four methods outlined above are described in detail in the following sections.

3.5.1 Genus Mean Value 5th Percentile Approach

Using the *recalculation dataset*, the acute RSWQT was calculated using the methods described in USEPA (2013; described in Appendix 6). The recalculated GMAVs were ordered and ranked from lowest to highest, and the four GMAVs closest to the 5th percentile were used to calculate the final acute value (FAV; calculation described in Addendum 1 and Stephan *et al.* [1985]). The FAV was divided by two to obtain an acute RSWQT for ammonia.

Similarly, the chronic RSWQT was calculated using the methods described in USEPA (2013; described in detail in Appendix 6). The recalculated GMCVs were ordered and ranked from lowest to highest, and the four GMCVs closest to the 5th percentile were used in the calculation of the final chronic value (FCV), following the example in Addendum 1 (from Appendix 2 of Stephan *et al.* [1985]). The FCV was adopted directly as the chronic RSWQT.

3.5.2 Species Mean Value 5th Percentile Approach

The acute RSWQT was calculated using the same methods described in USEPA (2013; described in Appendix 6), with the exception that the SMAVs replaced the GMAVs. The SMAVs were ordered and ranked from lowest to highest, and the four SMAVs closest to the 5th percentile of the mean values were used in the calculation of the FAV (Addendum 1; Stephan *et al.* 1985). The FAV was divided by two to obtain the acute RSWQT. This procedure was followed using the *USEPA (2013) dataset* and the *recalculation dataset*.

Similarly, the chronic RSWQT was calculated using SMCVs instead of GMCVs. The SMCVs were ordered and ranked from lowest to highest, and the four SMCVs closest to the 5th percentile of the data were used in the calculation of the FCV (Addendum 1; Stephan *et al.* 1985). The FCV was adopted directly as the chronic RSWQT. This procedure was followed using the *USEPA (2013) dataset* and the *recalculation dataset*.

3.5.3 Toxicity Test 5th Percentile Approach

This approach followed the methods described in USEPA (2013; also described in Appendix 6), but instead of using GMAVs and GMCVs, the results of individual toxicity tests were used directly to derive the acute and chronic RSWQTs. A total of 568 acute toxicity test results (LC_{50}s or EC_{50}s), used to calculate SMAVs in USEPA (2013), were ordered and ranked from lowest to highest, and the four test results closest to the 5th percentile were used in the calculation of the FAV (Addendum 1; Stephan *et al.* 1985). The FAV was divided by two to obtain the acute RSWQT. With the additional data from Miao *et al.* (2010) and Besser *et al.* (2013; i.e., the *recalculation dataset*), an alternative RSWQT was calculated using the same procedures.

Similarly, 37 results from chronic toxicity tests (EC_{20} values) used to calculate SMCVs in USEPA (2013) were ordered and ranked from lowest to highest, and the four results closest to the 5th percentile were used in the calculation of the FCV (Addendum 1; Stephan *et al.* 1985). The FCV was adopted directly as the chronic RSWQT. Using the *recalculation dataset*, 38 EC_{20} (or similar) estimates were ranked (only the result from the most sensitive biological endpoint from a particular test was included if one test reported results for multiple endpoints), and the chronic RSWQT was derived using the same procedures.

3.5.4 Modified British Columbia Ministry of Environment Water Quality Guideline Approach

WQGs for the protection of aquatic life in BC are derived by compiling a robust dataset of low-effect concentrations generated from toxicity tests that meet screening criteria. Specifically, the BCMOE compiles toxicity test data meeting the minimum requirements outlined in BCMOE (2012) and bases the WQG on the lowest effect value from an acceptable (i.e., primary) study. The lowest reliable LC_{50} or EC_{50} from an acute toxicity test forms the basis of the short-term WQG, while the lowest reliable EC_x or IC_x representing a low-effects threshold from a chronic toxicity test forms the basis of the long-term WQG (BCMOE

2012). These values are then divided by an appropriate uncertainty factor to derive a short-term maximum (i.e., acute) and long-term average (i.e., chronic) guideline (BCMOE 2012). The selection of an uncertainty factor is described in more detail in Section 2.0 of this appendix. To evaluate the effectiveness of the selected uncertainty factor, a sensitivity analysis was conducted using two approaches (described below). This approach was used with the *USEPA (2013) dataset*) and with the *recalculation dataset* to generate acute and chronic RSWQTs.

All 568 acute toxicity test results (LC_{50} or EC_{50} values) used to calculate SMAVs in USEPA (2013) were ordered and ranked from lowest to highest. Next, the lowest normalized LC_{50} or EC_{50} was selected for deriving the acute (i.e., short-term) RSWQT. A sensitivity analysis was conducted to evaluate the application of various methods for deriving uncertainty factors. Two uncertainty factors were used in the sensitivity analysis. For the first method, the uncertainty factor was defined as the ratio of the critical LC_{50} and the associated no observed effect concentration (NOEC). However, the study with the lowest LC_{50} (Kumar and Krishnamoorthi 1983) did not report the NOEC from the test, so the ratio of the LC_{50} to the estimated NOEC from another guppy (*Poecilia reticulata*) study (Rubin and Elmaraghy 1976) was used as the uncertainty factor. An uncertainty factor of five was also applied to the selected normalized LC_{50} value to evaluate an alternative method for selection of an uncertainty factor. Values between two and ten are typically used as uncertainty factors (BCMOE 2012), so an uncertainty factor of five was chosen for this sensitivity analysis because it represents a value approximately in the middle of this range. The same process was applied to the data in the *recalculation dataset*.

Similarly, 37 results from chronic toxicity tests (EC_{20} values) used to calculate SMCVs in USEPA (2013) were ordered and ranked from lowest to highest. The lowest normalized result was selected for deriving the chronic (i.e., long-term) RSWQT. A sensitivity analysis was conducted to evaluate the application of various methods for deriving uncertainty factors. The ratio of the reported IC_{25} and the IC_{10} from the same study (Wang *et al.* 2007a) was used as one method for

deriving an uncertainty factor. An uncertainty factor of five was also applied to the selected normalized EC_{20} value to evaluate an alternative method for selection of an uncertainty factor. Values between two and ten are typically used as uncertainty factors (BCMOE 2012), so an uncertainty factor of five was chosen for this sensitivity analysis because it represents a value approximately in the middle of this range. The same process was applied to the data in the *recalculation dataset*.

4.0 Results

Using the methods described above, a total of nine acute (i.e., short-term) and nine chronic (i.e., long-term) RSWQTs were derived. The candidate RSWQTs for ammonia derived using the various methods are presented in the following sections.

4.1 Genus Mean Value 5th Percentile Approach

The USEPA (2013) AWQC for ammonia were derived using the genus mean value 5th percentile approach. Hence, a RSWQT was not calculated with this method using the *USEPA (2013) dataset*. The acute AWQC (i.e., criterion maximum concentration; CMC) is 17 mg TAN/L, while the chronic AWQC (i.e., criterion continuous concentration; CCC) is 1.9 mg TAN/L. The acute RSWQT derived using the methods from USEPA (2013) and using the recalculated GMAVs (i.e., *recalculation dataset*) resulted in an RSWQT of 17 mg TAN/L, which is the same as the CMC (USEPA 2013). The chronic RSWQT calculated using GMCVs from the *recalculation dataset* (i.e., 1.0 mg TAN/L) was lower than the USEPA (2013) CCC value of 1.9 mg TAN/L (Table A7.1). Therefore, consideration of the additional toxicity data for sensitive taxa can have an important influence on the resultant RSWQTs.

4.2 Species Mean Value 5th Percentile Approach

A total of four candidate RSWQTs were derived using the species mean value 5th percentile approach. Using the *USEPA (2013) dataset*, an acute RSWQT of 18 mg TAN/L was calculated. The chronic RSWQT calculated using this dataset was 1.6 mg TAN/L. By comparison, the acute and chronic RSWQTs derived using the *recalculation dataset* were 18 mg TAN/L and 1.1 mg TAN/L, respectively (Table A7.1). Hence, consideration of the additional toxicological data did not markedly influence the RSWQTs that were derived for ammonia.

4.3 Toxicity Test 5th Percentile Approach

A total of four candidate RSWQTs were derived using the toxicity test 5th percentile approach. At a pH of 7 and a temperature of 20°C, using the *USEPA (2013) dataset* resulted in an acute RSWQT of 19 mg TAN/L. The chronic RSWQT calculated using this dataset was 2.1 mg TAN/L. By comparison, the acute and chronic RSWQTs derived using the *recalculation dataset* were 19 mg TAN/L and 1.3 mg TAN/L, respectively (Table A7.1). Therefore, consideration of additional toxicity data did not influence the acute RSWQT, but it did lower the chronic RSWQT.

4.4 Modified British Columbia Ministry of Environment Water Quality Guideline Approach

Using the modified BCMOE WQG approach, the acute (i.e., short-term) RSWQT for ammonia decreased compared to using the three 5th percentile approaches. The lowest LC_{50} normalized to a pH of 7 and a temperature of 20°C from a study used by USEPA (2013) to derive the AQWC for ammonia was 10.8 mg TAN/L. This value was reported from a 96-hour static test with the guppy (Kumar and Krishnamoorthi 1983). Applying an uncertainty factor of 1.5 (ratio of the LC_{50} to NOEC from Rubin and Elmaraghy 1976) resulted in an acute RSWQT of 7.2 mg

TAN/L. Applying an uncertainty factor of 5 resulted in an acute RSWQT of 2.2 mg TAN/L (Table A7.1). When the *recalculation dataset* was used and the two uncertainty factors were applied, the RSWQTs did not change (i.e., the lowest LC_{50} normalized to a pH of 7 and a temperature of 20°C from the *recalculation dataset* was still 10.8 mg TAN/L).

The chronic (i.e., long-term) RSWQTs for ammonia were also lower using this approach than using the three 5th percentile approaches. Using the *USEPA (2013) dataset*, the lowest EC_{20} normalized to a pH of 7 and temperature of 20°C was 1.4 mg TAN/L (as calculated by EPA's Toxicity Relationship Analysis Program [TRAP]). This value was from a 28-day test with the wavy-rayed lampmussel (Wang *et al.* 2007a). Applying an uncertainty factor of 3 (ratio of the IC_{25} to IC_{10} for wavy-rayed lampmussel from Wang *et al.* 2007a) resulted in a chronic RSWQT of 0.47 mg TAN/L. Applying an uncertainty factor of 5 resulted in a chronic RSWQT of 0.28 mg TAN/L. When the additional data from the *recalculation dataset* were considered, the lowest low-effect concentration was 1.1 mg TAN/L, which is the IC_{25} for survival from a 28-day test with the fatmucket mussel (Wang *et al.* 2007a). Applying an uncertainty factor of 2.5 (ratio of the IC_{25} to IC_{10} for fatmucket from Wang *et al.* 2007a) resulted in a chronic RSWQT of 0.42 mg TAN/L. Application of an uncertainty factor of 5 resulted in a chronic RSWQT of 0.21 mg TAN/L (Table A7.1). The selection of an uncertainty factor should be considered on a case-by-case basis. Factors that influence the selection of an appropriate uncertainty factor include the quality and quantity of the toxicity data, the severity of toxic effects, and the toxicity and bioaccumulation potential of the contaminant. Furthermore, the application of an uncertainty factor should be influenced by the narrative intent of the RSWQT. For Sensitive Waters, a more conservative approach may be warranted. While the use of an uncertainty factor of 5 (in this example) results in an overly conservative RSWQT, the application of 2.5 provides a reasonable basis for providing an enhanced level of protection (i.e., less than a 10% effect) for the most sensitive species. BCMOE (2012) recommends that an uncertainty factor between two and ten be applied to the lowest reliable effect concentration. See Section 2.0 of this

appendix for additional information on the selection of an appropriate uncertainty factor.

5.0 Evaluation and Discussion of the Various Approaches

The three approaches for deriving RSWQTs using the 5th percentile method (i.e., the genus mean, species mean, and toxicity test approaches) were applied to the *USEPA (2013) dataset* and the *recalculation dataset*. The resultant acute RSWQTs using the *USEPA (2013) dataset* were similar to the EPA AWQC for ammonia (Table A7.1). Incorporation of additional data in the *recalculation dataset* did not result in any changes to the acute RSWQTs. However, the modified BCMOE approach resulted in lower acute RSWQTs than were derived using the three 5th percentile methods. The chronic RSWQTs derived using the 5th percentile methods and the *USEPA (2013) dataset* were similar to the EPA AWQC for ammonia (Table A7.1). Incorporation of additional data in the *recalculation dataset* resulted in lower chronic RSWQTs. Similarly, using the modified BCMOE approach resulted in lower RSWQTs than those calculated using the 5th percentile methods with both the *USEPA (2013)* and *recalculation datasets* (Table A7.1).

A summary of the RSWQTs is provided in Table A7.1. The protectiveness of the RSWQTs resulting from application of the four approaches to the data compiled in the *USEPA (2013) dataset* and the *recalculation dataset* was visually evaluated by comparing the RSWQTs to the underlying toxicity data in the *evaluation dataset* (Figures A7.1 and A7.2). For the acute exposure data (Figure A7.1), only the RSWQTs based on the modified BCMOE approach (7.2 and 2.2 mg TAN/L) are protective of all species for which toxicity data were compiled. There are four toxicity test results (for the guppy, rainbow mussel, and pink mucket) that fall below the USEPA (2013) acute AWQC of 17 mg TAN/L. Two estimated effects concentrations for mussel species are between 17 and 18 mg TAN/L. Hence, all

sensitive aquatic species would be protected only if the modified BCMOE approach were used to derive the acute (i.e., short-term) RSWQTs. The results of the sensitivity analysis that was conducted indicated that uncertainty factors established as the ratio of the LC_{50} used to select the preliminary RSWQT to the appropriate NOEC (or analogous threshold) would likely be adequate for the purpose of deriving RSWQTs. As the use of larger uncertainty factors may result in RSWQTs that are overly conservative, selection of an appropriate uncertainty factor should be considered on a case-by-case basis.

For the chronic exposure data (Figure A7.2), the RSWQT based on GMAVs that incorporated additional data (1.0 mg TAN/L) is only marginally protective of all species for which toxicity data were compiled. The lowest result reported was an IC_{25} of 1.1 mg TAN/L for the fatmucket (from Wang *et al.* 2007a). The chronic RSWQTs based on the modified BCMOE approach (0.42 and 0.21 mg TAN/L) provide higher confidence that sensitive species such as mussels would be protected on NWRs. The results of the sensitivity analysis that was conducted indicated that uncertainty factors established as the ratio of the low-effect threshold (e.g., IC_{25}) used to select the preliminary RSWQT to the appropriate IC_{10} (or analogous threshold) would likely be adequate for the purpose of deriving RSWQTs. As the use of larger uncertainty factors may result in RSWQTs that are overly conservative, selection of an appropriate uncertainty factor should be considered on a case-by-case basis. Nonetheless, based on the results from comparing four methods for deriving *de novo* RSWQTs, it is recommended that the modified BCMOE approach (i.e., using the results of individual toxicity tests) be used to develop *de novo* RSWQTs for Sensitive Waters. Therefore, the modified BCMOE approach becomes the procedure for deriving *de novo* RSWQTs for Sensitive Waters.

6.0 Application of the Ammonia RSWQTs for Sensitive Waters

The recommended acute and chronic RSWQTs (i.e., 7.2 mg TAN/L and 0.42 mg TAN/L, respectively) for Sensitive Waters developed in this appendix are presented in Table A7.1. These values are directly applicable to site waters with a pH of 7 and water temperature of 20°C. However, site-specific estimates of pH and water temperature need to be used to evaluate local conditions relative to the derived RSWQT. Therefore, site-specific measurements of ammonia need to be normalized to a standard pH of 7 and water temperature of 20°C. The site-specific pH and temperature should be measured at the same time as the collection of the ammonia sample. If these measurements are not available, a conservative estimate of pH and temperature should be used. It is recommended that the 95th percentile of the background concentrations for pH and water temperature be used, as ammonia toxicity increases with increases in pH and temperature. Knowing the site-specific pH and temperature, refuge staff can normalize the ammonia concentration to a standard concentration (i.e., pH of 7 and water temperature of 20°C) using the following equations, which are described in more detail in Appendices D (acute equations) and E (chronic equations) in USEPA (2013).

For comparison to the acute RSWQT, the following equation is used to normalize an ammonia concentration in mg TAN/L to pH 7:

$$Ammonia_7 = \frac{Ammonia_s}{\left(\frac{0.0114}{1+10^{7.204-pH}} + \frac{1.6181}{1+10^{pH-7.204}}\right)}$$

Where: $Ammonia_s$ = ammonia concentration at site pH

$Ammonia_7$ = ammonia concentration at pH 7

pH = site pH

Then the ammonia concentration is normalized to a temperature of 20°C with the following equation:

$$\log(\text{Ammonia}_{7,20}) = \log(\text{Ammonia}_{7}) - [-0.036(T - 20)]$$

Where: Ammonia_7 = ammonia concentration at pH 7 and site temperature
$\text{Ammonia}_{7,20}$ = ammonia concentration at pH 7 and temperature of 20°C
T = site temperature in degrees Celsius

The $\text{Ammonia}_{7,20}$ concentration can then be compared to the acute RSWQT of 7.2 mg TAN/L to determine whether ammonia concentrations on the refuge are above or below the RSWQT.

To compare the ammonia concentration on the NWR to the chronic RSWQT the following equation is used first to normalize the concentration to a pH of 7:

$$Ammonia_7 = \frac{Ammonia_s}{\left(\frac{0.0278}{1+10^{7.688-pH}} + \frac{1.1994}{1+10^{pH-7.688}}\right)}$$

Where: Ammonia_s = ammonia concentration at site pH
Ammonia_7 = ammonia concentration at pH 7
pH = site pH

Then the ammonia concentration is normalized to a temperature of 20°C with the following equation:

$$\log(\text{Ammonia}_{7,20}) = \log(\text{Ammonia}_{7}) - [-0.028(T - 20)]$$

Where: Ammonia_7 = ammonia concentration at pH 7 and site temperature
$\text{Ammonia}_{7,20}$ = ammonia concentration at pH 7 and temperature of 20°C
T = site temperature in degrees Celsius

The $Ammonia_{7,20}$ concentration can then be compared to the chronic RSWQT of 0.42 mg TAN/L to determine whether ammonia concentrations on the refuge are above or below the RSWQT.

7.0 Conclusions

Sensitive Waters support sensitive species or taxa of concern on NWRs and, thus, should be afforded enhanced protection (i.e., beyond EPA AWQC). Two procedures are recommended for establishing RSWQTs for Sensitive Waters. The first involves compiling water quality benchmarks from appropriate jurisdictions and selecting the lowest for each substance. In some cases (e.g., ammonia, cadmium), other ancillary information (e.g., pH, temperature, or water hardness) also needs to be compiled in order to adjust the preliminary RSWQT to site-specific conditions. Preliminary RSWQTs derived using this approach should be evaluated to determine if they are relevant to the NWR under consideration and are protective of taxa of concern. If the preliminary RSWQTs are not appropriate for the site (e.g., sensitive species would not be protected), generic benchmarks do not exist, or preliminary RSWQTs are not presented in Table 4 of the main report, then RSWQTs may be derived *de novo*, provided the requisite toxicity data are available.

This appendix illustrates several candidate procedures for deriving *de novo* RSWQTs. Of the four different approaches to deriving RSWQTs investigated, the modified BCMOE approach resulted in the most protective RSWQTs. Therefore, it is recommended that refuge staff, FWS Contaminants Specialists, or FWS Water Resource Branch staff use the modified BCMOE approach (i.e., the procedure for deriving *de novo* RSWQTs for Sensitive Waters) when deriving *de novo* RSWQTs for Sensitive Waters. There are two options for this approach. The first is to only use toxicity data that were compiled by the EPA for AWQC. This is appropriate if data on the sensitive species or taxa of concern that are present on the NWR are included in the dataset. The second option is to compile toxicity data from a variety of sources, including the EPA AWQC document.

While this option will take more effort, it is recommended in situations where recent toxicity data have been generated or if the derivation of the EPA AWQC did not incorporate effects concentrations or key endpoints from sensitive species or taxa of concern present on the NWR. Using this approach, the lowest toxicity threshold is divided by an appropriate uncertainty factor to derive the RSWQTs. Section 3.5.4 describes a useful method for deriving an appropriate uncertainty factor when adequate data are available. Alternatively, an uncertainty factor between two and ten is typically applied (BCMOE 2012). The selection of an appropriate uncertainty factor is dependent on the quality and quantity of the toxicity data, the severity of toxic effects, and the toxicity and bioaccumulation potential of the contaminant (BCMOE 2012). In cases where minimum data requirements are not met (e.g., CCME Type B2 guidelines), a safety factor of 10 is typically applied. A FWS Contaminants Specialist should be consulted on the selection of an appropriate uncertainty factor.

8.0 References

Bader, J.A. and J.M. Grizzle. 1992. Effects of ammonia on growth and survival of recently hatched channel catfish. Journal of Aquatic Animal Health 4(1): 17-23. (As cited in USEPA 2013).

BCMOE (British Columbia Ministry of Environment). 2012. Derivation of water quality guidelines to protect aquatic life in British Columbia. Water Protection and Sustainability Branch, Environmental Sustainability and Strategic Policy Division, Ministry of Environment. Victoria, British Columbia. 34 p.

Besser, J., R. Warbritton, and C. Ingersoll. 2013. Data Summary for Project, 'Development of Methods for Propagation of ESA-Listed and Surrogate Species of Freshwater Snails for use in Toxicity Testing.' Draft. Columbia Environmental Research Center, United States Geological Survey, Columbia, MO.

Blahm, T.H. 1978. Toxicity of chemical fire retardants to juvenile coho salmon and rainbow trout. Ph.D. Thesis, University of Idaho, Moscow, ID. Available from: Dissertation Abstracts International B Sciences and Engineering 39(9):4115. (As cited in USEPA 2013).

Buhl, K.J. 2002. The relative toxicity of waterborne inorganic contaminants to the Rio Grande silvery minnow (*Hybognathus amarus*) and fathead minnow (*Pimephales promelas*) in a water quality simulating that in the Rio Grande, Albuquerque, NM. Final Report to the U.S. Fish and Wildlife Service, New Mexico Ecological Services Field Office, Albuquerque, New Mexico. (As cited in USEPA 2013).

Calamari, D., R. Marchetti and G. Vailati. 1981. Effects of long-term exposure to ammonia on the developmental stages of rainbow trout (*Salmo gairdneri*). Rapports et procès-verbaux des réunions / Conseil permanent international pour l'exploration de la mer 178:81-86. (As cited in USEPA 2013).

Diamond, J.M., D.G. Mackler, W.J. Rasnake and D. Gruber. 1993. Derivation of site-specific ammonia criteria for an effluent-dominated headwater stream. Environmental Toxicology and Chemistry 12(4): 649-658. (As cited in USEPA 2013).

Hickey, C.W. and M.L. Vickers. 1994. Toxicity of ammonia to nine native New Zealand freshwater invertebrate species. Archives of Environmental Contamination and Toxicology 26(3):292-298. (As cited in USEPA 2013).

Kumar, N.J. and K.P. Krishnamoorthi. 1983. Evaluation of toxicity of ammoniacal fertilizer effluents. Environmental Pollution Series A 30(1):77-86.

Miao, J., M.C. Barnhart, E.L. Brunson, D.K. Hardesty, C.G. Ingersoll, and N. Wang. 2010. An evaluation of the influence of substrate on the response of juvenile freshwater mussels (fatmucket, *Lampsilis siliquoidea*) in acute water exposures to ammonia. Environmental Toxicology and Chemistry 29: 2112-2116.

Reinbold, K.A. and S.M. Pescitelli. 1982. Effects of exposure to ammonia on sensitive life stages of aquatic organisms. Project Report, Contract No. 68-01-5832. Illinois Natural History Survey, Champaign, Illinois. (As cited in USEPA 2013).

Rubin, A.J. and M.A. Elmaraghy. 1976. Studies on the toxicity of ammonia, nitrate and their mixtures to the common guppy. Water Resource Center Report No.490. U.S. NTIS PB-255721 Ohio State University, Columbus, Ohio.

Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman, and W.A. Brungs. 1985. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. PB85-227049. United States Environmental Protection Agency. Washington, District of Columbia.

USEPA (United States Environmental Protection Agency). 2013. Aquatic life ambient water quality criteria for ammonia - freshwater 2013. EPA 822-R-13-001. Office of Water. Office of Science and Technology. Washington, District of Columbia.

Wang, N., C.G. Ingersoll, I.E. Greer, D.K. Hardesty, C.D. Ivey, J.L. Kunz, W.G. Brumbaugh, F.J. Dwyer, A.D. Roberts, T. Augspurger, C.M. Kane, R.J. Neves, and M.C. Barnhart. 2007a. Contaminant sensitivity of freshwater mussels: Chronic toxicity of copper and ammonia to juvenile freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10): 2048-2056.

Wang, N., C.G. Ingersoll , D.K. Hardesty, C.D. Ivey, J.L. Kunz, T.W. May, F.J. Dwyer, A.D. Roberts, T. Augspurger, C.M. Kane, R.J. Neves and M.C. Barnhart. 2007b. Contaminant sensitivity of freshwater mussels: Acute toxicity of copper, ammonia, and chlorine to glochidia and juveniles of freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10):2036-2047. (As cited in USEPA 2013).

Wang, N., R.A. Consbrock, C.G. Ingersoll, and M.C. Barnhart. 2011. Evaluation of influence of sediment on the sensitivity of a unionid mussel (*Lampsilis siliquoidea*) to ammonia in 28-day water exposures. Environmental Toxicology and Chemistry 30: 2270-2276.

Tables

Table A7.1. Comparison of methods used to calculate refuge-specific water quality targets for ammonia with data used in the calculation of the Environmental Protection Agency ambient water quality criteria (USEPA 2013) and additional toxicity data.[1]

Dataset	RSWQT Type	Units	RSWQT Calculation Method				
			Genus Mean Value 5th Percentile Approach	Species Mean Value 5th Percentile Approach	Toxicity Test 5th Percentile Approach	Modified BCMOE WQG Approach	
						Variable Uncertainty Factor [5]	Uncertainty Factor of 5
USEPA (2013)	Acute[2]	mg TAN/L	17 [4]	18	19	7.2	2.2
USEPA (2013)	Chronic[3]	mg TAN/L	1.9 [4]	1.6	2.1	0.47	0.28
Recalculation	Acute[2]	mg TAN/L	17	18	19	7.2 [6]	2.2
Recalculation	Chronic[3]	mg TAN/L	1.0	1.1	1.3	0.42 [6]	0.21

AWQC = ambient water quality criteria; BCMOE = British Columbia Ministry of Environment; RSWQT = refuge-specific water quality target; TAN = total ammonia nitrogen; USEPA = U.S. Environmental Protection Agency; WQG = water quality guideline.

[1] All refuge-specific water quality targets are applicable at pH 7.0 and a water temperature of 20°C.

[2] Application of acute thresholds: 1-hour average, not to be exceeded more than once in three years on average (USEPA 2013).

[3] Application of chronic thresholds: 30-day rolling average not to be exceeded more than once in three years on average, and not to exceed 2.5 times the criteria as a 4-day average within the 30-days, more than once in three years on average (USEPA 2013).

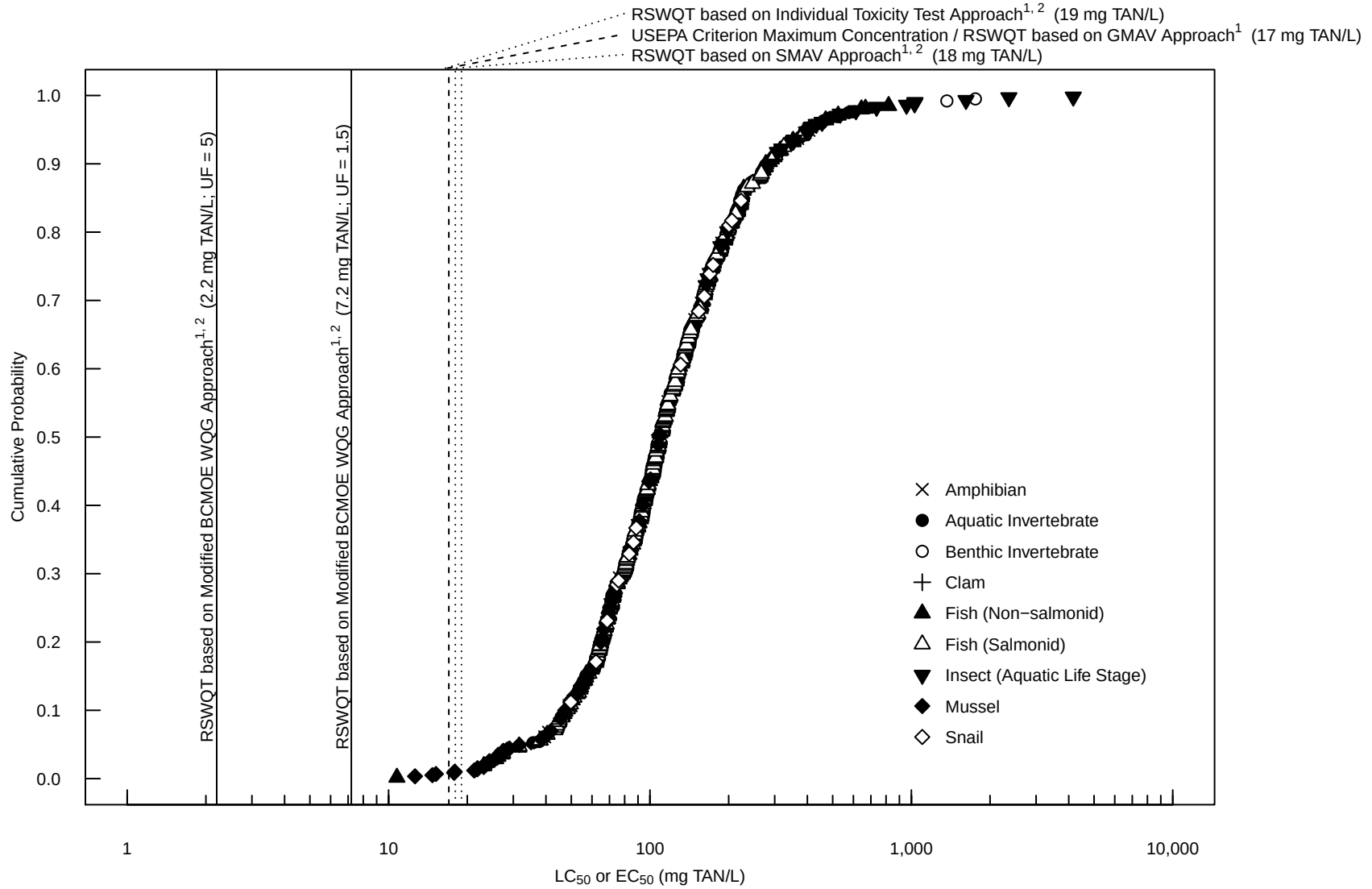
[4] This value is the USEPA (2013) AWQC for ammonia.

[5] Uncertainty factor of 1.5 for the acute criteria, 3 for the chronic criteria from the USEPA (2013) dataset, and 2.5 for the chronic criteria from the recalculation dataset.

[6] Recommended RSWQT for ammonia for Sensitive Waters.

Figures

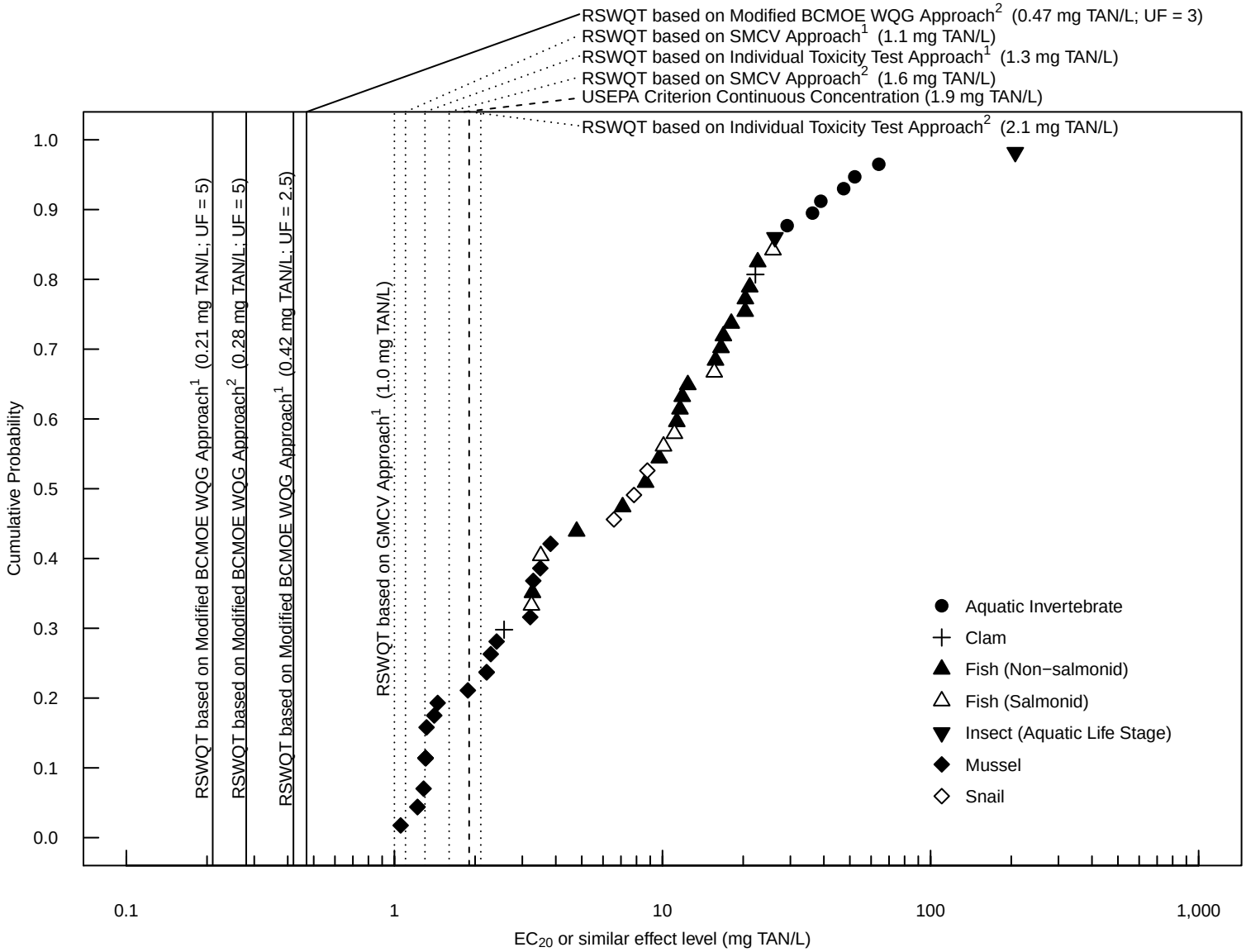
Figure A7.1. Comparison of candidate RSWQTs to the distribution of normalized LC_{50} and EC_{50} values from individual toxicity tests used in the derivation of the Environmental Protection Agency acute water quality criterion and additional data compiled from the scientific literature.



GMAV = Genus Mean Acute Value; RSWQT = Refuge−Specific Water Quality Target; SMAV = Species Mean Acute Value; TAN = total ammonia nitrogen; UF = Uncertainty Factor.

1 = Using the recalculation dataset; 2 = using the USEPA (2013) dataset

Figure A7.2. Comparison of candidate RSWQTs to the distribution of normalized EC_{20} or similar effect levels from individual toxicity tests used in the derivation of the Environmental Protection Agency chronic water quality criterion and additional data compiled from the scientific literature.



GMCV = Genus Mean Chronic Value; RSWQT = Refuge−Specific Water Quality Target; SMCV = Species Mean Chronic Value; TAN = total ammonia nitrogen; UF = Uncertainty Factor.

1 = Using the recalculation dataset; 2 = using the USEPA (2013) dataset

Addendum 1 - Equation for Calculating Final Acute and Chronic Values

In order to use the Genus Mean Value, Species Mean Value, and Toxicity Test 5th Percentile Approaches when evaluating candidate methods for deriving *de novo* refuge-specific water quality targets (RSWQTs), Final Acute Values (FAVs) and Final Chronic Values (FCVs) were calculated from the compiled data. An example of how to calculate the FAV is provided in Appendix 2 of Stephan *et al.* (1985). This example is reproduced below. The same method was used to calculate FCVs, but mean chronic values (MCVs) were used instead of mean acute values (MAVs). In this case, the term MAV is used to encompass genus mean acute values, species mean acute values, and LC_{50}s/EC_{50}s from individual toxicity tests, depending on which approach was being used. Similarly, the term MCV includes genus mean chronic values, species mean chronic values, and EC_{20}s or similar results from individual toxicity tests. The MAVs or MCVs used in this calculation were the four values that were closest to the 5th percentile of the distribution.

Example for Calculating a FAV (Stephan *et al.* 1985)

N = total number of MAVs in data set = 8

Rank	MAV	ln(MAV)	ln(MAV)^2	P = R / (N+1)	$\sqrt{P}$
4	6.4	1.8563	3.4458	0.44444	0.66667
3	6.2	1.8245	3.3290	0.33333	0.57735
2	4.8	1.5686	2.4606	0.22222	0.47140
1	0.4	-0.9163	0.8396	0.11111	0.33333
Sum		4.3331	10.0750	1.11110	2.04875

$$S^2 = \frac{10.0750 - (4.3331)^2 / 4}{1.11110 - (2.04875)^2 / 4} = 87.134$$

S = 9.3346
L = [4.3331 - (9.3346)(2.04875)] / 4 = -3.6978
A = (9.3346)($\sqrt{0.05}$) - 3.6978 = -1.6105
FAV = $e^{-1.6105}$ = 0.1998

References

Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman, and W.A. Brungs. 1985. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. PB85-227049. United States Environmental Protection Agency. Washington, District of Columbia.

Appendix 8

Case Studies for Deriving Refuge-Specific Water Quality Targets for Ammonia for Each Water Classification

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List of Acronyms

AWQC	-	ambient water quality criteria
COPC	-	chemical of potential concern
EC_x	-	effective concentration affecting x% of the population
EPA	-	Environmental Protection Agency
IC_x	-	inhibitory concentration causing an x% inhibition in tested organisms
LC_x	-	lethal concentration affecting x% of the population
MATC	-	maximum acceptable toxicant concentration
NWR	-	National Wildlife Refuge
RSWQT	-	refuge-specific water quality target
TAN	-	total ammonia nitrogen
UCL	-	upper confidence limit
WQS	-	water quality standard

1.0 Introduction

In order to better illustrate the process of classifying water bodies on National Wildlife Refuges (NWRs) and deriving refuge-specific water quality targets (RSWQTs) using the methods described in *Procedures for Deriving Refuge-Specific Water Quality Targets for the Protection of Natural Resources on National Wildlife Refuges*, three case studies are presented. While the information on the refuges presented in these case studies is loosely based on actual NWRs, synthetic data were used in the examples. These case studies are intended only to clarify the steps required for classifying NWR waters and the process for deriving RSWQTs.

2.0 Case Study 1: Illustration of the Methods for Deriving Refuge-Specific Water Quality Targets Using the Background-Concentration Procedure

This case study was developed to illustrate the methods for deriving RSWQTs used in the background-concentration procedure. This procedure is recommended for use in deriving RSWQTs for Waters of Special Significance. Such waters typically support aquatic-obligate threatened or endangered species through their entire life cycle and, hence, require a higher level of protection than other water bodies. Accordingly, the goal of water management activities should be to maintain water quality conditions at background levels. These procedures are illustrated using synthetic water quality data for a fictitious NWR located in Montana (Refuge A).

2.1 Background Information

Refuge A is located in north-central Montana. This NWR has many upland habitat types, including prairies, shrublands, woodlands, forested coulees, and badlands.

Wetland and riparian habitats make up a small percentage of the NWR, but they are densely populated with wildlife. Several species of birds, mammals, reptiles, and amphibians make use of the large river corridor, riparian habitat, and the shoreline of a large lake. Approximately 50 species of fish utilize aquatic habitats on the NWR, including trout, minnows, suckers, sunfishes, and perches, as well as the endangered pallid sturgeon (*Scaphirhynchus albus*). There have been 276 bird species recorded on or near the NWR, of which one is endangered (interior least tern; *Sternula antillarum*) and one is threatened (piping plover; *Charadrius melodus*). Both the least tern and the piping plover are aquatic-dependent birds that are known to nest on the NWR.

2.2 Water Classification

As there is an endangered fish species (pallid sturgeon) that relies on aquatic habitats in this NWR, the waters were designated as Waters of Special Significance. In this example, the waters of this NWR were designated as Waters of Special Significance year-round because the endangered pallid sturgeon is present in these waters all year (Table A8.1). For Waters of Special Significance, the goal is to prevent degradation of the water quality from background conditions. Hence, the background-concentration procedure was used to calculate RSWQTs for Refuge A.

2.3 Data Generation

A synthetic dataset was generated to support the development of RSWQTs for ammonia for this NWR. This dataset consisted of 60 values for a single sampling station located at a representative location on the main river in the NWR. These data include water quality samples collected monthly over a three year period, with five samples collected within 30 days during two months in each year (i.e, during low flow and high flow periods). The synthetic data were generated as total ammonia nitrogen (TAN) concentrations so they could be compared to the

Environmental Protection Agency (EPA) ambient water quality criteria (AWQC), which are presented in mg TAN/L.

2.4 Refuge-Specific Water Quality Targets Derivation Methods

Using the background-concentration procedure, background water quality conditions are defined by determining the central tendency and upper limit of background for priority chemicals of potential concern (COPCs), in this case ammonia. The 95% upper confidence limit (UCL) of the mean of the natural background concentrations of ammonia was calculated as the preliminary chronic (i.e., long-term average) RSWQT, while the 95th percentile of the concentrations was calculated as the preliminary acute (i.e., short-term maximum) RSWQT. See Section 5.1 of the main report and Appendix 5 for more detail on characterizing background concentrations. Studies have shown that ammonia concentrations tend to increase as flow decreases (Sosiak and Hazewinkel 2002) and in late summer when there is an increase in heterotrophic activity (Sigleo and Frick 2003). As water flow through the refuge is greatest from February to July (compared to the rest of the year), separate RSWQTs were developed for two periods, applying from February to July and from August to January. To support derivation of the RSWQTs, the data reported as below the analytical detection limit (i.e., non-detects) were substituted with one-half the detection limit in the data analyses (USACE 1995).

2.5 Results

The synthetic data that were used to illustrate the RSWQT derivation process are presented in Table A8.2. The 95% UCL of the mean of the background data generated for February through July was 0.534 mg TAN/L, while the 95th percentile of the background data during these months was 1.24 mg TAN/L. The 95% UCL of the mean of the background data generated for August through

January was 1.28 mg TAN/L, while the 95th percentile of the background data during these months was 2.03 mg TAN/L. As the primary water management goal for Waters of Special Significance is non-degradation from background conditions, these values are recommended as the chronic and acute RSWQTs, respectively, for each period of the year. Therefore, the 30-day average of ammonia concentrations should not exceed 0.534 mg TAN/L and the acute (i.e., maximum) RSWQT of 1.24 mg TAN/L should not be exceeded in any single water quality sample between February and July. The 30-day average of ammonia concentrations should not exceed 1.28 mg TAN/L and the acute (i.e., maximum) RSWQT of 2.03 mg TAN/L should not be exceeded in any single water quality sample between August and January.

3.0 Case Study 2: Illustration of the Methods for Deriving Refuge-Specific Water Quality Targets For Sensitive Waters

This case study was developed to illustrate the procedures for deriving RSWQTs for Sensitive Waters. Sensitive Waters are waters that are considered to support species having high sensitivity to chemical challenges or taxa of special concern, including listed or endangered species with limited exposure to the water bodies of interest. For these Sensitive Waters, water quality conditions should be maintained such that the most sensitive designated water use(s) is afforded an enhanced level of protection. Although Table 4 in the main text recommends RSWQTs for Sensitive Waters, this case study was designed to provide an example of how to calculate *de novo* RSWQTs, for situations where recommended RSWQTs do not exist or when the RSWQTs in Table 4 are not appropriate for the NWR. This case study illustrates the procedure for deriving *de novo* RSWQTs for Sensitive Waters (methods and rationale presented in Appendix 7) using synthetic water quality data for a NWR located in Utah (Refuge B).

3.1 Background Information

Refuge B is located in northern Utah. It contains wetlands and grasslands that are important habitat for migrating and resident birds. Over 200 species of birds have been recorded on this NWR, including the American white pelican, tundra swan, and white-faced ibis. This NWR also supports other types of animals, including mammals (e.g., mule deer, muskrat), fish (e.g., channel catfish, bullhead), reptiles (e.g., gopher snakes, rubber boas), amphibians (e.g., leopard frogs, western chorus frogs), and insects (e.g., dragonflies, grasshoppers). There are no threatened or endangered species on this NWR. One of the issues on this NWR is that when large numbers of migrating birds visit the refuge (generally from the end of March until May and from August to October) increases in ammonia concentrations have been observed in the water. While the NWR provides important habitat for many bird species, this must be balanced with protecting mussels living on the NWR that are sensitive to ammonia.

3.2 Water Classification

There are no threatened or endangered species on this NWR. However, there are Western pearlshell mussels (*Margaritifera falcata*) present, and mussels are known to be sensitive to ammonia exposure. In addition, the NWR provides important habitat to many migrating birds. Therefore, the waters in Refuge B should be designated as Sensitive Waters. In this example, the NWR was designated as Sensitive Waters year-round because the mussels inhabit the NWR at all times of year (Table A8.3). The goal for Sensitive Waters is to maintain water quality conditions so that designated water uses are given an enhanced level of protection. The ability to meet this goal at all times of year will be impacted by the large numbers of migratory birds that visit the NWR and leave their nitrogenous waste behind.

3.3 Data Generation

A synthetic dataset was generated to support the development of RSWQTs for ammonia for this NWR. This dataset consisted of 60 values for a single sampling station located at a representative location on the main river in the NWR. These data include water quality samples collected monthly over a three year period, with five samples collected within 30 days during two months in each year (i.e., during low flow and high flow periods). The synthetic data were generated as TAN concentrations so they could be compared to the EPA AWQC, which are presented in mg TAN/L.

3.4 Refuge-Specific Water Quality Targets Derivation Methods

See Section 5.2 of the text for additional detail on the calculation of RSWQTs for Sensitive Waters and see Appendix 7 for the rationale for this approach. First, the 95% UCL of the mean and 95th percentile of the natural background concentrations of ammonia were calculated to characterize the average and maximum concentrations of ammonia on the NWR under background conditions. Studies have shown that ammonia concentrations tend to increase as flow decreases (Sosiak and Hazewinkel 2002) and in late summer when there is an increase in heterotrophic activity (Sigleo and Frick 2003). As water flow through the refuge is greatest from February to July (compared to the rest of the year), the 95% UCL of the mean and 95th percentile were calculated separately for February to July and for August to January. To support derivation of the RSWQTs, the data below the analytical detection limit (i.e., non-detects) were substituted as one-half the detection limit in the data analyses (USACE 1995).

Next, the procedure for deriving *de novo* RSWQTs for Sensitive Waters (based on BCMOE [2012] methods and described in Appendix 7) was followed to develop RSWQTs for ammonia. First, relevant ammonia toxicity data were compiled from various sources, including the EPA AWQC document for ammonia (USEPA 2013)

and studies conducted since USEPA (2013) was published (i.e., Wang *et al.* 2007; 2011; Miao *et al.* 2010; Besser *et al.* 2013), identified by key researchers. Results from acute (i.e., short-term) toxicity tests were expressed as LC_{50} values (concentration lethal to 50% of the population) or EC_{50} values (concentration affecting 50% of the population), while chronic (i.e., long-term) toxicity data were expressed as EC_{20} values, IC_{25} values (concentration causing a 25% inhibition in tested organisms), and maximum acceptable toxicant concentrations (MATCs; term used interchangeably with chronic value). The USEPA (2013) dataset presented toxic effect values as TAN, normalized to pH 7.0 (for all species) and 20°C (for invertebrate species only). Additional data compiled for this evaluation (from Wang *et al.* 2007; 2011; Miao *et al.* 2010; Besser *et al.* 2013), which included only invertebrate species, were normalized to pH 7.0 according to the method outlined in USEPA (2013). All tests were performed at 20°C and results were reported as TAN. Next, all ammonia data were ordered and ranked from lowest to highest within each exposure scenario (i.e., acute and chronic) and the lowest value was chosen as the basis of a preliminary RSWQT. For more details on this process see Section 3.5.4 in Appendix 7. An uncertainty factor was applied to the selected values (acute and chronic) to make the preliminary RSWQTs protective of all species and life stages. An uncertainty factor of 1.5 (ratio of the LC_{50} to NOEC for the guppy [*Poecilia reticulata*] from Rubin and Elmaraghy 1976) was applied to the lowest value from short-term exposures and an uncertainty factor of 2.5 (ratio of the IC_{25} to IC_{10} for fatmucket [*Lampsilis siliquoidea*] from Wang *et al.* 2007) was applied to the lowest value from long-term exposures. See Sections 2.0, 3.5.4 and 4.4 of Appendix 7 for more details on the selection of these uncertainty factors.

These preliminary RSWQTs were subsequently adjusted to the site-specific pH and temperature. These adjustments were made using the methods reported in Appendices D and E of USEPA (2013). The 95% UCL of the mean was used for both pH (7.1) and water temperature (12°C) at the site to provide a conservative estimate of these conditions, as ammonia toxicity increases with increases in pH and temperature. Then, the chronic (i.e., 30-d average) preliminary RSWQT (from

long-term exposure data) was compared to the 95% UCL of the mean of background concentrations (separate values for February to July and August to January) and the acute (i.e., maximum) preliminary RSWQT (from short-term exposure data) was compared to the 95th percentile of background concentrations (separate values for February to July and August to January) to determine whether they were relevant to the site.

3.5 Results

The synthetic data that were used to determine background concentrations for Refuge B are presented in Table A8.4. The 95% UCL of the mean of the background ammonia data generated for February through July was 0.429 mg TAN/L, while the 95th percentile of the background concentrations during these months was 1.14 mg TAN/L. The 95% UCL of the mean of the background ammonia data generated for August through January was 0.817 mg TAN/L, while the 95th percentile of the background concentrations during these months was 1.62 mg TAN/L.

Using the procedure for deriving *de novo* RSWQTs for Sensitive Waters, the preliminary RSWQTs were calculated to be 0.675 mg TAN/L (chronic RSWQT) and 12.7 mg TAN/L (acute RSWQT). While the background concentrations of ammonia at the NWR from February through July are lower than the calculated RSWQTs, the RSWQTs developed using the procedure for deriving *de novo* RSWQTs for Sensitive Waters included information on the toxic effects of ammonia to mussels and should be protective of the sensitive species on this NWR. Therefore, these preliminary RSWQTs could be used as final RSWQTs between February and July. The 30-day average of ammonia concentrations should not exceed 0.675 mg TAN/L and the acute (i.e., maximum) RSWQT of 12.7 mg TAN/L should not be exceeded in any single water quality sample between February and July. From August through January, the 95% UCL of the mean background concentration (0.817 mg TAN/L) was greater than the preliminary chronic RSWQT (0.675 mg TAN/L), though the 95th percentile (1.62

mg TAN/L) was still below the preliminary acute RSWQT (12.7 mg TAN/L). Therefore, the 95% UCL of the mean background concentration should become the final chronic RSWQT, while the preliminary acute RSWQT should be kept as the final acute RSWQT. The 30-day average of ammonia concentrations should not exceed 0.817 mg TAN/L and the acute (i.e., maximum) RSWQT of 12.7 mg TAN/L should not be exceeded in any single water quality sample between August and January.

Additional considerations need to be made for certain times of the year on this NWR (e.g., in spring, August, and early fall). During these times, ammonia concentrations tend to increase above the RSWQTs. The potential risks to competing interests (i.e., birds and mussels) on the NWR must be evaluated to determine if it is necessary to invoke habitat management or mitigation activities during these times. Due to the uncertainty of mitigating ammonia loading during bird migration periods, refuge staff may need to develop alternative solutions to meet all of the protection goals.

4.0 Case Study 3: Illustration of the Methods for Deriving Refuge-Specific Water Quality Targets for Typical Waters

This case study was developed to illustrate the procedures for deriving RSWQTs for Typical Waters. Water bodies are classified as Typical Waters if they contain none of the characteristics outlined for Waters of Special Significance or Sensitive Waters (i.e., they support species having typical sensitivity to chemical challenges). As Typical Waters support typical aquatic communities, they should be adequately protected by the EPA AWQC. Nonetheless, data on background concentrations of COPCs should be compiled, so that they can be compared to EPA AWQC to ensure that the EPA AWQC are applicable to the particular NWR in question. This case study illustrates the procedures for deriving RSWQTs for

Typical Waters using synthetic water quality data for a NWR located in Minnesota (Refuge C).

4.1 Background Information

Refuge C is located in northwestern Minnesota. Habitat includes oak savanna, coniferous bog, and sedge meadow. Species that inhabit oak savanna include black bears and American kestrals, while the Connecticut warbler and carnivorous pitcher plant reside in coniferous bogs. Sedge meadows provide nesting and foraging habitat for birds such as the yellow rail and sedge wren. Amphibians and reptiles on this NWR include the tiger salamander, the wood frog, the snapping turtle, and the redbelly snake. Fish species include minnows, suckers, sunfish, and perches. The only endangered or threatened species on this NWR is the gray wolf (threatened). As the gray wolf is not an aquatic-obligate or aquatic-dependent species, it does not require water bodies on Refuge C to be designated as Waters of Special Significance or as Sensitive Waters.

4.2 Water Classification

There are no aquatic-obligate or aquatic-dependent endangered or threatened species on this NWR. There are also no sensitive taxa, such as mussels, living on the Refuge and the Refuge does not contain rare habitats or designated wilderness areas. Therefore, this NWR is designated as Typical Waters year-round (Table A8.5). The goal for Typical Waters is to maintain water quality conditions such that all of the designated water uses are afforded an adequate level of protection during all times of the year.

4.3 Data Generation

A synthetic dataset was generated to support the development of RSWQTs for ammonia for this NWR. This dataset consisted of 60 values for a single sampling station located at a representative location on the main river in the NWR. These data include water quality samples collected monthly over a three year period, with five samples collected within 30 days during two months in each year (i.e., during low flow and high flow periods). The synthetic data were generated as TAN concentrations so they could be compared to the EPA AWQC, which are presented in mg TAN/L.

4.4 Refuge-Specific Water Quality Targets Derivation Methods

See Section 5.3 of the text for more detail on determining RSWQTs for Typical Waters. First, the 95% UCL of the mean and 95th percentile of the natural background concentrations of ammonia were calculated to determine the average and upper limit of concentrations of ammonia on the NWR under background conditions. Studies have shown that ammonia concentrations tend to increase as flow decreases (Sosiak and Hazewinkel 2002) and in late summer when there is an increase in heterotrophic activity (Sigleo and Frick 2003). As water flow through the refuge is greatest from February to July (compared to the rest of the year), the 95% UCL of the mean and 95th percentile were calculated separately for February to July and for August to January. To support derivation of RSWQTs, the data below the analytical detection limit (i.e., non-detects) were substituted as one-half the detection limit in the data analyses (USACE 1995).

Second, EPA AWQC and Minnesota water quality standards (WQSs) were compiled for ammonia and adjusted to site-specific pH and temperature conditions. The 95% UCL of the mean was used for both pH (7.2) and water temperature (13°C) to provide a conservative estimate of these conditions, as ammonia toxicity increases with increases in pH and temperature. USEPA (2013) provides tables

that show how the EPA AWQC change as pH and temperature change, so the appropriate values were selected from these tables. However, Minnesota only provides a chronic WQS for un-ionized ammonia as nitrogen, which is not temperature and pH dependent (MPCA 2008). As the EPA AWQC in TAN are more reliable, they were selected as the preliminary RSWQTs.

4.5 Results

The synthetic data that were used to determine background concentrations for Refuge C are presented in Table A8.6. The 95% UCL of the mean of the background ammonia concentrations generated for February through July was 0.964 mg TAN/L, while the 95th percentile of the background concentrations during these months was 1.69 mg TAN/L. The 95% UCL of the mean of the background ammonia concentrations generated for August through January was 1.09 mg TAN/L, while the 95th percentile of the background concentrations during these months was 2.92 mg TAN/L. The chronic and acute preliminary RSWQTs adjusted to a pH of 7.2 and a temperature of 13°C were 2.7 mg TAN/L and 20 mg TAN/L, respectively. The background concentrations of ammonia from February through July and from August through January are lower than the preliminary RSWQTs that were developed. However, as these waters do not contain aquatic-dependent threatened, endangered, or sensitive species, the EPA AWQC should be protective of the species on this NWR. Therefore, the 30-day average of ammonia concentrations should not exceed 2.7 mg TAN/L and the acute (i.e., maximum) RSWQT of 20 mg TAN/L should not be exceeded in any single water sample at all times of the year.

5.0 References

BCMOE (British Columbia Ministry of Environment). 2012. Derivation of water quality guidelines to protect aquatic life in British Columbia. Water Protection and Sustainability Branch, Environmental Sustainability and Strategic Policy Division, Ministry of Environment. Victoria, British Columbia. 34 p.

Besser, J., R. Warbritton, and C. Ingersoll. 2013. Data Summary for Project, 'Development of Methods for Propagation of ESA-Listed and Surrogate Species of Freshwater Snails for use in Toxicity Testing.' Draft. Columbia Environmental Research Center, United States Geological Survey, Columbia, MO.

Miao, J., M.C. Barnhart, E.L. Brunson, D.K. Hardesty, C.G. Ingersoll, and N. Wang. 2010. An evaluation of the influence of substrate on the response of juvenile freshwater mussels (fatmucket, *Lampsilis siliquoidea*) in acute water exposures to ammonia. Environmental Toxicology and Chemistry 29: 2112-2116.

MPCA (Minnesota Pollution Control Agency). 2008. Minnesota Administrative Rules, Chapter 7050, Waters of The State. 7050.0220 - Specific water quality standards by associated use classes. Accessed at https://www.revisor.mn.gov/rules/?id=7050.0220 on 16 September 2013.

Rubin, A.J. and M.A. Elmaraghy. 1976. Studies on the toxicity of ammonia, nitrate and their mixtures to the common guppy. Water Resource Center Report No.490. U.S. NTIS PB-255721 Ohio State University, Columbus, Ohio.

Sigleo, A., and W. Frick. 2003. Seasonal variations in river flow and nutrient concentrations in a northwestern USA watershed. *In* Proceedings of the First Interagency Conference on Research in the Watersheds, Benson, AZ, 27-30 October 2003. *Edited by* K.G. McElroy Renard, S.A. Gburek, W.J. Canfield, H. Evan, and S.L Russell. U.S. Department of Agriculture, Agricultural Research Service. pp. 370-376.

Sosiak, A., and R. Hazewinkel. 2002. Flows required to protect water quality in the Little Bow River and Mosquito Creek. Air and Water Branch, Science and Standards Division, Alberta Environment. Edmonton, Alberta.

USACE (United States Army Corps of Engineers). 1995. Guidelines for statistical treatment of less than detection limit data in dredged sediment evaluations. EEDP-04-23. Waterways Experiment Station. Vicksburg, Mississippi.

USEPA (United States Environmental Protection Agency). 2013. Aquatic life ambient water quality criteria for ammonia - freshwater 2013. EPA 822-R-13-001. Office of Water. Office of Science and Technology. Washington, District of Columbia. Available at http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/ammonia/index.cfm.

Wang, N., C.G. Ingersoll, I.E. Greer, D.K. Hardesty, C.D. Ivey, J.L. Kunz, W.G. Brumbaugh, F.J. Dwyer, A.D. Roberts, T. Augspurger, C.M. Kane, R.J. Neves, and M.C. Barnhart. 2007. Contaminant sensitivity of freshwater mussels: Chronic toxicity of copper and ammonia to juvenile freshwater mussels (Unionidae). Environmental Toxicology and Chemistry 26(10): 2048-2056.

Wang, N., R.A. Consbrock, C.G. Ingersoll, and M.C. Barnhart. 2011. Evaluation of influence of sediment on the sensitivity of a unionid mussel (*Lampsilis siliquoidea*) to ammonia in 28-day water exposures. Environmental Toxicology and Chemistry 30: 2270-2276.

Tables

Table A8.1. Completed checklist for determining the water classification of National Wildlife Refuge A.

Questions / Species Present on Refuge

Q1. Does the NWR provide critical habitat for one or more aquatic-obligate endangered species? Yes: ✓ No: _____

Q2. If yes, list endangered species and habitat use by month.

	Month Species is Present											
	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Aquatic-Obligate Endangered Species												
Pallid sturgeon (*Scaphirhynchus albus*)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Q3. Do any of the following sensitive taxa, or other taxa of concern, utilize aquatic habitats within the NWR? Yes: ✓ No: _____

Q4. If yes, identify habitat use by month.

	Month Species is Present											
Sensitive Taxa or Taxa of Concern	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Freshwater mussels (Identify species)												
Fatmucket mussel (*Lampsilis siliquoidea*)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Western pearlshell mussel (*Margaritifera falcata*)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sturgeon (Identify species)												
Salmonids (Identify species)												
Other (Identify species)												
Month-Specific Water Class:	WSS	WSS	WSS	WSS	WSS	WSS	WSS	WSS	WSS	WSS	WSS	WSS

Overall Determination: Waters of Special Significance (WSS) for the entire year.

Table A8.2. Synthetic data used in the derivation of RSWQTs for Refuge A.

Sampling Date	Ammonia Concentration (mg TAN/L)		
	All Data	February to July	August to January
January 1, 2001	0.396		0.396
February 1, 2001	0.104	0.104	
March 1, 2001	1.15	1.15	
March 7, 2001	0.358	0.358	
March 13, 2001	0.177	0.177	
March 19, 2001	2.12	2.12	
March 25, 2001	0.0358	0.0358	
April 1, 2001	0.178	0.178	
May 1, 2001	0.149	0.149	
June 1, 2001	0.0628	0.0628	
July 1, 2001	0.0288	0.0288	
August 1, 2001	1.18		1.18
September 1, 2001	0.751		0.751
September 7, 2001	0.705		0.705
September 13, 2001	0.381		0.381
September 19, 2001	0.142		0.142
September 25, 2001	1.96		1.96
October 1, 2001	0.873		0.873
November 1, 2001	2.72		2.72
December 1, 2001	1.1		1.1
January 1, 2002	1.19		1.19
February 1, 2002	0.195	0.195	
March 1, 2002	0.495	0.495	
March 7, 2002	0.411	0.411	
March 13, 2002	0.0929	0.0929	
March 19, 2002	0.0257	0.0257	
March 25, 2002	0.144	0.144	
April 1, 2002	0.1	0.1	
May 1, 2002	0.748	0.748	
June 1, 2002	0.622	0.622	
July 1, 2002	0.145	0.145	
August 1, 2002	0.703		0.703
September 1, 2002	0.191		0.191
September 7, 2002	0.867		0.867
September 13, 2002	0.703		0.703
September 19, 2002	0.822		0.822
September 25, 2002	0.451		0.451
October 1, 2002	1.75		1.75
November 1, 2002	1.33		1.33
December 1, 2002	0.644		0.644
January 1, 2003	1.16		1.16
February 1, 2003	0.181	0.181	
March 1, 2003	1.32	1.32	
March 7, 2003	0.139	0.139	
March 13, 2003	0.0709	0.0709	
March 19, 2003	0.0342	0.0342	
March 25, 2003	0.225	0.225	

Table A8.2. Synthetic data used in the derivation of RSWQTs for Refuge A.

Sampling Date	Ammonia Concentration (mg TAN/L)		
	All Data	February to July	August to January
April 1, 2003	0.54	0.54	
May 1, 2003	0.379	0.379	
June 1, 2003	0.444	0.444	
July 1, 2003	0.209	0.209	
August 1, 2003	0.996		0.996
September 1, 2003	1.58		1.58
September 7, 2003	0.597		0.597
September 13, 2003	1.23		1.23
September 19, 2003	1.79		1.79
September 25, 2003	0.327		0.327
October 1, 2003	1.67		1.67
November 1, 2003	1.27		1.27
December 1, 2003	2.08		2.08
95% UCL of the Mean	**0.872**	**0.534**	**1.28**
95th Percentile	**1.97**	**1.24**	**2.03**

RSWQT = refuge-specific water quality target; TAN = total ammonia nitrogen;
UCL = upper confidence limit.

Table A8.3. Completed checklist for determining the water classification of National Wildlife Refuge B.

Questions / Species Present on Refuge

Q1. Does the NWR provide critical habitat for one or more aquatic-obligate endangered species? Yes: _____ No: ✓

Q2. If yes, list endangered species and habitat use by month.

	Month Species is Present											
Aquatic-Obligate Endangered Species	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**

Q3. Do any of the following sensitive taxa, or other taxa of concern, utilize aquatic habitats within the NWR? Yes: ✓ No: _____

Q4. If yes, identify habitat use by month.

	Month Species is Present											
Sensitive Taxa or Taxa of Concern	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Freshwater mussels (Identify species)												
Western pearlshell mussel (*Margaritifera falcata*)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sturgeon (Identify species)												
Salmonids (Identify species)												
Other (Identify species)												
Month-Specific Water Class:	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW

Overall Determination: Sensitive Waters (SW) for the entire year.

Table A8.4. Synthetic data used in the derivation of RSWQTs for Refuge B.

Sampling Date	Ammonia Concentration (mg TAN/L) [1]		
	All Data	February to July	August to January
January 1, 2001	1.25		1.25
February 1, 2001	0.0262	0.0262	
March 1, 2001	0.0298	0.0298	
March 7, 2001	0.135	0.135	
March 13, 2001	0.105	0.105	
March 19, 2001	0.305	0.305	
March 25, 2001	0.0992	0.0992	
April 1, 2001	1.33	1.33	
May 1, 2001	0.103	0.103	
June 1, 2001	0.0999	0.0999	
July 1, 2001	0.181	0.181	
August 1, 2001	0.281		0.281
September 1, 2001	0.914		0.914
September 7, 2001	0.24		0.24
September 13, 2001	0.176		0.176
September 19, 2001	0.0477		0.0477
September 25, 2001	0.0929		0.0929
October 1, 2001	0.154		0.154
November 1, 2001	0.455		0.455
December 1, 2001	0.194		0.194
January 1, 2002	1.78		1.78
February 1, 2002	0.207	0.207	
March 1, 2002	0.913	0.913	
March 7, 2002	0.197	0.197	
March 13, 2002	0.207	0.207	
March 19, 2002	0.229	0.229	
March 25, 2002	0.247	0.247	
April 1, 2002	0.111	0.111	
May 1, 2002	0.419	0.419	
June 1, 2002	0.0138	0.0138	
July 1, 2002	0.351	0.351	
August 1, 2002	0.64		0.64
September 1, 2002	0.603		0.603
September 7, 2002	0.111		0.111
September 13, 2002	2.89		2.89
September 19, 2002	1.42		1.42
September 25, 2002	0.0384		0.0384
October 1, 2002	0.471		0.471
November 1, 2002	0.247		0.247
December 1, 2002	0.542		0.542
January 1, 2003	0.747		0.747
February 1, 2003	0.0131	0.0131	
March 1, 2003	0.123	0.123	
March 7, 2003	0.0997	0.0997	
March 13, 2003	0.241	0.241	
March 19, 2003	< 0.01	< 0.01	
March 25, 2003	0.769	0.769	

Table A8.4. Synthetic data used in the derivation of RSWQTs for Refuge B.

Sampling Date	Ammonia Concentration (mg TAN/L) [1]		
	All Data	February to July	August to January
April 1, 2003	< 0.01	< 0.01	
May 1, 2003	0.137	0.137	
June 1, 2003	0.0385	0.0385	
July 1, 2003	1.7	1.7	
August 1, 2003	0.759		0.759
September 1, 2003	0.508		0.508
September 7, 2003	0.242		0.242
September 13, 2003	1.09		1.09
September 19, 2003	0.0643		0.0643
September 25, 2003	0.836		0.836
October 1, 2003	0.269		0.269
November 1, 2003	0.444		0.444
December 1, 2003	0.0706		0.0706
95% UCL of the Mean	**0.572**	**0.429**	**0.817**
95th Percentile	**1.43**	**1.14**	**1.62**

RSWQT = refuge-specific water quality target; TAN = total ammonia nitrogen;
UCL = upper confidence limit.

[1] Data below the detection limit were treated as one-half the detection limit in the analyses.

Table A8.5. Completed checklist for determining the water classification of National Wildlife Refuge C.

Questions / Species Present on Refuge

Q1. Does the NWR provide critical habitat for one or more aquatic-obligate endangered species? Yes: _____ No: ✓

Q2. If yes, list endangered species and habitat use by month.

	Month Species is Present											
Aquatic-Obligate Endangered Species	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**

Q3. Do any of the following sensitive taxa, or other taxa of concern, utilize aquatic habitats within the NWR? Yes: No: ✓

Q4. If yes, identify habitat use by month.

	Month Species is Present											
Sensitive Taxa or Taxa of Concern	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Freshwater mussels (Identify species)												
Sturgeon (Identify species)												
Salmonids (Identify species)												
Other (Identify species)												
Month-Specific Water Class:	TW	TW	TW	TW	TW	TW	TW	TW	TW	TW	TW	TW

Overall Determination: Typical Waters (TW) for the entire year.

Table A8.6. Synthetic data used in the derivation of RSWQTs for Refuge C.

Sampling Date	Ammonia Concentration (mg TAN/L) [1]		
	All Data	February to July	August to January
January 1, 2001	0.0166		0.0166
February 1, 2001	1.8	1.8	
March 1, 2001	0.0214	0.0214	
March 7, 2001	0.0278	0.0278	
March 13, 2001	0.149	0.149	
March 19, 2001	0.582	0.582	
March 25, 2001	1.69	1.69	
April 1, 2001	1.58	1.58	
May 1, 2001	0.205	0.205	
June 1, 2001	1.55	1.55	
July 1, 2001	0.193	0.193	
August 1, 2001	0.0442		0.0442
September 1, 2001	< 0.01		< 0.01
September 7, 2001	0.284		0.284
September 13, 2001	1.86		1.86
September 19, 2001	0.432		0.432
September 25, 2001	0.0429		0.0429
October 1, 2001	0.61		0.61
November 1, 2001	0.916		0.916
December 1, 2001	1.19		1.19
January 1, 2002	0.255		0.255
February 1, 2002	0.669	0.669	
March 1, 2002	0.343	0.343	
March 7, 2002	0.958	0.958	
March 13, 2002	0.369	0.369	
March 19, 2002	0.0212	0.0212	
March 25, 2002	1.19	1.19	
April 1, 2002	0.399	0.399	
May 1, 2002	0.895	0.895	
June 1, 2002	1.25	1.25	
July 1, 2002	0.108	0.108	
August 1, 2002	3.16		3.16
September 1, 2002	< 0.01		< 0.01
September 7, 2002	0.115		0.115
September 13, 2002	0.186		0.186
September 19, 2002	0.859		0.859
September 25, 2002	0.175		0.175
October 1, 2002	0.0127		0.0127
November 1, 2002	0.698		0.698
December 1, 2002	2.63		2.63
January 1, 2003	< 0.01		< 0.01
February 1, 2003	1.56	1.56	
March 1, 2003	0.262	0.262	
March 7, 2003	1.2	1.2	
March 13, 2003	1.12	1.12	
March 19, 2003	0.639	0.639	
March 25, 2003	1.69	1.69	

Table A8.6. Synthetic data used in the derivation of RSWQTs for Refuge C.

Sampling Date	Ammonia Concentration (mg TAN/L) [1]		
	All Data	February to July	August to January
April 1, 2003	0.233	0.233	
May 1, 2003	1.1	1.1	
June 1, 2003	0.347	0.347	
July 1, 2003	0.0281	0.0281	
August 1, 2003	< 0.01		< 0.01
September 1, 2003	0.0181		0.0181
September 7, 2003	0.939		0.939
September 13, 2003	4.22		4.22
September 19, 2003	0.319		0.319
September 25, 2003	< 0.01		< 0.01
October 1, 2003	0.564		0.564
November 1, 2003	0.3		0.3
December 1, 2003	1.32		1.32
95% UCL of the Mean	**0.938**	**0.964**	**1.09**
95th Percentile	**1.90**	**1.69**	**2.92**

RSWQT = refuge-specific water quality target; TAN = total ammonia nitrogen;
UCL = upper confidence limit.

[1] Data below the detection limit were treated as one-half the detection limit in the analyses.