Public Comment
Water Quality Obj. - Cadimum
Deadline: 10/23/08 by 12 noon

CENTRAL VALLEY CVCWA CLEAN WATER ASSOCIATION
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October 23, 2008

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Via Electronic and U.S. Mail

Ms. Jeanine Townsend
Clerk to the Board
State Water Resources Control Board
P.O. Box 100
Sacramento, CA 95812
commentletters@waterboards.ca.gov

Subject: **Proposed Amendment to the Policy for Implementation of Toxics Standards for Inland Surface Waters, Enclosed Bays, and Estuaries of California (the "SIP") to Establish Water Quality Objectives (WQOs) for Cadmium and Related Implementation Methods, CEQA Scoping Comments**

Dear Ms. Townsend:

The California Association of Sanitation Agencies (CASA), the Central Valley Clean Water Association (CVCWA), the Southern California Alliance of POTWs (SCAP) and Tri-TAC (collectively, "the Associations") appreciate the opportunity to provide our scoping comments regarding the proposed amendment to the Policy for Implementation of Toxics Standards for Inland Surface Waters, Enclosed Bays, and Estuaries of California (the "SIP") to establish water quality objectives (WQOs) for cadmium and related implementation methods. The constituency base for the Associations collects, treats and reclaims more than two billion gallons of wastewater each day and serves most of the sewered population of California.

We understand the State Water Board has requested early public comments by affected parties regarding the range of alternatives to be considered and the potential environmental impacts of those alternatives as part of the CEQA Scoping phase of proposed action. The proposed action merits significant attention since it involves the adoption of a statewide water quality objective for cadmium that will pertain to a number of important regulatory actions in California, including NPDES permitting, 303(d) listings and TMDL development. Because the proposed water quality objective for cadmium is significantly more stringent than the existing objective, its adoption could have considerable impacts on wastewater dischargers throughout the state.

The proposed amendments are also important because, in addition to establishing water quality objectives for cadmium, they would potentially establish implementation procedures for not only cadmium, but all other metals with hardness-based objectives as well. These metals include copper, chromium (III), lead, nickel, silver and zinc. Because these constituents are present in essentially all wastewater discharges, the proposed amendments could potentially have notable impacts throughout the state.

Proposed Alternatives

The notice issued by the State Water Board on June 16, 2008, describes three alternatives regarding adoption of a statewide water quality objective for cadmium, as follows:

(1) No action – Allow the cadmium objectives contained in the CTR to remain in force in California.
(2) Adopt the USEPA 2001 cadmium objectives for saltwater and fresh water regimes, with the exception that the freshwater cadmium objectives would be based on the default hardness value of 100 mg/L as $CaCO_3$.
(3) Adopt the USEPA 2001 cadmium objectives for saltwater and fresh water regimes. The USEPA fresh water cadmium objectives would be adjusted based on the hardness of the waters to which the objectives pertain. Additionally, an implementation policy would be developed to specify the hardness selection.

Our understanding is that California objectives will only be effective after the United States Environmental Protection Agency issues a rule amending the federal regulations to withdraw the federally applicable criteria from the CTR.[1]

Of the three alternatives described in the State Water Board's June 16, 2008 notice, the Associations have significant concerns regarding the appropriateness and

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[1] U.S. EPA clarified its process in approving site specific objectives for copper and nickel in San Francisco Bay: "Under the procedures set out in the National Toxics Rule, published December 22, 1992 (see 57 FR 60860, December 22, 1992), and referenced in the CTR, when a state adopts and EPA approves water quality criteria that meet the requirements of the CWA, EPA will issue a rule amending the federal regulations to withdraw the federally applicable criteria. If the State's criteria are no less stringent than the promulgated Federal criteria, EPA will withdraw its criteria without notice and comment rulemaking because additional comment is unnecessary. (68 Fed. Reg. 62744, 62746 (November 6, 2003).)

attainability of Alternative 2. Given that the cadmium criteria are dependent on the hardness of ambient waters (i.e. the conditions that organisms are exposed to), it would be technically and environmentally unsound to adopt an objective that is correct only in the rare case where the ambient hardness was equal to the fixed value upon which the objective would be based (e.g. hardness of 100 mg/L as $CaCO_3$). In some waters, the resulting effluent limitations may be insufficiently protective, while in many waters of the state the effluent limitations based on the fixed criteria would be unnecessarily stringent and costly to meet. Neither the costs of monitoring to determine actual hardness conditions, nor the effort to determine appropriate hardness values for interpretation of the objectives, rise to the level of significance to justify such an approach.

Alternative 1 should be selected only if it is shown that new objectives based on best available information would not represent a significant change from the California Toxics Rule (CTR) criteria.

New Alternative(s) to be Considered

The Associations recommend that the State Water Board add one or more additional alternatives to the list under consideration. The alternative(s) should address the following:

Updated objectives derived through recalculation of the USEPA 2001 criteria using USEPA approved methodologies based on the consideration of additional data not used in the 2001 USEPA criteria derivation. For example, new data is available for freshwater chronic toxicity caused by cadmium. This data meets USEPA data acceptability requirements for criteria derivation, and was used in development of water quality criteria for cadmium in the state of Colorado. These water quality criteria were subsequently approved by the USEPA. Similar work on updating the 2001 USEPA 2001 cadmium criteria with newer data has been performed in Idaho and is being proposed in New Mexico. Use of the additional data available in deriving cadmium objectives for California will allow the state to have more robust objectives that are based on the most recent science. Included with this letter is a technical report that presents the new data that is available and outlines a proposed set of cadmium objectives that incorporate the data.

Objectives expressed as proposed values multiplied by a Water Effect Ratio (WER). The CTR expresses trace metal criteria in California as a value times a WER, consistent with the USEPA Metals Policy (refer to May 2000 CTR (131.38 (b)(1), footnote i). California should incorporate the same approach to improve the site-specific applicability of cadmium trace metals objectives.

Implementation of hardness-based metals criteria using a technically sound approach. Because the proposed criteria for cadmium depend on hardness, it is not possible to adequately evaluate the environmental impacts of adoption of the criteria unless the method of implementation is known. Therefore, if different implementation methods are being considered for adoption, they should each be considered a separate alternative. This is particularly important because the State Water Board has indicated that any implementation method would likely be applied to other hardness-based metals as well.

Further discussion of the technical issues related to these proposed alternatives is provided below.

Cadmium Objective Determination

As stated above in the discussion of alternative proposals, the Associations endorse cadmium objectives comprised of a numeric value, derived from a hardness-adjusted formula where appropriate (e.g. fresh water), multiplied by a Water Effect Ratio, following the approach used in the May 2000 CTR (131.38 (b)(1), footnote i).

Furthermore, cadmium objectives should be based on the latest available data that passes USEPA criteria for data acceptability. At a minimum, the Associations recommend that the proposed cadmium freshwater objective should be based on a recalculation of the USEPA 2001 criteria using available chronic toxicity data for Daphnia. Preferably, we would recommend use of a recent, comprehensive update of the entire cadmium toxicity database.

GEI Consultants, Inc (GEI), Ecological Division, recently revised and updated current water quality objectives for cadmium, based on the USEPA criteria derivation methods. Extensive literature review on acute and chronic cadmium data resulted in many new data points added to the national toxicity database. USEPA methods for criteria derivation were followed to calculate an updated FAV/FCV for cadmium and provide updates to the corresponding equations. These updated equations are a result of the literature review, additional data on new and existing species in the toxicity databases, and reduced variability in the four most sensitive species. The resulting equations, including application of conversion factors for total to dissolved cadmium objectives, would be:

$$\text{Acute Cd} = 1.136672-[(\ln(\text{hardness})*(0.041838)] \quad e^{0.9151[\ln(\text{hardness})]-3.2488}$$
$$\text{Acute}_{(\text{trout})}\ \text{Cd} = 1.136672-[(\ln(\text{hardness})*(0.041838)]\ e^{0.9151[\ln(\text{hardness})]-3.6236}$$
$$\text{Chronic Cd} = 1.101672-[(\ln(\text{hardness})*(0.041838)]e^{0.7998[\ln(\text{hardness})]-4.4255}$$

These equations represent the most up-to-date science and, therefore, the Associations recommend their adoption as cadmium water quality objectives in California, with the appropriate WER adjustment and provisions to allow the equations to be adjusted with site-specific total to dissolved cadmium ratios. A technical report detailing the full basis for these equations is included with this letter.

Hardness

The method by which hardness-based criteria will be implemented merits considerable attention. Choice of an implementation method will have far-reaching impacts across the state, as essentially all wastewater discharges contain metals. The extent to which these metals may be toxic to aquatic life are evaluated by hardness-based criteria. It is therefore essential to adopt a scientifically sound approach that is appropriately protective of the state's water bodies without being overly stringent. Adoption of an overly stringent implementation method could result in installation of unnecessary wastewater treatment to meet the resulting overly stringent criteria, with significant associated adverse economic and environmental impacts and no additional environmental benefit.

The Associations have conducted a detailed technical analysis of the appropriate hardness to use for implementation of hardness-based metals criteria, and derived a recommended implementation approach. The full analysis is included with this letter, as is a summary of the analysis. The recommended approach ensures that the associated effluent concentration will not cause or contribute to exceedances of criteria in possible blends of effluent and receiving water. This is the case irrespective of whether ambient hardness is less than or greater than effluent hardness or metals concentrations in the receiving water. This approach yields criteria for the effluent, and subsequent effluent limits if necessary, that provide the intended level of protection to aquatic organisms in the whole effluent and possible blends of effluent and receiving water. The results do not depend on a mixing zone for dilution, and no regulatory mixing zone is required to ensure protection of aquatic life in the receiving water.

The approach relies on simultaneous consideration of effluent hardness, receiving water hardness, and blending of effluent and receiving water. Depending on the mathematical properties of the relationship between metal concentration and hardness, certain conclusions can be drawn regarding the effects of hardness and blending. The resulting equations for total recoverable criteria assuming the default WER to derive WQBELs for hardness-dependent metals are given below:

Chronic:

Cadmium, Copper, Chromium (III), Nickel, and Zinc:

$CCC_{eff} = \exp\{m_c * \ln(hardness_{eff}) + b_c\}$

Lead and Silver:

$$CCC_{eff} = \{(m_c/hardness_{R1})*(hardness_{eff} - hardness_{R1}) + 1\}*\exp\{m_c*\ln(hardness_{R1}) + b_c\}$$

Acute:

Copper, Chromium (III), Nickel, and Zinc:

$$CMC_{eff} = \exp\{m_A*\ln(hardness_{eff}) + b_A\}$$

Cadmium, Lead, and Silver:

$$CMC_{eff} = \{(m_A/hardness_{R1})*(hardness_{eff} - hardness_{R1}) + 1\}*\exp\{m_A*\ln(hardness_{R1}) + b_A\}$$

$Hardness_{eff}$ and $hardness_{R1}$ are the effluent and upstream receiving water hardness, respectively, and m_A, b_A, m_C, and b_c are constants that have previously been determined through the criteria calculation process for each of the trace metals. For the case of the chronic criteria for cadmium, copper, chromium (III), nickel, and zinc, and for the case of the acute criteria for copper, chromium (III), nickel and zinc, the criteria is simply the equation in the CTR, calculated using effluent hardness. For the case of the chronic criteria for lead and silver, and for the case of the acute criteria for cadmium, lead, and silver, the criteria depend upon the upstream receiving water hardness and the effluent hardness.

Use of this approach is fully protective of aquatic life in receiving water, and resolves many difficult issues that would otherwise have to be addressed on an individual permit basis. However, in some cases use of the above approach will result in overly stringent criteria. Therefore, an option should be provided to allow dischargers to propose an alternative approach that is sufficiently protective.

Additionally, note that these equations express the CMC and CCC as total recoverable values. A total to dissolved translator would also have to be included when criteria are developed.

Environmental Impacts

If the Water Board pursues either Alternative 2 or 3, many of our member agencies will face significant compliance challenges. Members of the Associations, particularly in the Central Valley and Southern California areas, have indicated that they would not likely be able to comply with criteria contemplated under Alternatives 2 or 3. Alternative methods of compliance would need to be employed by dischargers, and thus the foreseeable environmental impacts associated with these alternative method need to be evaluated. Specific alternative methods of compliance and reasonably foreseeable environmental impacts in several areas are detailed below.

Air

It is reasonably foreseeable that dischargers will need to install advanced treatment to achieve significant trace metals removal to comply with cadmium water quality standards, and potentially to comply with water quality standards for other hardness-based metals if an overly stringent implementation policy for hardness-based metals is adopted. While several different treatment options are available, reverse osmosis (RO) is a likely method of treatment. RO is highly energy intensive, resulting in increased electrical demands and associated air quality degradations including the release of atmospheric pollutants and greenhouse gases. It requires approximately 3,750 kWh to incorporate RO treatment for every million gallons of tertiary-treated wastewater. For a typical 20 MGD facility, this would result in an additional 27,375 MWh of energy usage per year. This would result in an annual increase of over 17,000 tons of CO_2, 7.5 tons of NO_x, and over 200 pounds of SO_2.[2] These CO_2 emissions are equivalent to over 2,800 passenger vehicles or 1.7 million gallons of gasoline. It has been estimated that the total volume from POTWs to rivers and effluent dominated waterbodies is approximately 1000 mgd. If all of these POTWs had to install RO treatment on their full flow, it would result in an additional 1,368,750 MWh of energy usage per year, with a resulting annual increase of over 850,000 tons of CO_2, 375 tons of NO_x, and over 10,000 pounds of SO_2. The resulting CO_2 emissions would be the equivalent of putting 140,000 passenger vehicles on the road, or use of 85 million gallons of gasoline annually.

Additionally, when RO is employed, approximately 15 to 20% of the water entering the RO treatment unit is wasted as brine, which cannot be discharged to inland freshwater surface waters. For the inland dischargers that do not have access to a brine line, additional drying and disposal methods must be employed which can also significantly increase atmospheric pollution through additional energy use and transportation.

Water and Groundwater

Furthermore, as discussed above, if Alternatives 2 or 3 are adopted it is reasonably foreseeable that some dischargers may install RO treatment to comply with metals water quality standards. The resulting brine waste, which cannot be discharged to most inland surface waters, would decrease surface water flow in some basins. Changes to surface water flow patterns could also impact groundwater flow patterns, as some surface waters have a hydraulic connection with ground waters. The State Board needs to fully evaluate the methods of compliance available and their reasonably foreseeable impacts on water and groundwater flows.

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[2] Based on average 2002 emissions data from all California power generating facilities.

Plant Life and Animal Life

As discussed above, if Alternatives 2 or 3 are adopted it is reasonably foreseeable that some dischargers may install additional treatment to comply with metals water quality standards. The State Board needs to fully evaluate the methods of compliance available and their reasonably foreseeable impacts on plant life and animal life.

Energy

If Alternative 2 or 3 is adopted, dischargers that are unable to divert flows will need to incorporate advanced treatment capable of reducing metals, potentially resulting in increased electrical demands. As previously discussed, it will require approximately 3,750 kWh to incorporate advanced RO treatment for every million gallons of tertiary-treated wastewater, resulting in an additional 27,375 MWh of energy annually for a single 20 MGD facility or a total of 1,368,750 MWh of energy annually if all POTWs discharging to rivers or effluent dominated waterbodies had to install full RO treatment

Cost Considerations

Adoption of Alternatives 2 or 3 could have considerable cost implications for dischargers. If RO treatment is necessary, considerable costs would be incurred. Using a Cost Parametric Estimating System, the approximate cost to install RO treatment (with pretreatment using microfiltration) for facilities from 5 to 50 MGD is $1,055,000 x (Flow, MGD) + $6,918,000. For a 20 MGD facility, the capital cost is approximately $28 million. The State Water Board needs to fully explore the potential costs of compliance of implementation of the proposed policy. To the extent that a methodology for determining hardness is included as part of this effort, the State Water Board should evaluate the costs and environmental impacts which may result as a result of the proposed hardness methodologies for all metals that are hardness dependent.

Legal and Policy Issues

In light of the attainability issues and potential adverse environmental impacts raised by the development of revised water quality objectives, it is critical that the Water Board thoroughly analyze the factors required under Water Code Section 13241, in particular consideration of ability to achieve proposed objective and the economics of compliance and Section 13242, consideration of the means by which the proposed objective would be achieved.

The State Water Board is to regulate to attain the highest water quality that is "reasonable." (Water Code §13000.) The Water Boards are under "an affirmative duty to consider economics when adopting water quality objectives in water quality control plans." (Memorandum to Regional Water Board Executive Officers from William R. Attwater, Chief Counsel, January 4, 1994 at p.1.) To fulfill this duty, the State Water Board must assess the costs of the proposed WQOs for cadmium, including a review of available information to determine:

- Whether the objective is currently being attained.
- What methods are available to achieve compliance with the objective, if it is not currently being achieved.
- The costs of those methods. (Ibid.)

The Associations question whether an amendment to the SIP is the proper vehicle for adopting statewide water quality objectives. The State Water Board may adopt water quality control plans for waters of the United States. (Water Code §13170.) Such plans are to be developed in accordance with Water Code sections 13241 through 13244, which set forth specific factors to be considered in developing water quality objectives, and require development of an implementation program to achieve objectives. However, the SIP is arguably not a water quality control plan and specifically does not apply to either storm water or combined sewer overflows. The State Water Board should address these issues in its follow up to the CEQA scoping meeting.

Our Associations appreciate the opportunity to make these early comments regarding proposed cadmium objectives and seek to work collaboratively with the State Water Board in the adoption of objectives and implementing provisions that provide reasonable protection for beneficial uses in California.

Sincerely,

Roberta L Larson
Roberta Larson, CASA

Jim Colston
Jim Colston, Tri-TAC

Debbie Webster
Debbie Webster, CVCWA

J Pastore
John Pastore, SCAP

Attachments:

- Attachment 1: Summary of Hardness Approach
- Attachment 2: Cadmium Criteria Update

RLL:mb

Attachment 1:

Summary of Hardness Approach

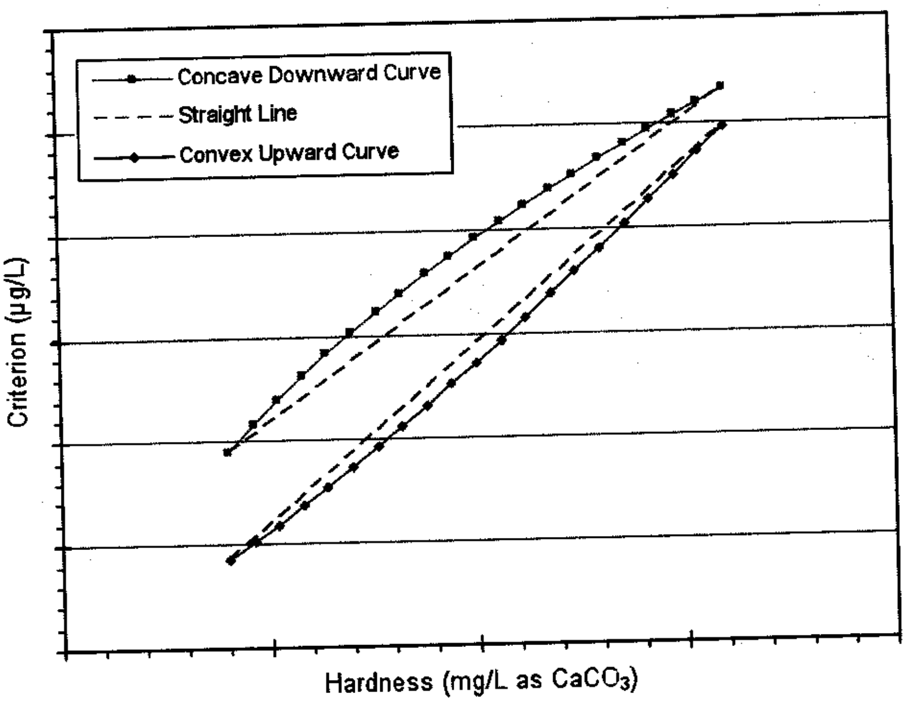


Figure 1: Metals Criteria Curve Shapes with Reference Straight Lines it Highlight Curvature.

The following are the curve shapes for acute and chronic criteria for the following metals:

Downward: Cadmium (chronic), Chromium (III), Copper, Nickel, Zinc
Upward: Cadmium (acute), Lead, Silver (acute)

Both the CTR and SIP state that criteria should be properly adjusted for hardness. Lacking in the CTR and the SIP is a discussion of where hardness should be measured and what value of hardness should be used to determine compliance with water quality criteria but it is generally understood that any water quality-based effluent limit should not cause or contribute to a receiving water WQO exceedance. In instances where an upstream receiving water is exceeding the WQO, it can be assumed that the receiving water is listed as impaired on the 303(d) list and that a TMDL with calculated waste load allocations (WLAs) is in place or is at least being developed to address the impairment. Furthermore, lacking a TMDL, it is still possible to demonstrate that the discharge is not contributing to the exceedance. Therefore, the most critical condition necessary to consider when selecting the appropriate hardness selection for hardness-adjusted trace metal effluent limit calculations under the CTR would be a condition where the receiving water and effluent discharge metal concentrations are both at the WQO calculated using at their respective hardness levels. The process for selecting the appropriate hardness that results in trace metal objectives protective under these conditions differs depending on the metal and its distinctive curve shape.

Selection of Hardness Values for derivation of water quality –based effluent limitations for trace metals

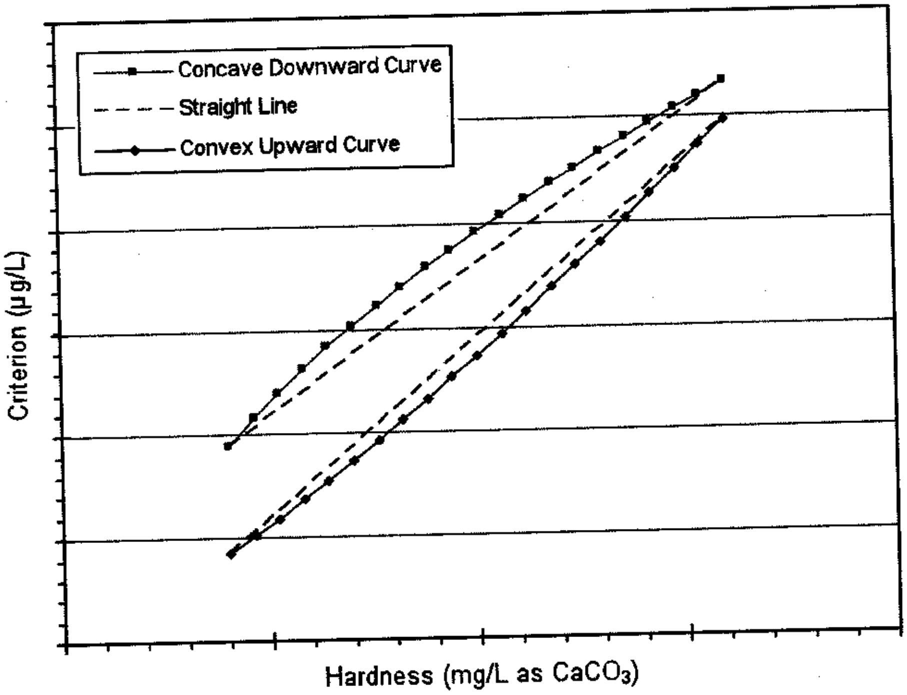
Mitchell J Mysliwiec; Tom Grovhoug, Larry Walker Associates, Davis, CA

October, 2008

As established in the California Toxics Rule (CTR), the calculation of water quality objectives (WQOs) for some trace metals are dependent on the water column hardness. Toxicity testing has demonstrated that toxic effects associated with these metals is a function of the concentration of dissolved metal and the co-occurring hardness concentration that aquatic organisms are exposed to in receiving waters with increasing toxic effects observed as hardness decreases. The trace metals with hardness-dependent criteria are:

- Cadmium
- Chromium (III)
- Copper
- Lead
- Nickel
- Silver
- Zinc

The CTR provides mathematical formulas to determine WQOs at varying hardness for each of these metals and these formulas can be represented as curves with one of two distinct shapes: either (a) downward facing (concave) or (b) upward facing (convex) as illustrated in Figure 1 A straight line is included for each curve to highlight the "upward" and "downward" curvature.



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Both the CTR and SIP state that criteria should be properly adjusted for hardness. Lacking in the CTR and the SIP is a discussion of where hardness should be measured and what value of hardness should be used to determine compliance with water quality criteria but it is generally understood that any water quality-based effluent limit should not cause or contribute to a receiving water WQO exceedance. In instances where an upstream receiving water is exceeding the WQO, it can be assumed that the receiving water is listed as impaired on the 303(d) list and that a TMDL with calculated waste load allocations (WLAs) is in place or is at least being developed to address the impairment. Furthermore, lacking a TMDL, it is still possible to demonstrate that the discharge is not contributing to the exceedance. Therefore, the most critical condition necessary to consider when selecting the appropriate hardness selection for hardness-adjusted trace metal effluent limit calculations under the CTR would be a condition where the receiving water and effluent discharge metal concentrations are both at the WQO calculated using at their respective hardness levels. The process for selecting the appropriate hardness that results in trace metal objectives protective under these conditions differs depending on the metal and its distinctive curve shape.

Cadmium (chronic), Chromium (III), Copper, Nickel, Zinc

For cadmium (chronic), chromium (III), copper, nickel, zinc (downward facing criteria curves), using effluent hardness will result in a WQO that is protective throughout the receiving water regardless of effluent or receiving hardness. The scatter plot in Figure 2 illustrates the copper CCC calculated at a hardness ranging from 40 to 160 mg/L $CaCO_3$. If we assume that the background ambient receiving water (R1) is represented by the 40 mg/L $CaCO_3$ hardness data point and the effluent is represented by the 160 mg/L $CaCO_3$ hardness data point, the straight dashed line connecting the two represents the entire range of possible receiving water metal concentrations affected by the discharge due to the blending of the effluent and receiving water, noting that infinite dilution would be required to reach the ambient background levels. The metal concentration across this inclusive range is at or below the calculated CCC. The most critical point in the receiving water is at the point of discharge where the metal concentration equals the criterion. The same holds true if we assume that the background ambient receiving water is represented by the 160 mg/L $CaCO_3$ hardness data point and the effluent is represented by the 40 mg/L $CaCO_3$ hardness data point, where the labels "Point of Discharge" and "Infinite Dilution" would be switched in Figure 2. Therefore, using receiving water hardness at the point of discharge best represented by the effluent hardness for all metals exhibiting a downward facing curve (Cadmium (chronic), Chromium (III), Copper, Nickel, Zinc) will result in sufficiently protective objectives across the entire range of receiving water condition.

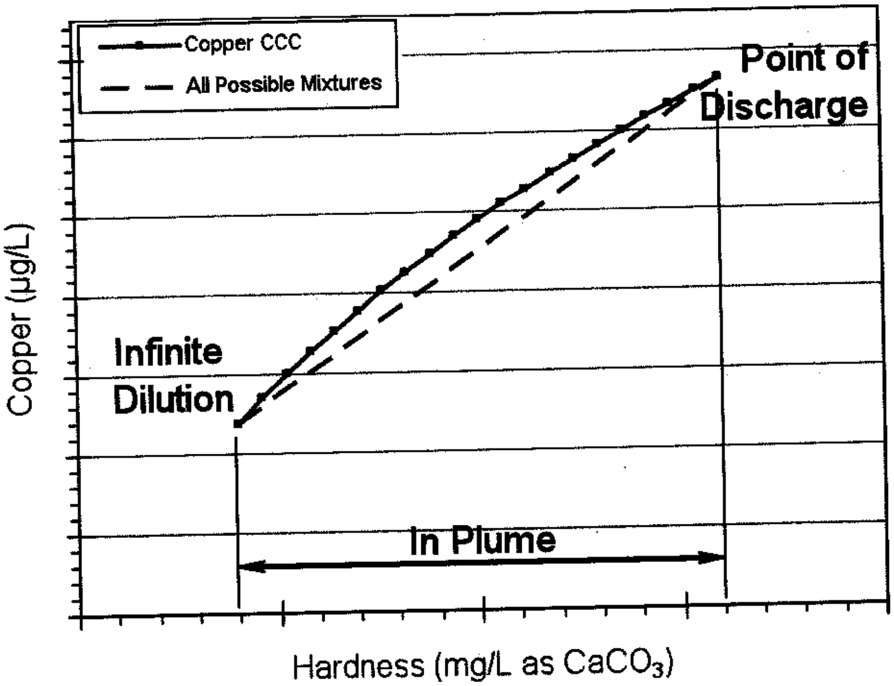


Figure 2: Copper Chronic Criterion Typical of all Metals with Downward Facing Criteria Curves.

Cadmium (acute), Lead, Silver (acute)

For metals represented by upward facing curves (acute cadmium, lead, and silver), a slightly modified approach is required for these metals to ensure that effluent limits will always be protective along the discharge gradient. The scatter plot in Figure 3 illustrates the lead CCC calculated at a hardness ranging from 40 to 160 mg/L $CaCO_3$. If we assume that the ambient background receiving water is represented by the 40 mg/L $CaCO_3$ hardness data point and the effluent is represented by the 160 mg/L $CaCO_3$ hardness data point lower, the straight dashed line connecting the two represents the entire range of possible receiving water metal concentrations based on the blending of the effluent and receiving water. Unfortunately, the metal concentration across this inclusive range is not at or below the calculated CCC indicating that using only effluent hardness to calculate the CCC would not be protective of all possible receiving water conditions. In fact, using effluent hardness alone would only be protective if the receiving water and effluent hardness were equal. Furthermore, use of only the receiving water hardness would only be protective if the upstream hardness was lower than or equal to the effluent levels. The use of a modified approach is necessary to account for the possibility of the receiving water hardness being greater or less than the effluent hardness. For this approach, it is necessary to project a tangent line from the receiving water hardness point on the characteristic curve to a point of intersection with the vertical line extending down from the effluent hardness point on the characteristic curve. This one approach results in criteria that are protective for any combination of effluent and receiving water hardness levels and amount of available dilution. This approach is illustrated in Figure 3 by the straight line tangent to the criteria curve at the ambient background criterion. As is evident in Figure 3, the metal concentration across this inclusive range is at or below the calculated CCC across the entire range of possible effluent/receiving water combinations. The case where ambient background hardness is greater than the effluent hardness is illustrated in Figure 4. The determination of this controlling criteria value requires the use of both effluent and receiving water hardness data in the following formula:

$$CCC_{eff} = \left\{\frac{m_C}{H_{R1}} \cdot \left(H_{eff} - H_{R1}\right) + 1\right\} \cdot exp\left\{m_C \cdot ln\left(H_{R1}\right) + b_C\right\}$$

$$CMC_{eff} = \left\{\frac{m_A}{H_{R1}} \cdot \left(H_{eff} - H_{R1}\right) + 1\right\} \cdot exp\left\{m_A \cdot ln\left(H_{R1}\right) + b_A\right\}$$

Note that in cases where the effluent hardness is low (generally below 100 mg/L as $CaCO_3$) and the receiving water hardness is much greater than the effluent hardness, the formulas may result in a negative criterion. Under these conditions, a simple criterion for the effluent cannot be calculated without considering the available assimilative capacity of the receiving water. Generally, the condition resulting in negative criteria does not occur.

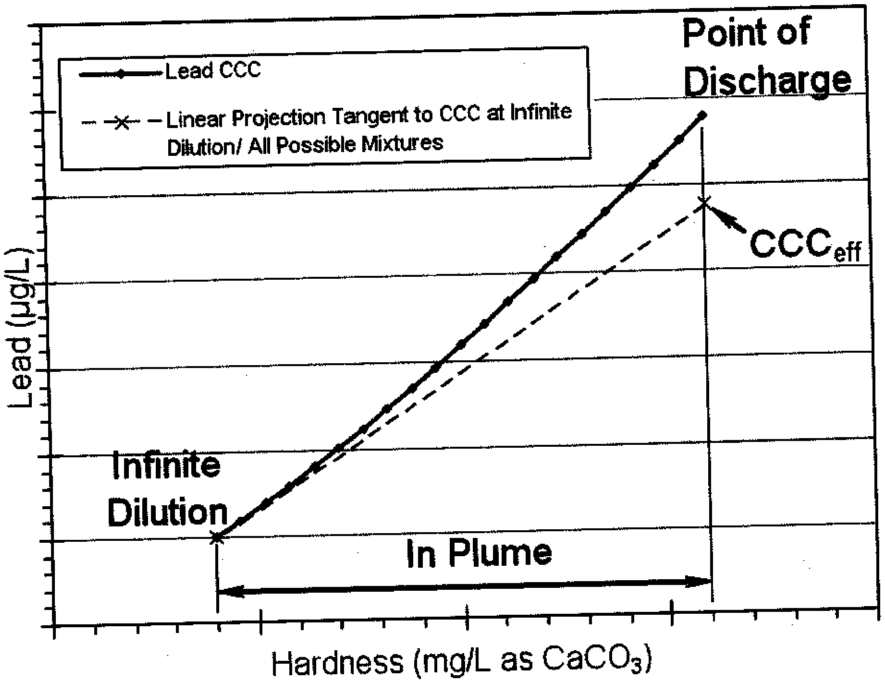


Figure 3: Lead Chronic Criterion Typical of all Metals with Upward Facing Criteria Curves where Effluent Hardness is Greater than Receiving Water Hardness.

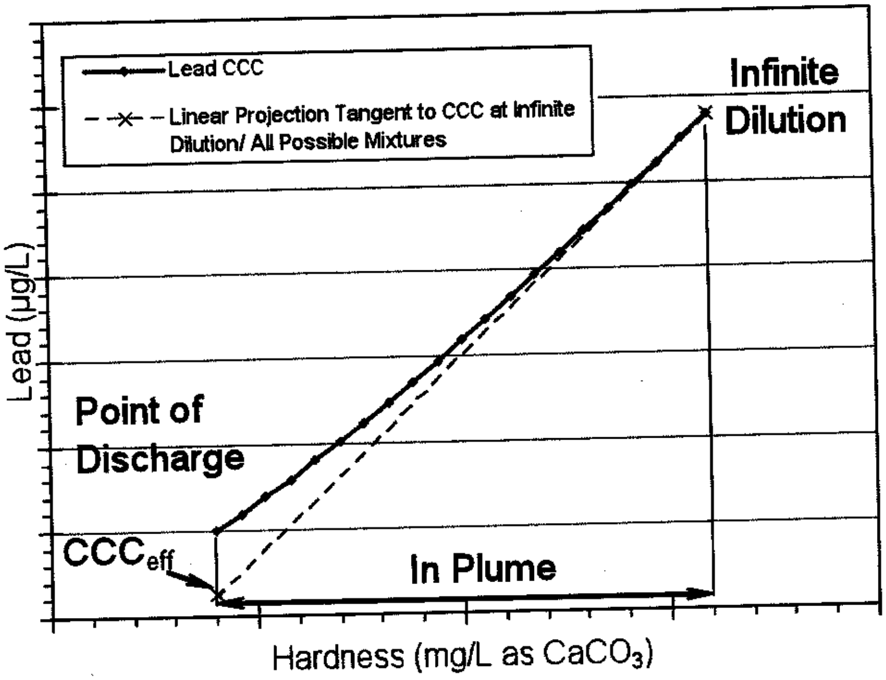


Figure 4: Lead Chronic Criterion Typical of all Metals with Upward Facing Criteria Curves where Effluent Hardness is Less than Receiving Water Hardness.

Concerning Upstream WQO Exceedances

If the receiving water exceeds a WQO upstream of the discharge, using the above method will also ensure that the discharge does not cause or contribute to the exceedance. In fact the above method will result in improved water quality for all blends of effluent and receiving water. For example if the upstream receiving water in the above examples exceeded WQOs by a factor of 1.4, all possible concentrations of effluent and receiving water are plotted in Figure 5. The information in Figure 5 is plotted as percent of criterion and percent effluent in Figure 6. The critical feature of Figure 6 is that for all concentrations of effluent and receiving water, the blend is closer to or below WQOs. The discharge with effluent WQOs based on effluent hardness for downward facing curves (copper) and upward facing curves (lead) does not cause of contribute to exceedances in the receiving water.

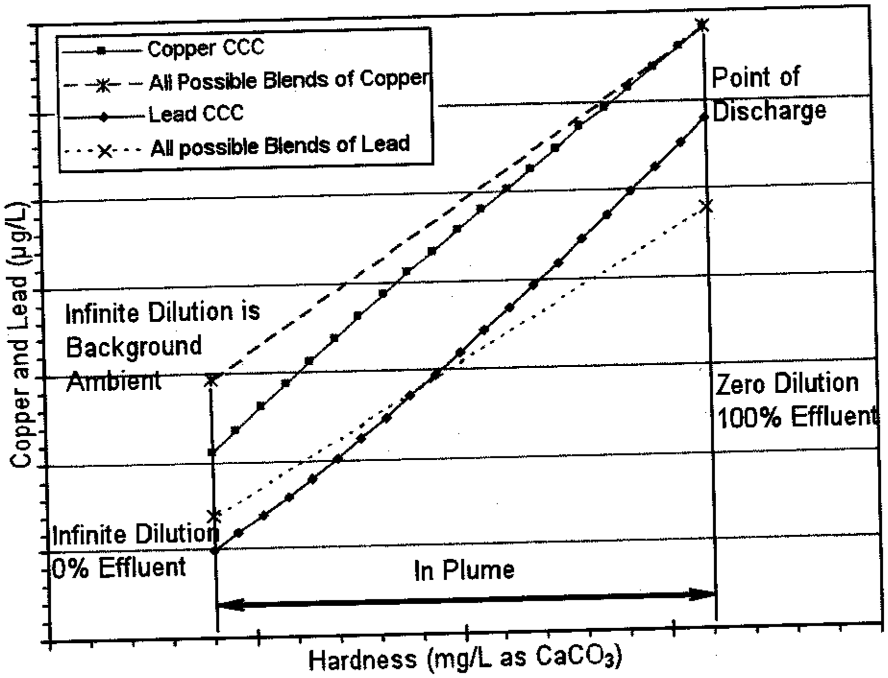


Figure 5: Copper and Lead Criteria and In plume Concentrations for Ambient Background Exceeding Criteria by a Factor of 1.4.

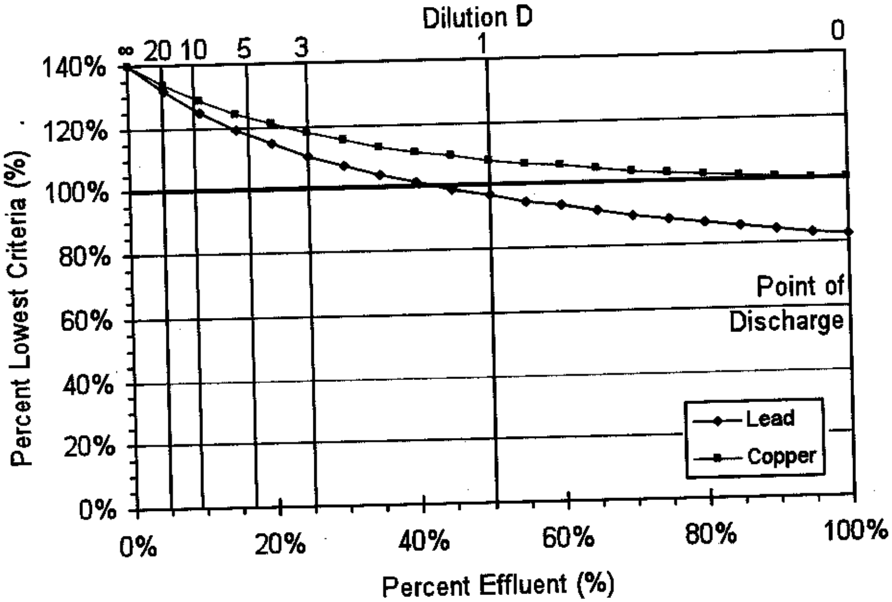


Figure 6: Percent of Lowest Criteria for Blends of Effluent and Receiving Water. For the Example of R1 Exceeding WQOs by a Factor of 1.4 and Effluent Meeting Criteria Based.

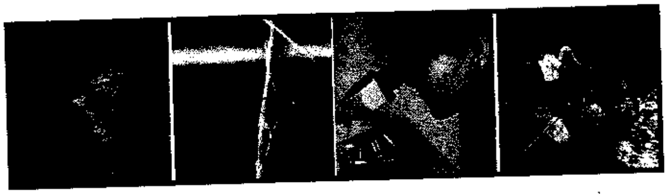
Conclusions

For trace metals with concave (downward curved) hardness dependent criteria (cadmium (chronic), chromium (III), copper, nickel, zinc), selecting the effluent hardness as representative point of discharge receiving water hardness will result in effluent criteria protective of receiving water aquatic life regardless of receiving water flowrate or hardness levels. For trace metals with convex (upward curved) hardness dependent criteria (cadmium (acute), lead, silver (acute)), both background ambient hardness and effluent hardness must be utilized to determine the effluent criteria protective of receiving water affected by the discharge. Where the effluent hardness is low and the receiving water hardness is much greater than the effluent hardness, consideration of the assimilative capacity of the receiving water may be necessary to determine the appropriate effluent criterion. In the case where the background ambient concentrations exceed the criteria, using the above hardness selection will result in effluent criteria such that the discharge will not contribute to the background exceedance.

The proposed hardness selection method is applicable to all discharges and receiving waters. All possible receiving water flowrates are considered from zero upstream flow to an infinite upstream flow. All possible combinations of background ambient hardness and effluent hardness are considered in the proposed method. The proposed method is developed for meeting criteria at the point of discharge (i.e. no dilution credits), but the method could be modified for regulatory mixing zones as applicable, by meeting criteria at the prescribed dilution at the edge of the mixing zone. The proposed method is uniformly applicable to all discharges and results in metals criteria for the effluent that are protective of aquatic life in all areas in the receiving water affected by the discharge.

Attachment 2:

Cadmium Criteria Update



GEI Consultants

Water Quality Objectives for Cadmium – Review and Update

Submitted to:
Santa Ana River Dischargers Association; Los Angeles County Sanitation District

Submitted by:
GEI Consultants, Inc.
Ecological Division
5575 South Sycamore Street, Suite 101
Littleton, Colorado 80120

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Water Resources
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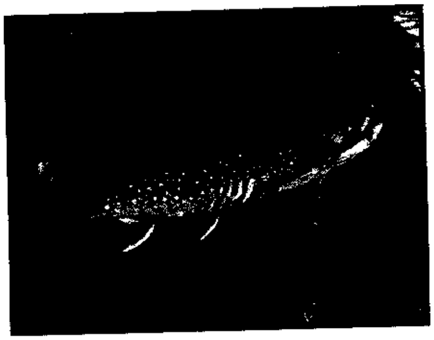

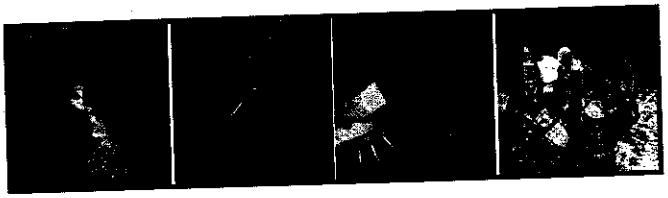

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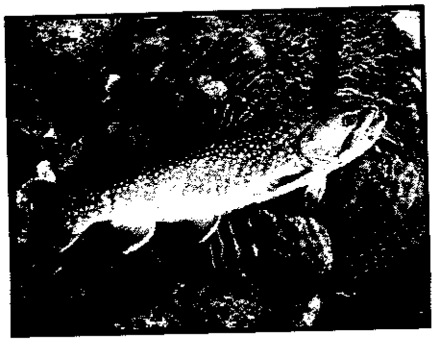

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The purpose of this analysis was to revise and update acute and chronic Cd objectives using EPA criteria derivation methods. This report is based primarily on a previous technical review and update of the 2001 revised EPA Cd criteria conducted by GEI (formerly Chadwick Ecological Consultants, Inc. CEC 2004a, 2004b).

The first step of the EPA recalculation procedure is a technical review of the most up-to-date EPA ambient water quality criteria (AWQC) documents to determine if 1) suitable and correct data were included in national toxicity databases, and 2) EPA criteria development methods were followed for deriving AWQC. The EPA's *Guidelines for Deriving Numerical Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses* (Stephan et al. 1985), hereafter referred to as the 1985 Guidelines, provide details on the acceptable data and criteria derivation methods, including minimum data requirements for the toxicity database, often referred to as the "eight-family rule" (Stephan et al. 1985). The next step is to update the national toxicity databases, with an emphasis on literature available since the most recently published database. Following the compilation of literature and development of the revised database, each acute and chronic AWQC is recalculated using methods as described by the 1985 Guidelines.

Current Cd objectives in California are based on an EPA report entitled *1995 Updates: Water Quality Criteria Documents for the Protection of Aquatic Life in Ambient Water* (EPA 1996). The EPA revised its aquatic life criteria for Cd on April 12, 2001, with the publication entitled *2001 Update of Ambient Water Quality Criteria for Cadmium* (EPA 2001) hereafter referred to as the 2001 Cadmium Document. This document established an updated (from the 1996 document) toxicity database with recommended AWQC to protect freshwater organisms. This 2001 update is the basis for recommended Cd objectives by the SWRCB staff, as outlined in the notice.

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2.1 2001 Acute Criteria for Cadmium

The 2001 Cadmium Document presents acute data for 55 genera of aquatic biota, including 39 species of invertebrates, 24 species of fish, one salamander, and one frog species. These 65 species satisfy the "eight-family rule" as specified in the 1985 Guidelines. However, we have determined three papers used in the 2001 Cadmium Document were unsuitable for acute criteria evaluation (Table 1).

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Species	Reference	Reason
Acute:		
Salvelinus fontinalis	Carroll et al. 1979	control had higher Cd concentration than LC_{50}, but no response
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Finally, data from Sunderman et al. (1991) for the African clawed frog (*Xenopus laevis*) were used in the acute criteria development in the 2001 Cadmium Document. *X. laevis* is not native to North America. In fact, its distribution in North America is restricted to isolated regions in the southwestern U.S. where it was accidentally introduced and is considered a pest species.

After data from the aforementioned publications were removed from the acute database, the resultant acute database consists of 64 species occupying 54 genera. Only one species (*X. laevis*) constituting the entire data set for its genus was removed entirely from the revised acute database. The "eight-family rule" is still met by this database according to the 1985 Guidelines.

2.2 Existing Chronic Criteria for Cadmium

The 2001 Cadmium Document presents chronic data for 16 genera of freshwater organisms, including seven species of invertebrates and 14 species of fishes. These 21 species satisfy the "eight-family rule" as specified in the 1985 Guidelines. The resultant revised chronic Cd database is the same as the 2001 Cadmium Document, in terms of the number and composition of genera and species, following the Phase 1 review.

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3.0 Phase 2 – Update to the National Cadmium Database

3.1 New Acute Cadmium Toxicity Data

A comprehensive literature review of all Cd documents not used in the 2001 Cd update was originally conducted by GEI in 2004 (CEC 2004a). This included a review of all documents published since the 2001 Cadmium Document, as well as those published prior to 2001 that were not used in the criteria derivation. Relevant Cd toxicity documents were obtained and reviewed for relevance of the toxicological data and adherence to EPA methodology (Stephan et al. 1985). Approximately 130 papers were reviewed, including unpublished toxicity data from recent studies conducted on behalf of Thompson Creek Mining Company (TCMC) (CEC 2003), as well as acute and chronic trout toxicity data from the Colorado Division of Wildlife (CDOW) published as "Federal Aid to Fisheries" (i.e., gray literature) reports.

Following review of these studies, we were able to add 21 acute data points from seven studies to the revised acute Cd database (Table 2). Of the seven studies added to the database, four were published prior to the 2001 Cadmium Document. Two of these studies published prior to 2001 were not cited in either Table 1a (Acute toxicity of Cd to freshwater animals) or Table 6a (Other data on effects of Cd on freshwater organisms) of the 2001 Cadmium Document and apparently represent data unknown to EPA.

Suedel et al. (1997) tested the effects of exposure duration, test organism, and test endpoint on the toxicity of Cd to a variety of freshwater species. Suitable acute 48- and 96-hour data points were reported in this study for *Ceriodaphnia dubia*, *D. magna*, *Pimephales promelas*, *Hyalella azteca*, and *Chironomus tentans* and were incorporated into the revised acute database. The other study not mentioned in the 2001 Cadmium Document is an internal report published by the CDOW in which brown trout (*Salmo trutta*) were exposed to various concentrations of Cd sulfate in a static renewal toxicity test (Davies and Brinkman 1994). One acute value for *S. trutta* was utilized from this study. There are three studies listed in Table 6a ("Other Data") in the 2001 Cadmium Document that we believe provide useful data. One data point for the arctic grayling (*Thymallus arcticus*) from Buhl and Hamilton (1991) was added to the revised acute Cd database. The data point is listed in Table 6a of the 2001 Cadmium Document because the EPA claims the toxicity test was conducted improperly due to low dissolved oxygen. Indeed, the authors stated there were dissolved oxygen problems in one of their selenite tests; yet, dissolved oxygen levels never fell below 40 percent saturation for their Cd tests. We believe this Cd data point is appropriate for use. Additional data listed in Table 6a of the 2001 Cadmium Document was for *Oncorhynchus mykiss* data from Davies et al. (1993), with no reason provided for the exclusion. Davies et al. (1993) tested acute and chronic toxicity of Cd to *O. mykiss* at three different target hardness values (50, 200, and 400 mg/L). The acute values listed in Table 6a are inconsistent

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Suedel et al. (1997) tested the effects of exposure duration, test organism, and test endpoint on the toxicity of Cd to a variety of freshwater species. Suitable acute 48- and 96-hour data points were reported in this study for *Ceriodaphnia dubia*, *D. magna*, *Pimephales promelas*, *Hyalella azteca*, and *Chironomus tentans* and were incorporated into the revised acute database. The other study not mentioned in the 2001 Cadmium Document is an internal report published by the CDOW in which brown trout (*Salmo trutta*) were exposed to various concentrations of Cd sulfate in a static renewal toxicity test (Davies and Brinkman 1994). One acute value for *S. trutta* was utilized from this study. There are three studies listed in Table 6a ("Other Data") in the 2001 Cadmium Document that we believe provide useful data. One data point for the arctic grayling (*Thymallus arcticus*) from Buhl and Hamilton (1991) was added to the revised acute Cd database. The data point is listed in Table 6a of the 2001 Cadmium Document because the EPA claims the toxicity test was conducted improperly due to low dissolved oxygen. Indeed, the authors stated there were dissolved oxygen problems in one of their selenite tests; yet, dissolved oxygen levels never fell below 40 percent saturation for their Cd tests. We believe this Cd data point is appropriate for use. Additional data listed in Table 6a of the 2001 Cadmium Document was for *Oncorhynchus mykiss* data from Davies et al. (1993), with no reason provided for the exclusion. Davies et al. (1993) tested acute and chronic toxicity of Cd to *O. mykiss* at three different target hardness values (50, 200, and 400 mg/L). The acute values listed in Table 6a are inconsistent

3.0 Phase 2 – Update to the National Cadmium Database

3.1 New Acute Cadmium Toxicity Data

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Table 2: Acute Cd toxicity data added to the acute database (CEC 2004a, 2004b).

Species	Method[a]	Chemical	Hardness (mg/L)	LC_{50} (µg/L)	Adjusted LC_{50}[b]	Reference
Ceriodaphnia dubia	S, M, T	$CdCl_2$	17	63.01	170.37	Suedel et al. 1997
Daphnia magna	S, M, T	$CdCl_2$	17	26.40	71.28	Suedel et al. 1997
Pimephales promelas	S, M, T	$CdCl_2$	17	4.80	12.96	Suedel et al. 1997
*Hyalella azteca**	S, M, T	$CdCl^2$	17	2.80	7.56	Suedel et al. 1997
*Chironomus tentans***	S, M, T	$CdCl_2$	17	2,956.00	7,981.27	Suedel et al. 1997
Salmo trutta	F, M, T	$CdSO_4$	37.6	2.37	3.08	Davies and Brinkman 1994
Salmo trutta	F, M, D	$CdSO_4$	151.4	3.66	3.66	Brinkman and Hansen 2004
Salmo trutta	F, M, D	$CdSO_4$	29.2	1.23	2.01	Brinkman and Hansen 2004
Salmo trutta	F, M, D	$CdSO_4$	67.6	3.9	2.96	Brinkman and Hansen 2004
*Thymallus arcticus** (juvenile)	S, M, T	$CdCl_2$	41	4.00	4.80	Buhl and Hamilton 1991
Oncorhynchus mykiss	R, M, T	$CdCl_2$	420 (388-490)	7.40	1.04	Davies et al. 1993
Oncorhynchus mykiss	F, M, T	$CdCl_2$	427 (406-444)	5.92	0.82	Davies et al. 1993
Oncorhynchus mykiss	F, M, T	$CdCl_2$	217 (203-240)	4.20	1.09	Davies et al. 1993
Oncorhynchus mykiss	F, M, T	$CdCl_2$	227 (212-243)	6.57	1.63	Davies et al. 1993
Oncorhynchus mykiss	F, M, T	$CdCl_2$	46 (45-48)	2.64	2.85	Davies et al. 1993
Oncorhynchus mykiss	F, M, T	$CdCl_2$	49 (48-50)	3.08	3.14	Davies et al. 1993
*Chironomus plumosus***	S, U	$CdCl_2$	80	12,700.00	8,238.92	Fargasova 2003
Daphnia magna	R, M, T	$CdCl_2$	50	4.00	4.00	CEC 2003
Daphnia magna	R, M, T	$CdCl_2$	100	8.00	4.23	CEC 2003
Daphnia pulex	R, M, T	$CdCl_2$	50	16.00	16.00	CEC 2003
Daphnia pulex	R, M, T	$CdCl_2$	100	20.00	10.57	CEC 2003

[a] S = static, R = renewal, M = measured, U = unmeasured, T = total measured concentration, F = flow-through, and D = dissolved measured concentration

[b] Value adjusted to hardness = 50 using the revised acute slope (0.9207) listed in Table 6.

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Salmo trutta	F, M, D	$CdSO_4$	151.4	3.66	3.66	Brinkman and Hansen 2004
Salmo trutta	F, M, D	$CdSO_4$	29.2	1.23	2.01	Brinkman and Hansen 2004
Salmo trutta	F, M, D	$CdSO_4$	67.6	3.9	2.96	Brinkman and Hansen 2004
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Oncorhynchus mykiss	R, M, T	$CdCl_2$	420 (388-490)	7.40	1.04	Davies et al. 1993
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Daphnia pulex	R, M, T	$CdCl_2$	50	16.00	16.00	CEC 2003
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* New genus.

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In early 2008, GEI supplemented the 2004 effort by conducting another scientific literature review to further update the Cd toxicity database. This search resulted in the addition of new acute data for five species (Table 3), two of which are new to the dataset, increasing the acute database from 56 to 58 genera.

Table 3: New acute Cd data from the literature review performed by GEI (2008).

Species	Common Name	Method	Hardness as $CaCO_3$ (mg/L)	Test Duration	LC_{50} (µg/L)	Adjusted LC_{50} (µg/L)	Reference
Salmo trutta	Brown trout	M, F	29.2	96-hr	1.23	2.01	Brinkman and Hansen 2007
Salmo trutta	Brown trout	M, F	67.6	96-hr	3.9	2.96	Brinkman and Hansen 2007
Salmo trutta	Brown trout	M, F	151	96-hr	10.1	3.67	Brinkman and Hansen 2007
Oncorhynchus mykiss	Rainbow trout	M, R	29	96-hr	0.84	1.38	Mebane et al. 2007
Oncorhynchus mykiss	Rainbow trout	M, R	20	96-hr	0.89	2.06	Mebane et al. 2007
Oncorhynchus mykiss	Rainbow trout	M, F	103	96-hr	4.7	2.43	Besser et al. 2007
Chironomus riparius	Midge		140	48-hr	1,106,000	431,083	Gillis and Wood 2007
Cottus bairdi	Mottled sculpin	M, F	103	96-hr	4.6	2.37	Besser et al. 2007
Cottus bairdi	Mottled sculpin	M, F, D	48.7	96-hr	1.92	1.97	CDOW 2007
Rhithrogena hageni	Mayfly	M, F, D	48	96-hr	10,500	10,900	CDOW 2007

3.2 New Chronic Cadmium Toxicity Data

Sixteen chronic data points from six studies were added by the revised chronic database (Table 4) as a result of the literature review in 2004. Two of these studies were published prior to 2001, and were not cited in the 2001 Cadmium Document. Suedel et al. (1997) examined the long-term chronic effect of Cd on several species, in addition to the acute effects previously mentioned. Long-term toxicity tests were conducted for the same five species (*C. dubia*, *D. magna*, *P. promelas*, *H. azteca*, and *C. tentans*) as the acute toxicity tests reported in that study. However, we only added the data for *C. dubia* to the revised chronic Cd database because the test duration for the other species did not meet EPA chronic criteria development standards (Stephan et al. 1985). Additionally, Davies and Brinkman (1994) conducted a long-term toxicity test of Cd on *S. trutta* in soft water that satisfies criteria development standards (Stephan et al. 1985). The reported chronic value from this study was added to the revised chronic database.

Two data sources (Canton and Slooff 1982 and Davies et al. 1993) were listed in Table 6a (Other Data) of the 2001 Cadmium Document as unused data for acute data points. However, both of these papers contain chronic data in addition to acute data. Chronic data from these papers are not mentioned in Table 2a (Chronic Toxicity of Cd to Freshwater Animals) or Table 6a. We determined three rainbow trout data points (Davies *et al.* 1993) and one *D. magna* data point (Canton and Slooff 1982) were suitable for use and added these data to the revised chronic database. Finally, chronic Cd tests were conducted on behalf of TCMC using three freshwater species, including *D. pulex*, *D. magna*, and *H. azteca* (CEC 2003). Chronic values from these tests were added to the revised chronic database.

In early 2008, GEI supplemented the 2004 effort by conducting another scientific literature review to further update the Cd toxicity database. This search resulted in the addition of new acute data for five species (Table 3), two of which are new to the dataset, increasing the acute database from 56 to 58 genera.

Table 3: New acute Cd data from the literature review performed by GEI (2008).

Species	Common Name	Method	Hardness as $CaCO_3$ (mg/L)	Test Duration	LC_{50} (µg/L)	Adjusted LC_{50} (µg/L)	Reference
Salmo trutta	Brown trout	M, F	29.2	96-hr	1.23	2.01	Brinkman and Hansen 2007
Salmo trutta	Brown trout	M, F	67.6	96-hr	3.9	2.96	Brinkman and Hansen 2007
Salmo trutta	Brown trout	M, F	151	96-hr	10.1	3.67	Brinkman and Hansen 2007
Oncorhynchus mykiss	Rainbow trout	M, R	29	96-hr	0.84	1.38	Mebane et al. 2007
Oncorhynchus mykiss	Rainbow trout	M, R	20	96-hr	0.89	2.06	Mebane et al. 2007
Oncorhynchus mykiss	Rainbow trout	M, F	103	96-hr	4.7	2.43	Besser et al. 2007
Chironomus riparius	Midge		140	48-hr	1,106,000	431,083	Gillis and Wood 2007
Cottus bairdi	Mottled sculpin	M, F	103	96-hr	4.6	2.37	Besser et al. 2007
Cottus bairdi	Mottled sculpin	M, F, D	48.7	96-hr	1.92	1.97	CDOW 2007
Rhithrogena hageni	Mayfly	M, F, D	48	96-hr	10,500	10,900	CDOW 2007

3.2 New Chronic Cadmium Toxicity Data

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In early 2008, GEI supplemented the 2004 effort by conducting another scientific literature review to further update the Cd toxicity database. This search resulted in the addition of new acute data for five species (Table 3), two of which are new to the dataset, increasing the acute database from 56 to 58 genera.

Table 3: New acute Cd data from the literature review performed by GEI (2008).

Species	Common Name	Method	Hardness as $CaCO_3$ (mg/L)	Test Duration	LC_{50} (µg/L)	Adjusted LC_{50} (µg/L)	Reference
Salmo trutta	Brown trout	M, F	29.2	96-hr	1.23	2.01	Brinkman and Hansen 2007
Salmo trutta	Brown trout	M, F	67.6	96-hr	3.9	2.96	Brinkman and Hansen 2007
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Table 4: Chronic Cd toxicity data added to the chronic database (CEC 2004a, 2004b).

Species	Method[a]	Chemical	Hardness (mg/L)	Chronic Value (µg/L)	Adjusted Chronic Value[b]	Reference
Ceriodaphnia dubia	LC	$CdCl_2$	17.0	2.00	4.459	Suedel *et al.* 1997
Salmo trutta	ELS	$CdSO_4$	39.8	1.33	1.576	Davies and Brinkman 1994
Daphnia magna	LC	$CdCl_2$	209.2	0.69	0.231	Canton and Slooff 1982
Oncorhynchus mykiss	LC	$CdCl_2$	46.2 (45-48)	1.47	1.559	Davies *et al.* 1993
Oncorhynchus mykiss	LC	$CdCl_2$	217.0 (203-240)	3.58	1.203	Davies *et al.* 1993
Oncorhynchus mykiss	LC	$CdCl_2$	413.8 (383-438)	3.64	0.757	Davies *et al.* 1993
Hyalella azteca	ELS	$CdCl_2$	280.0	1.40	0.389	Ingersoll and Kemble 2001
Daphnia magna	LC	$CdCl_2$	50.0	3.43	3.430	CEC 2003
Daphnia pulex	LC	$CdCl_2$	50.0	1.45	1.450	CEC 2003
Daphnia magna	LC	$CdCl_2$	50.0	2.32	2.320	CEC 2003
Daphnia magna	LC	$CdCl_2$	50.0	2.80	2.800	CEC 2003
Daphnia magna	LC	$CdCl_2$	100.0	2.60	1.553	CEC 2003
Daphnia pulex	LC	$CdCl_2$	50.0	2.50	2.500	CEC 2003
Hyalella azteca	ELS	$CdCl_2$	120.0	0.62	0.323	CEC 2003
Hyalella azteca	ELS	$CdCl_2$	150.0	0.73	0.323	CEC 2003
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[a] ELS = early life stage and LC = life cycle or partial life cycle.

[b] Value adjusted to hardness = 50 using the revised chronic slope (0.7432) found in Table 8.

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Species	Common name	Hardness	Chronic Value	Reference
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3.3 Updated Acute and Chronic Cadmium Toxicity Databases

After excluding inappropriate data used in the 2001 Cadmium Document and adding data deemed suitable for inclusion from our literature review, revised acute (Table 6) and chronic (Table 7) databases were compiled. These databases can serve as the basis for the subsequent recalculation of updated Cd water quality objectives. For each species with at least one acute value, the species mean acute value (SMAV) was calculated as the geometric mean of the individual acute values (Stephan *et al.* 1985). Results from all flow-through tests and those in which the concentrations of the test material were measured took precedence over tests using static or renewal methods and unmeasured concentrations (Stephan *et al.* 1985). For each genus with more than one SMAV, the genus mean acute value (GMAV) was calculated as the geometric mean of all available SMAVs for the genus. Otherwise, the GMAV was equal to the SMAV if data for only one species was available (Stephan *et al.* 1985).

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3.3.1 Updated Acute Database

The revised acute Cd AWQC database consists of 70 species (increased from 65) occupying 58 genera (increased from 55) of freshwater organisms Table 6). Only one species and its corresponding genus (*X. laevis*) in the 2001 Cadmium Document database is not present in the revised acute database. Six species (*C. bairdi, R. hageni, T. arcticus, H. azteca, C. tentans*, and *C. plumosus*) were added to the acute database, resulting in four additional genera (*Cottus*, *Rhithrogena*, *Thymallus*, and *Hyalella*). The revised acute database meets the "eight-family rule." Genus mean acute values range from the most sensitive at 1.91 µg/L for the genus *Salvelinus* to the least sensitive at 14,880 µg/L for the genus *Dendrocoelum*. The top four most sensitive genera are all fish, and include *Salvelinus* (1.91 µg/L), *Cottus* (2.16 µg/L), *Salmo* (2.88 µg/L), and *Morone* (3.16 µg/L).

Table 6: Revised acute Cd criteria database.

Rank	Species	GMAV (µg/L)	SMAV (µg/L)	Common Name	Family
58	*Dendrocoelum lacteum*	14,880.09	14,880.09	Planaria	Planariidae
57	*Orconectes virilis* *Orconectes immunis*	<11,193.54	11,097.25 <11,371.23	Crayfish Crayfish	Cambaridae Cambaridae
56	*Rhithrogena hageni*	10,899.66	10,899.66	Mayfly	Heptageniidae
55	*Oreochromis mossambica*	10,068.09	10,068.09	Tilapia	Cichlidae
54	*Chironomus riparius** *Chironomus tentans* *Chironomus plumosus*	7,933.19	216,223.17 7,933.19 8,260.64	Midge Midge Midge	Chironomidae Chironomidae Chironomidae
53	*Gasterosteus aculeatus*	5,897.00	5,897.00	Threespine stickleback	Gasterosteidae
52	*Gambusia affinis*	5,578.08	5,578.08	Mosquitofish	Poeciliidae
51	*Ictalurus punctatus*	4,994.42	4,994.42	Channel catfish	Ictaluridae
50	*Rhyacodrilus montana*	4,912.28	4,912.28	Tubificid worm	Tubificidae
49	*Lepomis cyanellus* *Lepomis macrochirus*	4,812.28	3,595.94 6,440.04	Green sunfish Bluegill	Centrarchidae Centrarchidae
48	*Cyprinus carpio*	4,547.36	4,547.36	Common carp	Cyprinidae
47	*Stylodrilus heringianus*	4,228.50	4,228.50	Tubificid worm	Tubificidae
46	*Notropis lutrensis*	4,051.76	4,051.76	Red shiner	Cyprinidae
45	*Spirosperma ferox* *Spirosperma nikolskyi*	3,094.45	2,729.04 3,508.77	Tubificid worm Tubificid worm	Tubificidae Tubificidae
44	*Varichaeta pacifica*	2,962.96	2,962.96	Tubificid worm	Tubificidae
43	*Catostomus commersoni*	2,827.16	2,827.16	White sucker	Catostomidae
42	*Jordanella floridae*	2,810.24	2,810.24	Flagfish	Cyprinodontidae
41	*Poecilia reticulata*	2,569.18	2,569.18	Guppy	Poeciliidae
40	*Quistradilus multisetosus*	2,495.13	2,495.13	Tubificid worm	Tubificidae
39	*Ephemerella grandis*	2,248.19	2,248.19	Mayfly	Ephemerellidae
38	*Branchiura sowerbyi*	1,871.34	1,871.34	Tubificid worm	Tubificidae
37	*Crangonyx pseudogracilis*	1,700.00	1,700.00	Amphipod	Crangonyctidae
36	*Procambarus clarkii*	1,659.77	1,659.77	Crayfish	Cambaridae
35	*Tubifex tubifex*	1,344.34	1,344.34	Tubificid worm	Tubificidae
34	*Limnodrilus hoffmeisteri*	867.63	867.63	Tubificid worm	Tubificidae
33	*Carassius auratus*	833.89	833.89	Goldfish	Cyprinidae
32	*Asellus bicrenata*	548.72	548.72	Isopod	Asellidae
31	*Ambystoma gracile*	515.81	515.81	Salamander	Ambystomatidae
30	*Plumatella emarginata*	299.69	299.69	Bryozoan	Plumatellidae
29	*Alona affinis*	267.59	267.59	Cladoceran	Chydoridae
28	*Cyclops varicans*	241.62	241.62	Copepod	Cyclopidae

3.3.1 *Updated Acute Database*

The revised acute Cd AWQC database consists of 70 species (increased from 65) occupying 58 genera (increased from 55) of freshwater organisms Table 6). Only one species and its corresponding genus (*X. laevis*) in the 2001 Cadmium Document database is not present in the revised acute database. Six species (*C. bairdi, R. hageni, T. arcticus*, *H. azteca*, *C. tentans*, and *C. plumosus*) were added to the acute database, resulting in four additional genera (*Cottus*, *Rhithrogena*, *Thymallus*, and *Hyalella*). The revised acute database meets the "eight-family rule." Genus mean acute values range from the most sensitive at 1.91 µg/L for the genus *Salvelinus* to the least sensitive at 14,880 µg/L for the genus *Dendrocoelum*. The top four most sensitive genera are all fish, and include *Salvelinus* (1.91 µg/L), *Cottus* (2.16 µg/L), *Salmo* (2.88 µg/L), and *Morone* (3.16 µg/L).

Table 6: Revised acute Cd criteria database.

Rank	Species	GMAV (µg/L)	SMAV (µg/L)	Common Name	Family
58	*Dendrocoelum lacteum*	14,880.09	14,880.09	Planaria	Planariidae
57	*Orconectes virilis* *Orconectes immunis*	<11,193.54	11,097.25 <11,371.23	Crayfish Crayfish	Cambaridae Cambaridae
56	*Rhithrogena hageni*	10,899.66	10,899.66	Mayfly	Heptageniidae
55	*Oreochromis mossambica*	10,068.09	10,068.09	Tilapia	Cichlidae
54	*Chironomus riparius** *Chironomus tentans* *Chironomus plumosus*	7,933.19	216,223.17 7,933.19 8,260.64	Midge Midge Midge	Chironomidae Chironomidae Chironomidae
53	*Gasterosteus aculeatus*	5,897.00	5,897.00	Threespine stickleback	Gasterosteidae
52	*Gambusia affinis*	5,578.08	5,578.08	Mosquitofish	Poeciliidae
51	*Ictalurus punctatus*	4,994.42	4,994.42	Channel catfish	Ictaluridae
50	*Rhyacodrilus montana*	4,912.28	4,912.28	Tubificid worm	Tubificidae
49	*Lepomis cyanellus* *Lepomis macrochirus*	4,812.28	3,595.94 6,440.04	Green sunfish Bluegill	Centrarchidae Centrarchidae
48	*Cyprinus carpio*	4,547.36	4,547.36	Common carp	Cyprinidae
47	*Stylodrilus heringianus*	4,228.50	4,228.50	Tubificid worm	Tubificidae
46	*Notropis lutrensis*	4,051.76	4,051.76	Red shiner	Cyprinidae
45	*Spirosperma ferox* *Spirosperma nikolskyi*	3,094.45	2,729.04 3,508.77	Tubificid worm Tubificid worm	Tubificidae Tubificidae
44	*Varichaeta pacifica*	2,962.96	2,962.96	Tubificid worm	Tubificidae
43	*Catostomus commersoni*	2,827.16	2,827.16	White sucker	Catostomidae
42	*Jordanella floridae*	2,810.24	2,810.24	Flagfish	Cyprinodontidae
41	*Poecilia reticulata*	2,569.18	2,569.18	Guppy	Poeciliidae
40	*Quistradilus multisetosus*	2,495.13	2,495.13	Tubificid worm	Tubificidae
39	*Ephemerella grandis*	2,248.19	2,248.19	Mayfly	Ephemerellidae
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36	*Procambarus clarkii*	1,659.77	1,659.77	Crayfish	Cambaridae
35	*Tubifex tubifex*	1,344.34	1,344.34	Tubificid worm	Tubificidae
34	*Limnodrilus hoffmeisteri*	867.63	867.63	Tubificid worm	Tubificidae
33	*Carassius auratus*	833.89	833.89	Goldfish	Cyprinidae
32	*Asellus bicrenata*	548.72	548.72	Isopod	Asellidae
31	*Ambystoma gracile*	515.81	515.81	Salamander	Ambystomatidae
30	*Plumatella emarginata*	299.69	299.69	Bryozoan	Plumatellidae
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54	*Chironomus riparius** *Chironomus tentans* *Chironomus plumosus*	7,933.19	216,223.17 7,933.19 8,260.64	Midge Midge Midge	Chironomidae Chironomidae Chironomidae
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31	*Ambystoma gracile*	515.81	515.81	Salamander	Ambystomatidae
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32	*Asellus bicrenata*	548.72	548.72	Isopod	Asellidae
31	*Ambystoma gracile*	515.81	515.81	Salamander	Ambystomatidae
30	*Plumatella emarginata*	299.69	299.69	Bryozoan	Plumatellidae
29	*Alona affinis*	267.59	267.59	Cladoceran	Chydoridae
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Rank	Species	GMAV (µg/L)	SMAV (µg/L)	Common Name	Family
27	*Glossiphonia complanata*	210.93	210.93	Leech	Glossiphoniidae
26	*Pectinatella magnifica*	192.46	192.46	Bryozoan	Pectinatellidae
25	*Lumbriculus variegatus*	156.13	156.13	Worm	Lumbriculidae
24	*Physa gyrina*	115.30	115.30	Snail	Physidae
23	*Aplexa hypnorum*	102.73	102.73	Snail	Physidae
22	*Gammarus pseudolimnaeus*	77.58	77.58	Amphipod	Gammaridae
21	*Lirceus alabamae*	54.23	54.23	Isopod	Asellidae
20	*Ceriodaphnia dubia* *Ceriodaphnia reticulata*	48.15	49.86 46.50	Cladoceran Cladoceran	Daphniidae Daphniidae
19	*Moina macrocopa*	45.31	45.31	Cladoceran	Moinidae
18	*Utterbackia imbecilis*	44.90	44.90	Mussel	Unionidae
17	*Gila elegans*	44.55	44.55	Bonytail	Cyprinidae
16	*Xyrauchen texanus*	42.13	42.13	Razorback sucker	Catostomidae
15	*Lophopodella carteri*	41.24	41.24	Bryozoan	Lophopodidae
14	*Vilosa vibex*	37.18	37.18	Mussel	Unionidae
13	*Actinonaia pectorosa*	35.59	35.59	Mussel	Unionidae
12	*Lampsilis straminea claibornensis* *Lampsilis teres*	33.00	46.61 23.37	Mussel Mussel	Unionidae Unionidae
11	*Pimephales promelas*	28.45	28.45	Fathead minnow	Cyprinidae
10	*Simocephalus serrulatus*	27.79	27.79	Cladoceran	Daphniidae
9	*Daphnia magna* *Daphnia pulex*	27.43	15.36 48.98	Colorado pikeminnow Northern pikeminnow	Cyprinidae Cyprinidae
8	*Ptychocheilus lucius** *Ptychocheilus oregonensis*	25.93	25.93 2,070.47	Cladoceran Cladoceran	Daphniidae Daphniidae
7	*Hyallela azteca*	7.51	7.51	Amphipod	Hyalellidae
6	*Thymallus arcticus*	4.80	4.80	Arctic grayling	Salmonidae
5	*Oncorhynchus kisutch* *Oncorhynchus tshawytscha* *Oncorhynchus mykiss*	3.48	5.72 3.98 1.85	Coho salmon Chinook salmon Rainbow trout	Salmonidae Salmonidae Salmonidae
4	*Morone saxatilis*	3.16	3.16	Striped bass	Percichthyidae
3	*Salmo trutta*	2.88	2.88	Brown trout	Salmonidae
2	*Cottus bairdi*	2.16	2.16	Mottled sculpin	Cottidae
1	*Salvelinus fontinalis* *Salvelinus confluentus*	1.91	<1.76 2.08	Brook trout Bull trout	Salmonidae Salmonidae

* Only the most sensitive species was used to calculate the GMAV.

3.3.2 Updated Chronic Database

The revised chronic Cd AWQC database consists of 22 species occupying 17 genera and 14 families (Table 7). While no species or genera were deleted from the 2001 Cd document, one species was added. Both the existing and revised chronic Cd databases exactly meet the "eight-family rule." Genus mean chronic values (GMCV) range from the most sensitive at 0.26 µg/L for the genus *Hyalella* to the least sensitive at >22.19 µg/L for the genus *Oreochromis*. The top four most sensitive genera in terms of chronic toxicity to Cd are *Hyalella* (0.26 µg/L), *Cottus* (1.07 µg/L), *Daphnia* (1.33 µg/L), and *Oncorhynchus* (2.31 µg/L).

Rank	Species	GMAV (µg/L)	SMAV (µg/L)	Common Name	Family
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25	*Lumbriculus variegatus*	156.13	156.13	Worm	Lumbriculidae
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13	*Actinonaia pectorosa*	35.59	35.59	Mussel	Unionidae
12	*Lampsilis straminea claibornensis* *Lampsilis teres*	33.00	46.61 23.37	Mussel Mussel	Unionidae Unionidae
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The revised chronic Cd AWQC database consists of 22 species occupying 17 genera and 14 families (Table 7). While no species or genera were deleted from the 2001 Cd document, one species was added. Both the existing and revised chronic Cd databases exactly meet the "eight-family rule." Genus mean chronic values (GMCV) range from the most sensitive at 0.26 µg/L for the genus *Hyalella* to the least sensitive at >22.19 µg/L for the genus *Oreochromis*. The top four most sensitive genera in terms of chronic toxicity to Cd are *Hyalella* (0.26 µg/L), *Cottus* (1.07 µg/L), *Daphnia* (1.33 µg/L), and *Oncorhynchus* (2.31 µg/L).

Rank	Species	GMAV (µg/L)	SMAV (µg/L)	Common Name	Family
27	*Glossiphonia complanata*	210.93	210.93	Leech	Glossiphoniidae
26	*Pectinatella magnifica*	192.46	192.46	Bryozoan	Pectinatellidae
25	*Lumbriculus variegatus*	156.13	156.13	Worm	Lumbriculidae
24	*Physa gyrina*	115.30	115.30	Snail	Physidae
23	*Aplexa hypnorum*	102.73	102.73	Snail	Physidae
22	*Gammarus pseudolimnaeus*	77.58	77.58	Amphipod	Gammaridae
21	*Lirceus alabamae*	54.23	54.23	Isopod	Asellidae
20	*Ceriodaphnia dubia* *Ceriodaphnia reticulata*	48.15	49.86 46.50	Cladoceran Cladoceran	Daphniidae Daphniidae
19	*Moina macrocopa*	45.31	45.31	Cladoceran	Moinidae
18	*Utterbackia imbecilis*	44.90	44.90	Mussel	Unionidae
17	*Gila elegans*	44.55	44.55	Bonytail	Cyprinidae
16	*Xyrauchen texanus*	42.13	42.13	Razorback sucker	Catostomidae
15	*Lophopodella carteri*	41.24	41.24	Bryozoan	Lophopodidae
14	*Vilosa vibex*	37.18	37.18	Mussel	Unionidae
13	*Actinonaia pectorosa*	35.59	35.59	Mussel	Unionidae
12	*Lampsilis straminea claibornensis* *Lampsilis teres*	33.00	46.61 23.37	Mussel Mussel	Unionidae Unionidae
11	*Pimephales promelas*	28.45	28.45	Fathead minnow	Cyprinidae
10	*Simocephalus serrulatus*	27.79	27.79	Cladoceran	Daphniidae
9	*Daphnia magna* *Daphnia pulex*	27.43	15.36 48.98	Colorado pikeminnow Northern pikeminnow	Cyprinidae Cyprinidae
8	*Ptychocheilus lucius** *Ptychocheilus oregonensis*	25.93	25.93 2,070.47	Cladoceran Cladoceran	Daphniidae Daphniidae
7	*Hyallela azteca*	7.51	7.51	Amphipod	Hyalellidae
6	*Thymallus arcticus*	4.80	4.80	Arctic grayling	Salmonidae
5	*Oncorhynchus kisutch* *Oncorhynchus tshawytscha* *Oncorhynchus mykiss*	3.48	5.72 3.98 1.85	Coho salmon Chinook salmon Rainbow trout	Salmonidae Salmonidae Salmonidae
4	*Morone saxatilis*	3.16	3.16	Striped bass	Percichthyidae
3	*Salmo trutta*	2.88	2.88	Brown trout	Salmonidae
2	*Cottus bairdi*	2.16	2.16	Mottled sculpin	Cottidae
1	*Salvelinus fontinalis* *Salvelinus confluentus*	1.91	<1.76 2.08	Brook trout Bull trout	Salmonidae Salmonidae

* Only the most sensitive species was used to calculate the GMAV.

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Table 7: Updated chronic Cd criteria database.

Rank	Species	GMCV (µg/L)	SMCV (µg/L)	Common Name	Family
17	*Oreochromis aurea*	>22.19	>22.19	Blue tilapia	Cichlidae
16	*Aeolosoma headleyi*	20.42	20.42	Oligochaete	Aeolosomatidae
15	*Lepomis macrochirus*	15.99	15.99	Bluegill	Centrarchidae
14	*Pimephales promelas*	15.09	15.09	Fathead minnow	Cyprinidae
13	*Ceriodaphnia dubia*	11.66	11.66	Cladoceran	Daphniidae
12	*Micropterus dolomieui*	8.19	8.19	Smallmouth bass	Centrarchidae
11	*Esox lucius*	8.15	8.15	Northern pike	Esocidae
10	*Catostomus commersoni*	7.86	7.86	White sucker	Catostomidae
9	*Jordanella floridae*	5.34	5.34	Flagfish	Cyprinidontidae
8	*Aplexa hypnorum*	4.85	4.85	Snail	Physidae
7	*Salmo salar* *Salmo trutta*	4.73	8.28 2.70	Atlantic salmon brown trout	Salmonidae Salmonidae
6	*Salvelinus fontinalis* *Salvelinus namaycush*	4.66	2.66 8.15	Brook trout Lake trout	Salmonidae Salmonidae
5	*Chironomus tentans*	2.53	2.53	Midge	Chironomidae
4	*Oncorhynchus kisutch* *Oncorhynchus mykiss* *Oncorhynchus tshawytscha*	2.31	4.30 1.05 2.72	Coho salmon Rainbow trout Chinook salmon	Salmonidae Salmonidae Salmonidae
3	*Daphnia magna* *Daphnia pulex*	1.33	0.49 3.57	Cladoceran Cladoceran	Daphniidae Daphniidae
2	*Cottus bairdi*	1.07	1.07	Mottled sculpin	Cottidae
1	*Hyalella azteca*	0.26	0.26	Amphipod	Hyalellidae

[1] Used in coldwater calculations.

[2] Used in warmwater calculations.

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8	*Aplexa hypnorum*	4.85	4.85	Snail	Physidae
7	*Salmo salar*	4.73	8.28	Atlantic salmon	Salmonidae
	Salmo trutta		2.70	brown trout	Salmonidae
6	*Salvelinus fontinalis*	4.66	2.66	Brook trout	Salmonidae
	Salvelinus namaycush		8.15	Lake trout	Salmonidae
5	*Chironomus tentans*	2.53	2.53	Midge	Chironomidae
4	*Oncorhynchus kisutch*	2.31	4.30	Coho salmon	Salmonidae
	Oncorhynchus mykiss		1.05	Rainbow trout	Salmonidae
	Oncorhynchus tshawytscha		2.72	Chinook salmon	Salmonidae
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4.0 Phase 3 – Recalculation of Acute and Chronic Water Quality Objectives for Cadmium

4.1 Updating the Acute Hardness Relationship

When enough data are available to show that the toxicity of a substance is related to a water quality characteristic for two or more species, the relationship is accounted for using an analysis of covariance (Stephan *et al.* 1985). This appears to be the case for the relationship between Cd toxicity and water hardness. The 2001 Cadmium Document normalized data and used analysis of covariance (Stephen *et al.* 1985) to obtain the acute hardness slope.

Definitive acute values were available for 12 species over a range of hardness values such that the highest hardness was at least three times the lowest, and the highest was also at least 100 mg/L higher than the lowest. Only acute tests initiated with individuals less than 24-hour old neonates were used to estimate the hardness slope for *D. magna.* The individual species slopes ranged from 0.1086 (*D. magna*) to 2.03 (*P. promelas*), and the pooled slope was 1.17. However, the EPA decided that there was too much variability associated with the slopes for *D. magna* and *P. promelas.* Therefore, only the Chapman *et al.* manuscript data were used to compute the slope for *D. magna* (1.18) and only adult data were used to compute the slope for *P. promelas* (1.22). When the adjusted data set was used, the resultant pooled slope was 1.0166. This value was used by EPA to adjust all acute values to a common hardness (50 mg/L) and is also included in the final acute equation.

Reviewing data used to calculate the acute hardness slope in the 2001 Cadmium Document and adding data from the revised acute database allowed development of a revised acute hardness relationship (Table 8). One major conflict with data selection for the 2001 Cadmium Document acute hardness relationship and that used by GEI is EPA's decision to limit fathead minnow Cd vs. hardness data to adults, when only the toxicity data of the more sensitive age classes (juvenile and fry) were used in the SMAV calculations. EPA justified this apparent conflict because excluding juvenile and fry hardness related data decreased undesirable variability within the species and pooled slope. Yet in this situation, when data for multiple age classes are available, we believe data used to calculate the hardness relationship should be more consistent with data used to calculate the SMAV. This approach should be honored (even if data are more variable) as long as resulting slopes are within the range of other species. Therefore, instead of only adult data (slope = 1.220, $R^2 = 0.70$), juvenile data for fathead minnow (slope = 0.9210, $R^2 = 0.29$) were used in the revised pooled acute hardness slope. Davies *et al.* (1993) provided 6 data points for *O. mykiss* that increased the range of water hardness tested for this species, making it possible to add this previously unused species to the revised acute hardness slope calculations. Data points for *O. mykiss* from four other studies were also added to the hardness relationship database.

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Analysis of covariance determined the individual species slopes of the revised database set are not significantly different ($p = 0.69$). Overall, with a revised slope for *D. magna* (1.1824) and *P. promelas* (1.9210) and the addition of *O. mykiss* (0.7679), the resultant pooled slope is 0.9151 (replacing the existing acute hardness pooled slope of 1.0166). This revised slope was used to adjust all values in the revised acute database to a common hardness (50 mg/L) and was placed in the revised final acute equation.

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Table 8: Updated acute Cd hardness slope. SMAS = species mean acute slope.

Species	Hardness (mg/L)	Geomean (hardness)	Normalized hardness	LC_{50}/EC_{50} (µg/L)	Geomean (acute)	Normalized acute	Reference	ln (norm hard)	ln (norm acute)	SMAS	R^2
Limnodrilus hoffmeisteri	5.3		0.19	170.00		0.27	Chapman *et al.* 1982	-1.678	-1.324		--
Limnodrilus hoffmeisteri	152.0	28.38	5.36	2,400.00	638.75	3.76	Williams *et al.* 1985	1.678	1.324	0.7888	--
Tubifex tubifex	128.0		2.89	3,200.00		2.66	Reynoldson *et al.* 1996	1.061	0.978		
Tubifex tubifex	128.0		2.89	1,700.00		1.41	Reynoldson *et al.* 1996	1.061	0.346		
Tubifex tubifex	5.3	44.28	0.12	320.00	1,202.96	0.27	Chapman *et al.* 1982	-2.123	-1.324	0.6238	0.93
Vilosa vibex	40.0		0.46	30.00		0.49	Keller as cited in U.S. EPA 2001	-0.768	-0.714		
Vilosa vibex	186.0	86.26	2.16	125.00	61.24	2.04	Keller as cited in U.S. EPA 2001	0.768	0.714	0.9286	--
Daphnia magna	51.0		0.50	9.90		0.51	Chapman et al. Manuscript	-0.839	-1.178		
Daphnia magna	104.0		1.02	33.00		1.69	Chapman et al. Manuscript	-0.127	0.026		
Daphnia magna	105.0		1.03	34.00		1.74	Chapman et al. Manuscript	-0.117	0.056		
Daphnia magna	197.0		1.93	63.00		3.22	Chapman et al. Manuscript	0.512	0.673		
Daphnia magna	209.0	118.05	2.05	49.00	32.14	2.50	Chapman et al. Manuscript	0.571	0.422	1.1824	0.91
Daphnia pulex	57.0		0.60	47.00		0.53	Bertram and Hart 1979	-0.508	-0.636		
Daphnia pulex	240.0		2.53	319.00		3.59	Elnabarawy et al. 1986	0.930	1.279		
Daphnia pulex	120.0		1.27	80.00		0.90	Hall et al. 1986	0.237	-0.104		
Daphnia pulex	120.0		1.27	100.00		1.13	Hall et al. 1986	0.237	0.119		
Daphnia pulex	53.5		0.56	70.10		0.79	Stackhouse and Benson 1988	-0.571	-0.236		
Daphnia pulex	85.0		0.90	66.00		0.74	Roux et al. 1993	-0.108	-0.296		
Daphnia pulex	85.0		0.90	99.00		1.12	Roux et al. 1993	-0.108	0.109		
Daphnia pulex	85.0	94.71	0.90	70.00	88.74	0.79	Roux et al. 1993	5.52	-0.237	1.0633	0.79
Oncorhynchus tshawytscha	211.0		4.05	26.00		5.27	Hamilton and Buhl 1990	1.398	1.661		
Oncorhynchus tshawytscha	343.0		6.58	57.00		11.55	Hamilton and Buhl 1990	1.884	2.446		
Oncorhynchus tshawytscha	23.0		0.44	1.80		0.36	Chapman 1975, 1978	-0.819	-1.009		
Oncorhynchus tshawytscha	23.0		0.44	3.50		0.71	Chapman 1975, 1978	-0.819	-0.344		
Oncorhynchus tshawytscha	25.0		0.48	1.41		0.29	Chapman 1982	-0.735	-1.253		
Oncorhynchus tshawytscha	21.0	52.14	0.40	1.10	4.94	0.22	Finlayson and Verrue 1982	-0.909	-1.501	1.2576	0.95
Carassius auratus	20.0		0.50	2,340.00		0.64	Pickering and Henderson 1966	-0.686	-0.440		
Carassius auratus	20.0		0.50	2,130.00		0.59	McCarty et al. 1978	-0.686	-0.534		
Carassius auratus	140.0		3.53	46,800.00		12.88	McCarty et al. 1978	1.260	2.555		
Carassius auratus	44.4	39.71	1.12	748.00	3,634.43	0.21	Phipps and Holcombe 1985	0.112	-1.581	1.4608	0.57
Pimephales promelas (juvenile)	44.0		0.87	13.20		0.40	Spehar and Fiandt 1986	-0.138	-0.909		
Pimephales promelas (juvenile)	290.0		5.74	60.00		1.83	Schubauer-Berigan et al. 1993	1.748	0.605		

Table 8: Updated acute Cd hardness slope. SMAS = species mean acute slope.

Species	Hardness (mg/L)	Geomean (hardness)	Normalized hardness	LC_{50}/EC_{50} (µg/L)	Geomean (acute)	Normalized acute	Reference	ln (norm hard)	ln (norm acute)	SMAS	R^2
Limnodrilus hoffmeisteri	5.3		0.19	170.00		0.27	Chapman *et al.* 1982	-1.678	-1.324		--
Limnodrilus hoffmeisteri	152.0	28.38	5.36	2,400.00	638.75	3.76	Williams *et al.* 1985	1.678	1.324	0.7888	--
Tubifex tubifex	128.0		2.89	3,200.00		2.66	Reynoldson *et al.* 1996	1.061	0.978		
Tubifex tubifex	128.0		2.89	1,700.00		1.41	Reynoldson *et al.* 1996	1.061	0.346		
Tubifex tubifex	5.3	44.28	0.12	320.00	1,202.96	0.27	Chapman *et al.* 1982	-2.123	-1.324	0.6238	0.93
Vilosa vibex	40.0		0.46	30.00		0.49	Keller as cited in U.S. EPA 2001	-0.768	-0.714		
Vilosa vibex	186.0	86.26	2.16	125.00	61.24	2.04	Keller as cited in U.S. EPA 2001	0.768	0.714	0.9286	--
Daphnia magna	51.0		0.50	9.90		0.51	Chapman et al. Manuscript	-0.839	-1.178		
Daphnia magna	104.0		1.02	33.00		1.69	Chapman et al. Manuscript	-0.127	0.026		
Daphnia magna	105.0		1.03	34.00		1.74	Chapman et al. Manuscript	-0.117	0.056		
Daphnia magna	197.0		1.93	63.00		3.22	Chapman et al. Manuscript	0.512	0.673		
Daphnia magna	209.0	118.05	2.05	49.00	32.14	2.50	Chapman et al. Manuscript	0.571	0.422	1.1824	0.91
Daphnia pulex	57.0		0.60	47.00		0.53	Bertram and Hart 1979	-0.508	-0.636		
Daphnia pulex	240.0		2.53	319.00		3.59	Elnabarawy et al. 1986	0.930	1.279		
Daphnia pulex	120.0		1.27	80.00		0.90	Hall et al. 1986	0.237	-0.104		
Daphnia pulex	120.0		1.27	100.00		1.13	Hall et al. 1986	0.237	0.119		
Daphnia pulex	53.5		0.56	70.10		0.79	Stackhouse and Benson 1988	-0.571	-0.236		
Daphnia pulex	85.0		0.90	66.00		0.74	Roux et al. 1993	-0.108	-0.296		
Daphnia pulex	85.0		0.90	99.00		1.12	Roux et al. 1993	-0.108	0.109		
Daphnia pulex	85.0	94.71	0.90	70.00	88.74	0.79	Roux et al. 1993	5.52	-0.237	1.0633	0.79
Oncorhynchus tshawytscha	211.0		4.05	26.00		5.27	Hamilton and Buhl 1990	1.398	1.661		
Oncorhynchus tshawytscha	343.0		6.58	57.00		11.55	Hamilton and Buhl 1990	1.884	2.446		
Oncorhynchus tshawytscha	23.0		0.44	1.80		0.36	Chapman 1975, 1978	-0.819	-1.009		
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Oncorhynchus tshawytscha	21.0	52.14	0.40	1.10	4.94	0.22	Finlayson and Verrue 1982	-0.909	-1.501	1.2576	0.95
Carassius auratus	20.0		0.50	2,340.00		0.64	Pickering and Henderson 1966	-0.686	-0.440		
Carassius auratus	20.0		0.50	2,130.00		0.59	McCarty et al. 1978	-0.686	-0.534		
Carassius auratus	140.0		3.53	46,800.00		12.88	McCarty et al. 1978	1.260	2.555		
Carassius auratus	44.4	39.71	1.12	748.00	3,634.43	0.21	Phipps and Holcombe 1985	0.112	-1.581	1.4608	0.57
Pimephales promelas (juvenile)	44.0		0.87	13.20		0.40	Spehar and Fiandt 1986	-0.138	-0.909		
Pimephales promelas (juvenile)	290.0		5.74	60.00		1.83	Schubauer-Berigan et al. 1993	1.748	0.605		

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Species	Hardness (mg/L)	Geomean (hardness)	Normalized hardness	LC_{50}/EC_{50} (µg/L)	Geomean (acute)	Normalized acute	Reference	ln (norm hard)	ln (norm acute)	SMAS	R^2
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Carassius auratus	140.0		3.53	46,800.00		12.88	McCarty et al. 1978	1.260	2.555		
Carassius auratus	44.4	39.71	1.12	748.00	3,634.43	0.21	Phipps and Holcombe 1985	0.112	-1.581	1.4608	0.57
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Pimephales promelas (fry)	17.0		0.34	4.80		0.15	Suedel et al. 1997	-1.089	-1.920		
Pimephales promelas (fry)	60.0		1.19	210.00		6.41	Rifici et al. 1996	0.172	1.858		
Pimephales promelas (fry)	60.0		1.19	180.00		5.50	Rifici et al. 1996	0.172	1.704		
Pimephales promelas (fry)	40.0		0.79	21.50		0.66	Spehar 1982	-0.233	-0.421		
Pimephales promelas (fry)	48.0		0.95	11.70		0.36	Spehar 1982	-0.051	-1.029		
Pimephales promelas (fry)	39.0		0.77	19.30		0.59	Spehar 1982	-0.258	-0.529		
Pimephales promelas (fry)	45.0		0.89	42.40		1.29	Spehar 1982	-0.115	0.258		
Pimephales promelas (fry)	47.0		0.93	54.20		1.65	Spehar 1982	-0.072	0.504		
Pimephales promelas (fry)	44.0		0.87	9.00	32.75	0.89	Spehar 1982	-0.138	-0.122	0.9210	0.29
Pimephales promelas (fry)	20.0	50.49	0.26	1,270.00		0.34	Pickering and Henderson 1966	-1.335	-1.088		
Poecilia reticulata	105.0		1.38	3,800.00		1.01	Canton and Slooff 1982	0.323	0.008		
Poecilia reticulata	209.2	76.02	2.75	11,100.00	3,769.67	2.94	Canton and Slooff 1982	1.012	1.080	0.8752	0.95
Poecilia reticulata	34.5		0.57	1.00		0.33	Hughes 1973	-0.565	-1.096		
Morone saxatilis	34.5		0.57	2.00		0.67	Hughes 1973	-0.565	-0.402		
Morone saxatilis	40.0		0.66	4.00		1.34	Palawski et al. 1985	-0.417	0.291		
Morone saxatilis	285.0	60.69	4.70	10.00	2.99	3.34	Palawski et al. 1985	1.547	1.207	0.8089	0.72
Morone saxatilis	20.0		0.17	2,840.00		0.20	Pickering and Henderson 1966	-1.790	-1.631		
Lepomis cyanellus	360.0		3.00	66,000.00		4.55	Pickering and Henderson 1966	1.100	1.515		
Lepomis cyanellus	85.5		0.71	11,520.00		0.79	Carrier and Beitinger 1988b	-0.338	-0.230		
Lepomis cyanellus	335.0	119.84	2.80	20,500.00	14,504.98	1.41	Jude 1973	1.028	0.346	0.8986	0.88
Lepomis macrochirus	20.0		0.56	1,940.00		0.46	Pickering and Henderson 1966	-0.585	-0.786		
Lepomis macrochirus	18.0		0.50	2,300.00		0.54	Bishop and McIntosh 1981	-0.690	-0.616		
Lepomis macrochirus	18.0		0.50	2,300.00		0.54	Bishop and McIntosh 1981	-0.690	-0.616		
Lepomis macrochirus	207.0		5.77	21,100.00		4.95	Eaton 1980	1.752	1.600		
Lepomis macrochirus	44.4	35.89	1.24	6,470.00	4,258.80	1.52	Phipps and Holcombe 1985	0.213	0.418	0.9531	0.95
Oncorhynchus mykiss	420.0		6.93	7.40		4.04	Davies et al. 1993	1.935	1.397		
Oncorhynchus mykiss	427.0		7.04	5.92		3.23	Davies et al. 1993	1.952	1.174		
Oncorhynchus mykiss	217.0		3.58	4.20		2.29	Davies et al. 1993	1.275	0.830		
Oncorhynchus mykiss	227.0		3.74	6.57		3.59	Davies et al. 1993	1.320	1.278		
Oncorhynchus mykiss	46.0		0.76	2.64		1.44	Davies et al. 1993	-0.276	0.366		
Oncorhynchus mykiss	49.0		0.81	3.08		1.68	Davies et al. 1993	-0.213	0.520		
Oncorhynchus mykiss	23.0		0.38	1.30		0.71	Chapman 1975, 1978	-0.969	-0.342		
Oncorhynchus mykiss	23.0		0.38	1.00		0.55	Chapman 1978	-0.969	-0.605		

Species	Hardness (mg/L)	Geomean (hardness)	Normalized hardness	LC_{50}/EC_{50} (µg/L)	Geomean (acute)	Normalized acute	Reference	ln (norm hard)	ln (norm acute)	SMAS	R^2
Pimephales promelas (fry)	17.0		0.34	4.80		0.15	Suedel et al. 1997	-1.089	-1.920		
Pimephales promelas (fry)	60.0		1.19	210.00		6.41	Rifici et al. 1996	0.172	1.858		
Pimephales promelas (fry)	60.0		1.19	180.00		5.50	Rifici et al. 1996	0.172	1.704		
Pimephales promelas (fry)	40.0		0.79	21.50		0.66	Spehar 1982	-0.233	-0.421		
Pimephales promelas (fry)	48.0		0.95	11.70		0.36	Spehar 1982	-0.051	-1.029		
Pimephales promelas (fry)	39.0		0.77	19.30		0.59	Spehar 1982	-0.258	-0.529		
Pimephales promelas (fry)	45.0		0.89	42.40		1.29	Spehar 1982	-0.115	0.258		
Pimephales promelas (fry)	47.0		0.93	54.20		1.65	Spehar 1982	-0.072	0.504		
Pimephales promelas (fry)	44.0		0.87	9.00	32.75	0.89	Spehar 1982	-0.138	-0.122	0.9210	0.29
Pimephales promelas (fry)	20.0	50.49	0.26	1,270.00		0.34	Pickering and Henderson 1966	-1.335	-1.088		
Poecilia reticulata	105.0		1.38	3,800.00		1.01	Canton and Slooff 1982	0.323	0.008		
Poecilia reticulata	209.2	76.02	2.75	11,100.00	3,769.67	2.94	Canton and Slooff 1982	1.012	1.080	0.8752	0.95
Poecilia reticulata	34.5		0.57	1.00		0.33	Hughes 1973	-0.565	-1.096		
Morone saxatilis	34.5		0.57	2.00		0.67	Hughes 1973	-0.565	-0.402		
Morone saxatilis	40.0		0.66	4.00		1.34	Palawski et al. 1985	-0.417	0.291		
Morone saxatilis	285.0	60.69	4.70	10.00	2.99	3.34	Palawski et al. 1985	1.547	1.207	0.8089	0.72
Morone saxatilis	20.0		0.17	2,840.00		0.20	Pickering and Henderson 1966	-1.790	-1.631		
Lepomis cyanellus	360.0		3.00	66,000.00		4.55	Pickering and Henderson 1966	1.100	1.515		
Lepomis cyanellus	85.5		0.71	11,520.00		0.79	Carrier and Beitinger 1988b	-0.338	-0.230		
Lepomis cyanellus	335.0	119.84	2.80	20,500.00	14,504.98	1.41	Jude 1973	1.028	0.346	0.8986	0.88
Lepomis macrochirus	20.0		0.56	1,940.00		0.46	Pickering and Henderson 1966	-0.585	-0.786		
Lepomis macrochirus	18.0		0.50	2,300.00		0.54	Bishop and McIntosh 1981	-0.690	-0.616		
Lepomis macrochirus	18.0		0.50	2,300.00		0.54	Bishop and McIntosh 1981	-0.690	-0.616		
Lepomis macrochirus	207.0		5.77	21,100.00		4.95	Eaton 1980	1.752	1.600		
Lepomis macrochirus	44.4	35.89	1.24	6,470.00	4,258.80	1.52	Phipps and Holcombe 1985	0.213	0.418	0.9531	0.95
Oncorhynchus mykiss	420.0		6.93	7.40		4.04	Davies et al. 1993	1.935	1.397		
Oncorhynchus mykiss	427.0		7.04	5.92		3.23	Davies et al. 1993	1.952	1.174		
Oncorhynchus mykiss	217.0		3.58	4.20		2.29	Davies et al. 1993	1.275	0.830		
Oncorhynchus mykiss	227.0		3.74	6.57		3.59	Davies et al. 1993	1.320	1.278		
Oncorhynchus mykiss	46.0		0.76	2.64		1.44	Davies et al. 1993	-0.276	0.366		
Oncorhynchus mykiss	49.0		0.81	3.08		1.68	Davies et al. 1993	-0.213	0.520		
Oncorhynchus mykiss	23.0		0.38	1.30		0.71	Chapman 1975, 1978	-0.969	-0.342		
Oncorhynchus mykiss	23.0		0.38	1.00		0.55	Chapman 1978	-0.969	-0.605		

Species	Hardness (mg/L)	Geomean (hardness)	Normalized hardness	LC_{50}/EC_{50} (µg/L)	Geomean (acute)	Normalized acute	Reference	ln (norm hard)	ln (norm acute)	SMAS	R^2
Pimephales promelas (fry)	17.0		0.34	4.80		0.15	Suedel et al. 1997	-1.089	-1.920		
Pimephales promelas (fry)	60.0		1.19	210.00		6.41	Rifici et al. 1996	0.172	1.858		
Pimephales promelas (fry)	60.0		1.19	180.00		5.50	Rifici et al. 1996	0.172	1.704		
Pimephales promelas (fry)	40.0		0.79	21.50		0.66	Spehar 1982	-0.233	-0.421		
Pimephales promelas (fry)	48.0		0.95	11.70		0.36	Spehar 1982	-0.051	-1.029		
Pimephales promelas (fry)	39.0		0.77	19.30		0.59	Spehar 1982	-0.258	-0.529		
Pimephales promelas (fry)	45.0		0.89	42.40		1.29	Spehar 1982	-0.115	0.258		
Pimephales promelas (fry)	47.0		0.93	54.20		1.65	Spehar 1982	-0.072	0.504		
Pimephales promelas (fry)	44.0		0.87	9.00	32.75	0.89	Spehar 1982	-0.138	-0.122	0.9210	0.29
Pimephales promelas (fry)	20.0	50.49	0.26	1,270.00		0.34	Pickering and Henderson 1966	-1.335	-1.088		
Poecilia reticulata	105.0		1.38	3,800.00		1.01	Canton and Slooff 1982	0.323	0.008		
Poecilia reticulata	209.2	76.02	2.75	11,100.00	3,769.67	2.94	Canton and Slooff 1982	1.012	1.080	0.8752	0.95
Poecilia reticulata	34.5		0.57	1.00		0.33	Hughes 1973	-0.565	-1.096		
Morone saxatilis	34.5		0.57	2.00		0.67	Hughes 1973	-0.565	-0.402		
Morone saxatilis	40.0		0.66	4.00		1.34	Palawski et al. 1985	-0.417	0.291		
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Morone saxatilis	20.0		0.17	2,840.00		0.20	Pickering and Henderson 1966	-1.790	-1.631		
Lepomis cyanellus	360.0		3.00	66,000.00		4.55	Pickering and Henderson 1966	1.100	1.515		
Lepomis cyanellus	85.5		0.71	11,520.00		0.79	Carrier and Beitinger 1988b	-0.338	-0.230		
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Lepomis macrochirus	20.0		0.56	1,940.00		0.46	Pickering and Henderson 1966	-0.585	-0.786		
Lepomis macrochirus	18.0		0.50	2,300.00		0.54	Bishop and McIntosh 1981	-0.690	-0.616		
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Pimephales promelas (fry)	39.0		0.77	19.30		0.59	Spehar 1982	-0.258	-0.529		
Pimephales promelas (fry)	45.0		0.89	42.40		1.29	Spehar 1982	-0.115	0.258		
Pimephales promelas (fry)	47.0		0.93	54.20		1.65	Spehar 1982	-0.072	0.504		
Pimephales promelas (fry)	44.0		0.87	9.00	32.75	0.89	Spehar 1982	-0.138	-0.122	0.9210	0.29
Pimephales promelas (fry)	20.0	50.49	0.26	1,270.00		0.34	Pickering and Henderson 1966	-1.335	-1.088		
Poecilia reticulata	105.0		1.38	3,800.00		1.01	Canton and Slooff 1982	0.323	0.008		
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Lepomis macrochirus	18.0		0.50	2,300.00		0.54	Bishop and McIntosh 1981	-0.690	-0.616		
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Lepomis macrochirus	44.4	35.89	1.24	6,470.00	4,258.80	1.52	Phipps and Holcombe 1985	0.213	0.418	0.9531	0.95
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Oncorhynchus mykiss	427.0		7.04	5.92		3.23	Davies et al. 1993	1.952	1.174		
Oncorhynchus mykiss	217.0		3.58	4.20		2.29	Davies et al. 1993	1.275	0.830		
Oncorhynchus mykiss	227.0		3.74	6.57		3.59	Davies et al. 1993	1.320	1.278		
Oncorhynchus mykiss	46.0		0.76	2.64		1.44	Davies et al. 1993	-0.276	0.366		
Oncorhynchus mykiss	49.0		0.81	3.08		1.68	Davies et al. 1993	-0.213	0.520		
Oncorhynchus mykiss	23.0		0.38	1.30		0.71	Chapman 1975, 1978	-0.969	-0.342		
Oncorhynchus mykiss	23.0		0.38	1.00		0.55	Chapman 1978	-0.969	-0.605		

Species	Hardness (mg/L)	Geomean (hardness)	Normalized hardness	LC_{50}/EC_{50} (µg/L)	Geomean (acute)	Normalized acute	Reference	ln (norm hard)	ln (norm acute)	SMAS	R^2
Oncorhynchus mykiss	31.0		0.51	1.75		0.96	Davies 1976	-0.671	-0.045		
Oncorhynchus mykiss	44.4		0.73	3.00		1.64	Phipps and Holcombe 1985	-0.312	0.494		
Oncorhynchus mykiss	30.7		0.51	0.71		0.39	Stratus Consulting 1999	-0.681	-0.947		
Oncorhynchus mykiss	29.3		0.48	0.47		0.26	Stratus Consulting 1999	-0.727	-1.360		
Oncorhynchus mykiss	31.7		0.52	0.51		0.28	Stratus Consulting 1999	-0.649	-1.278		
Oncorhynchus mykiss	30.2		0.50	0.38		0.21	Stratus Consulting 1999	-0.697	-1.572		
Oncorhynchus mykiss	30.0		0.49	1.29		0.70	Stratus Consulting 1999	-0.704	-0.350		
Oncorhynchus mykiss	89.3	60.64	1.47	2.85	1.83	1.56	Stratus Consulting 1999	0.387	0.442	0.7679	0.68
Salmo trutta	43.5		0.80	1.40		0.51	Spehar and Carlson 1984	-0.229	-0.680		
Salmo trutta	37.6		0.69	2.37		0.86	Davies and Brinkman 1994	-0.374	-0.153		
Salmo trutta	29.2		0.53	1.23		0.45	Brinkman and Hansen 2004	-0.627	-0.809		
Salmo trutta	67.6		1.24	3.90		1.41	Brinkman and Hansen 2004	0.212	0.345		
Salmo trutta	151.4	54.68	2.77	10.10	2.76	3.66	Brinkman and Hansen 2004	1.018	1.297	1.2671	0.91
							Revised pooled acute slope = 0.9151				**0.69**

Species	Hardness (mg/L)	Geomean (hardness)	Normalized hardness	LC_{50}/EC_{50} (µg/L)	Geomean (acute)	Normalized acute	Reference	ln (norm hard)	ln (norm acute)	SMAS	R^2
Oncorhynchus mykiss	31.0		0.51	1.75		0.96	Davies 1976	-0.671	-0.045		
Oncorhynchus mykiss	44.4		0.73	3.00		1.64	Phipps and Holcombe 1985	-0.312	0.494		
Oncorhynchus mykiss	30.7		0.51	0.71		0.39	Stratus Consulting 1999	-0.681	-0.947		
Oncorhynchus mykiss	29.3		0.48	0.47		0.26	Stratus Consulting 1999	-0.727	-1.360		
Oncorhynchus mykiss	31.7		0.52	0.51		0.28	Stratus Consulting 1999	-0.649	-1.278		
Oncorhynchus mykiss	30.2		0.50	0.38		0.21	Stratus Consulting 1999	-0.697	-1.572		
Oncorhynchus mykiss	30.0		0.49	1.29		0.70	Stratus Consulting 1999	-0.704	-0.350		
Oncorhynchus mykiss	89.3	60.64	1.47	2.85	1.83	1.56	Stratus Consulting 1999	0.387	0.442	0.7679	0.68
Salmo trutta	43.5		0.80	1.40		0.51	Spehar and Carlson 1984	-0.229	-0.680		
Salmo trutta	37.6		0.69	2.37		0.86	Davies and Brinkman 1994	-0.374	-0.153		
Salmo trutta	29.2		0.53	1.23		0.45	Brinkman and Hansen 2004	-0.627	-0.809		
Salmo trutta	67.6		1.24	3.90		1.41	Brinkman and Hansen 2004	0.212	0.345		
Salmo trutta	151.4	54.68	2.77	10.10	2.76	3.66	Brinkman and Hansen 2004	1.018	1.297	1.2671	0.91
							Revised pooled acute slope = 0.9151				**0.69**

Species	Hardness (mg/L)	Geomean (hardness)	Normalized hardness	LC_{50}/EC_{50} (µg/L)	Geomean (acute)	Normalized acute	Reference	ln (norm hard)	ln (norm acute)	SMAS	R^2
Oncorhynchus mykiss	31.0		0.51	1.75		0.96	Davies 1976	-0.671	-0.045		
Oncorhynchus mykiss	44.4		0.73	3.00		1.64	Phipps and Holcombe 1985	-0.312	0.494		
Oncorhynchus mykiss	30.7		0.51	0.71		0.39	Stratus Consulting 1999	-0.681	-0.947		
Oncorhynchus mykiss	29.3		0.48	0.47		0.26	Stratus Consulting 1999	-0.727	-1.360		
Oncorhynchus mykiss	31.7		0.52	0.51		0.28	Stratus Consulting 1999	-0.649	-1.278		
Oncorhynchus mykiss	30.2		0.50	0.38		0.21	Stratus Consulting 1999	-0.697	-1.572		
Oncorhynchus mykiss	30.0		0.49	1.29		0.70	Stratus Consulting 1999	-0.704	-0.350		
Oncorhynchus mykiss	89.3	60.64	1.47	2.85	1.83	1.56	Stratus Consulting 1999	0.387	0.442	0.7679	0.68
Salmo trutta	43.5		0.80	1.40		0.51	Spehar and Carlson 1984	-0.229	-0.680		
Salmo trutta	37.6		0.69	2.37		0.86	Davies and Brinkman 1994	-0.374	-0.153		
Salmo trutta	29.2		0.53	1.23		0.45	Brinkman and Hansen 2004	-0.627	-0.809		
Salmo trutta	67.6		1.24	3.90		1.41	Brinkman and Hansen 2004	0.212	0.345		
Salmo trutta	151.4	54.68	2.77	10.10	2.76	3.66	Brinkman and Hansen 2004	1.018	1.297	1.2671	0.91
							Revised pooled acute slope = 0.9151				**0.69**

Species	Hardness (mg/L)	Geomean (hardness)	Normalized hardness	LC$_{50}$/EC$_{50}$ (µg/L)	Geomean (acute)	Normalized acute	Reference	ln (norm hard)	ln (norm acute)	SMAS	R^2
Oncorhynchus mykiss	31.0		0.51	1.75		0.96	Davies 1976	-0.671	-0.045		
Oncorhynchus mykiss	44.4		0.73	3.00		1.64	Phipps and Holcombe 1985	-0.312	0.494		
Oncorhynchus mykiss	30.7		0.51	0.71		0.39	Stratus Consulting 1999	-0.681	-0.947		
Oncorhynchus mykiss	29.3		0.48	0.47		0.26	Stratus Consulting 1999	-0.727	-1.360		
Oncorhynchus mykiss	31.7		0.52	0.51		0.28	Stratus Consulting 1999	-0.649	-1.278		
Oncorhynchus mykiss	30.2		0.50	0.38		0.21	Stratus Consulting 1999	-0.697	-1.572		
Oncorhynchus mykiss	30.0		0.49	1.29		0.70	Stratus Consulting 1999	-0.704	-0.350		
Oncorhynchus mykiss	89.3	60.64	1.47	2.85	1.83	1.56	Stratus Consulting 1999	0.387	0.442	0.7679	0.68
Salmo trutta	43.5		0.80	1.40		0.51	Spehar and Carlson 1984	-0.229	-0.680		
Salmo trutta	37.6		0.69	2.37		0.86	Davies and Brinkman 1994	-0.374	-0.153		
Salmo trutta	29.2		0.53	1.23		0.45	Brinkman and Hansen 2004	-0.627	-0.809		
Salmo trutta	67.6		1.24	3.90		1.41	Brinkman and Hansen 2004	0.212	0.345		
Salmo trutta	151.4	54.68	2.77	10.10	2.76	3.66	Brinkman and Hansen 2004	1.018	1.297	1.2671	0.91
							Revised pooled acute slope = 0.9151				**0.69**

4.2 Updated Acute Cadmium Objectives

The recalculated FAV was then determined using the GMAVs for the four most sensitive genera in the revised acute database. Calculations followed the EPA methods for criteria derivation (Stephan et al. 1985), and are presented in Table 9. The revised FAV at a hardness of 50 mg/L is 2.785 µg/L, which results in a final acute equation of $e^{0.9151[\ln(\text{hardness})] - 3.2488}$ and criteria maximum concentration (CMC), or acute objective, of 1.393 µg/L for Cd. This value is slightly higher than the FAV reported in the 2001 Cadmium Document (2.763 µg/L), and is higher than the SMAVs for many, but not all, commercially important trout. To further protect trout, the 2001 Cadmium Document replaced the FAV with the SMAV of rainbow trout in the criterion calculation, which resulted in a FAV of 2.014 µg/L. This value was higher than the SMAV for the brook trout, yet lower than all other SMAVs in the 2001 Cadmium Document database. Following this approach, but in an effort to be more protective, we lowered the revised FAV to the lowest GMAV (*Salvelinus*) of 1.915 µg/L to better protect trout (Table 9). The revised "trout-specific" equation becomes e0.9151[ln(hardness)]-3.6236 and a CMC if 0.9573 µg/L, again at hardness of 50 mg/L, using the lowered "trout" FAV.

Table 9: Recalculation of the final acute values for Cd using the updated acute database. N = 58 genera, R = sensitivity rank in database, P = rank / N+1.

Rank	Genus	GMAV	ln GMAV	(ln GMAV)^2	P = R/(N+1)	√P
4	*Morone*	3.159	1.1502	1.3229	0.0678	0.2604
3	*Salmo*	2.883	1.0590	1.1215	0.0508	0.2255
2	*Cottus*	2.374	0.8647	0.7477	0.0339	0.1841
1	*Salvelinus*	1.915	0.6495	0.4218	0.0169	0.1302
		Sum	3.7234	3.6140	0.1695	0.8002

Calculations:

Acute Criterion

$$S^2 = \frac{\Sigma(\ln GMAV)^2 - (\Sigma \ln GMAV)^2/4}{\Sigma P - (\Sigma\sqrt{P})^2/4} = \frac{3.6140 - (3.7234)^2/4}{0.1695 - (0.8002)^2/4} = 15.7167 \qquad S = 3.9644$$

$L = [\Sigma \ln GMAV - S(\Sigma\sqrt{P})]/4 = [3.7234 - 3.9644\,(0.8002)]/4 = 0.1378$

$A = S(\sqrt{0.05}) + L = (3.9644)(0.2236) + 0.1378 = 1.0243$

Final Acute Value = FAV = e^A = 2.785

CMC = ½ FAV = 1.3925

Pooled Slope = 0.9151

ln (Criterion Maximum Intercept)

= lnCMC - [pooled slope × ln (standardized hardness level)]

= ln (1.3925) - [0.9151 × ln (50)]

= -3.2488

Recalculated Acute Cadmium Criterion = $e^{0.9151\,[\ln(\text{hardness})]\,-3.2488}$

@ Hardness 100 = 2.626 µg/L

Lowered to protect trout

FAV = 1.9146

CMC = 0.9573

= ln(0.9573)-[0.9151×ln(50)]

= -3.6236

Criterion to protect trout = $e^{0.9151[\ln(\text{hardness})]-3.6236}$

@ Hardness 100 = 1.805 µg/L

4.2 Updated Acute Cadmium Objectives

The recalculated FAV was then determined using the GMAVs for the four most sensitive genera in the revised acute database. Calculations followed the EPA methods for criteria derivation (Stephan et al. 1985), and are presented in Table 9. The revised FAV at a hardness of 50 mg/L is 2.785 µg/L, which results in a final acute equation of $e^{0.9151[\ln(\text{hardness})] - 3.2488}$ and criteria maximum concentration (CMC), or acute objective, of 1.393 µg/L for Cd. This value is slightly higher than the FAV reported in the 2001 Cadmium Document (2.763 µg/L), and is higher than the SMAVs for many, but not all, commercially important trout. To further protect trout, the 2001 Cadmium Document replaced the FAV with the SMAV of rainbow trout in the criterion calculation, which resulted in a FAV of 2.014 µg/L. This value was higher than the SMAV for the brook trout, yet lower than all other SMAVs in the 2001 Cadmium Document database. Following this approach, but in an effort to be more protective, we lowered the revised FAV to the lowest GMAV (*Salvelinus*) of 1.915 µg/L to better protect trout (Table 9). The revised "trout-specific" equation becomes e0.9151[ln(hardness)]-3.6236 and a CMC if 0.9573 µg/L, again at hardness of 50 mg/L, using the lowered "trout" FAV.

Table 9: Recalculation of the final acute values for Cd using the updated acute database. N = 58 genera, R = sensitivity rank in database, P = rank / N+1.

Rank	Genus	GMAV	ln GMAV	(ln GMAV)^2	P = R/(N+1)	√P
4	*Morone*	3.159	1.1502	1.3229	0.0678	0.2604
3	*Salmo*	2.883	1.0590	1.1215	0.0508	0.2255
2	*Cottus*	2.374	0.8647	0.7477	0.0339	0.1841
1	*Salvelinus*	1.915	0.6495	0.4218	0.0169	0.1302
		Sum	3.7234	3.6140	0.1695	0.8002

Calculations:
Acute Criterion

$$S^2 = \frac{\Sigma(\ln GMAV)^2 - (\Sigma \ln GMAV)^2/4}{\Sigma P - (\Sigma\sqrt{P})^2/4} = \frac{3.6140 - (3.7234)^2/4}{0.1695 - (0.8002)^2/4} = 15.7167 \qquad S = 3.9644$$

$$L = [\Sigma \ln GMAV - S(\Sigma\sqrt{P})]/4 = [3.7234 - 3.9644\,(0.8002)]/4 = 0.1378$$

$$A = S(\sqrt{0.05}) + L = (3.9644)(0.2236) + 0.1378 = 1.0243$$

Final Acute Value = FAV = e^A = 2.785
CMC = ½ FAV = 1.3925
Pooled Slope = 0.9151

ln (Criterion Maximum Intercept)
= lnCMC - [pooled slope × ln (standardized hardness level)]
= ln (1.3925) - [0.9151 × ln (50)]
= -3.2488

Recalculated Acute Cadmium Criterion = $e^{0.9151\,[\ln(\text{hardness})] - 3.2488}$
@ Hardness 100 = 2.626 µg/L

Lowered to protect trout
FAV = 1.9146
CMC = 0.9573

= ln(0.9573)-[0.9151×ln(50)]
= -3.6236

Criterion to protect trout = $e^{0.9151[\ln(\text{hardness})] - 3.6236}$
@ Hardness 100 = 1.805 µg/L

4.2 Updated Acute Cadmium Objectives

The recalculated FAV was then determined using the GMAVs for the four most sensitive genera in the revised acute database. Calculations followed the EPA methods for criteria derivation (Stephan et al. 1985), and are presented in Table 9. The revised FAV at a hardness of 50 mg/L is 2.785 µg/L, which results in a final acute equation of $e^{0.9151[\ln(\text{hardness})] - 3.2488}$ and criteria maximum concentration (CMC), or acute objective, of 1.393 µg/L for Cd. This value is slightly higher than the FAV reported in the 2001 Cadmium Document (2.763 µg/L), and is higher than the SMAVs for many, but not all, commercially important trout. To further protect trout, the 2001 Cadmium Document replaced the FAV with the SMAV of rainbow trout in the criterion calculation, which resulted in a FAV of 2.014 µg/L. This value was higher than the SMAV for the brook trout, yet lower than all other SMAVs in the 2001 Cadmium Document database. Following this approach, but in an effort to be more protective, we lowered the revised FAV to the lowest GMAV (*Salvelinus*) of 1.915 µg/L to better protect trout (Table 9). The revised "trout-specific" equation becomes e0.9151[ln(hardness)]-3.6236 and a CMC if 0.9573 µg/L, again at hardness of 50 mg/L, using the lowered "trout" FAV.

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Calculations:

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4.3 Updating the Chronic Hardness Relationship

The 2001 Cadmium Document also used the same procedures as the acute slope to obtain a slope that defines the chronic hardness relationship. The chronic hardness relationship was derived from three species, *D. magna*, *S. trutta*, and *P. promelas*. The individual species slopes ranged from 0.5212 (*S. trutta*) to 1.579 (*D. magna*), and the pooled slope was 0.9685. However, as with the acute slope, the *D. magna* data was determined too variable and, therefore, only data from the Chapman et al. manuscript was used. The resultant pooled slope with the reduced data set was 0.7409.

The revised and updated chronic hardness relationship was derived by reviewing data used to calculate the chronic hardness slope calculation in the 2001 Cadmium Document and adding data from the updated chronic database (Table 10). The revised pooled chronic slope was derived from 13 individual data points (increased from 7) that encompasses four species (increased from three). Individual species slopes ranged from 0.4779 (*O. mykiss*) to 1.0034 (*P. promelas*). The Davies et al. (1993) toxicity tests for *O. mykiss* increased the range of hardness values tested. Target values ranged from 50 mg/L to 400 mg/L enabling us to add this previously unused species to the chronic hardness slope database. Analysis of covariance determined the individual species slopes of the revised chronic slope database are not different (p = 0.72). Therefore, all data were grouped and the pooled slope of this revised database is 0.7998. This slope is used to standardize all chronic toxicity values to a common hardness and in the final equation to compute the chronic AWQC at a given hardness.

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Table 10: Updated chronic Cd hardness slope. SMCS = species mean chronic slope.

Species	Hardness (mg/L)	Geomean (hard)	Normalized hardness	Chronic value (µg/L)	Geomean (chronic)	Normalized chronic	Reference	Ln (norm hard)	Ln (norm acute)	SMCS	R^2
Daphnia magna	209.2		1.68	0.67		2.15	Canton and Slooff 1982	0.5206	0.7654		
Daphnia magna	53.0		0.43	1.52		0.49	Chapman et al. Manuscript	-0.8524	-0.7180		
Daphnia magna	103.0		0.83	0.21		0.68	Chapman et al. Manuscript	-0.1879	-0.3853		
Daphnia magna	209.0	124.30	1.68	0.44	0.31	1.40	Chapman et al. Manuscript	0.5197	0.3380	0.9659	0.89
Salmo trutta	39.8		0.52	1.33		0.25	Davies and Brinkman 1994	-0.65	-1.38		
Salmo trutta	44.0		0.58	6.67		1.27	Eaton et al. 1978	-0.55	-0.24		
Salmo trutta	250.0	75.93	3.29	16.49	5.27	3.13	Brown et al. 1994	1.19	1.14	0.9931	0.65
Pimephales promelas	201.0		2.14	45.92		2.14	Pickering and Gast 1972	0.76	0.76		
Pimephales promelas	44.0	94.04	0.47	10.00	21.43	0.47	Spehar and Fiandt 1986	-0.76	-0.76	1.0034	--
Oncorhynchus mykiss	46.2		0.26	1.47		0.49	Davies et al. 1993	-1.36	-0.72		
Oncorhynchus mykiss	217.0		1.21	3.58		1.19	Davies et al. 1993	0.19	0.17		
Oncorhynchus mykiss	413.8		2.31	3.64		1.21	Davies et al. 1993	0.84	0.19		
Oncorhynchus mykiss	250.0	179.46	1.39	4.31	3.01	1.43	Brown et al. 1994	0.33	0.36	0.4779	0.86
							Revised pooled chronic slope =			**0.7998**	**0.72**

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							Revised pooled chronic slope =			**0.7998**	**0.72**

4.4 Updated Chronic Cadmium Objectives

The recalculated FCV was then determined using the GMCVs for the four most sensitive genera in the revised chronic database. Calculations followed the EPA methods for criteria derivation (Stephan et al. 1985) and are presented in Table 11. The recalculated FCV is 0.2734 µg/L, whereas the FCV from the 2001 Cadmium Document was 0.162 µg/L. This results in a final chronic equation of $e^{0.7998\,[\ln(\text{hardness})]\,-4.4255}$ for Cd. At a hardness of 100 mg/L, the revised chronic Cd objective based upon this equation is 0.476 µg/L.

Table 11: Recalculation of the final chronic values for Cd using the updated chronic database (N = 17 genera, R = sensitivity rank in database, P = rank / N+1).

Rank	Genus	GMCV	ln GMCV	(ln GMCV)^2	P = R/(N+1)	√P
4	*Oncorhynchus*	2.308	0.8365	0.6997	0.2222	0.4714
3	*Daphnia*	1.326	0.2821	0.0796	0.1667	0.4082
2	*Cottus*	1.066	0.0638	0.0041	0.1111	0.3333
1	*Hyalella*	0.264	-1.3316	1.7733	0.0556	0.2357
		Sum	-0.1493	2.5566	0.5556	1.4487

Calculations:

Chronic Criterion

$$S^2 = \frac{\Sigma\,(\ln GMCV)^2 - (\Sigma \ln GMCV)^2/4}{\Sigma P - (\Sigma\,\sqrt{P})^2/4} = \frac{2.5566 - (-0.1493)^2/4}{0.5556 - (1.4487)^2/4} = 82.6070 \qquad S = 9.0888$$

$L = [\Sigma \ln GMCV - S(\Sigma\sqrt{P})]/4 = [-0.1493 - 9.0888\,(1.4487)]/4 = -3.3290$

$A = S\,(\sqrt{0.05}) + L = (9.0888)(0.2236) + -3.3290 = -1.2967$

Final Chronic Value = FCV = $e^{A} = 0.2734$

Pooled Slope = 0.7998

$$\begin{aligned} \ln(\text{Final Chronic Intercept}) &= \ln FCV - [\text{chronic slope} \times \ln(\text{standardized hardness level})] \\ &= \ln(0.2734) - [0.7998 \times \ln(50)] \\ &= -4.4255 \end{aligned}$$

Recalculated Chronic Cadmium Criterion = $e^{0.7998\,[\ln(\text{hardness})]\,-4.4255}$ @ Hardness 100 = 0.476 µg/L

4.4 Updated Chronic Cadmium Objectives

The recalculated FCV was then determined using the GMCVs for the four most sensitive genera in the revised chronic database. Calculations followed the EPA methods for criteria derivation (Stephan et al. 1985) and are presented in Table 11. The recalculated FCV is 0.2734 µg/L, whereas the FCV from the 2001 Cadmium Document was 0.162 µg/L. This results in a final chronic equation of $e^{0.7998\,[\ln(\text{hardness})]\,-4.4255}$ for Cd. At a hardness of 100 mg/L, the revised chronic Cd objective based upon this equation is 0.476 µg/L.

Table 11: Recalculation of the final chronic values for Cd using the updated chronic database (N = 17 genera, R = sensitivity rank in database, P = rank / N+1).

Rank	Genus	GMCV	ln GMCV	(ln GMCV)^2	P = R/(N+1)	√P
4	*Oncorhynchus*	2.308	0.8365	0.6997	0.2222	0.4714
3	*Daphnia*	1.326	0.2821	0.0796	0.1667	0.4082
2	*Cottus*	1.066	0.0638	0.0041	0.1111	0.3333
1	*Hyalella*	0.264	-1.3316	1.7733	0.0556	0.2357
		Sum	-0.1493	2.5566	0.5556	1.4487

Calculations:
Chronic Criterion

$$S^2 = \frac{\Sigma(\ln GMCV)^2 - (\Sigma \ln GMCV)^2/4}{\Sigma P - (\Sigma\sqrt{P})^2/4} = \frac{2.5566 - (-0.1493)^2/4}{0.5556 - (1.4487)^2/4} = 82.6070 \qquad S = 9.0888$$

$L = [\Sigma \ln GMCV - S(\Sigma\sqrt{P})]/4 = [-0.1493 - 9.0888\,(1.4487)]/4 = -3.3290$
$A = S(\sqrt{0.05}) + L = (9.0888)(0.2236) + -3.3290 = -1.2967$
Final Chronic Value = FCV = e^A = 0.2734
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$$\begin{aligned}\ln(\text{Final Chronic Intercept}) &= \ln \text{FCV} - [\text{chronic slope} \times \ln(\text{standardized hardness level})] \\ &= \ln(0.2734) - [0.7998 \times \ln(50)] \\ &= -4.4255\end{aligned}$$

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Final Chronic Value = FCV = $e^A = 0.2734$

Pooled Slope = 0.7998

ln (Final Chronic Intercept) = ln FCV - [chronic slope × ln(standardized hardness level)]
= ln (0.2734) - [0.7998 × ln (50)]
= -4.4255

Recalculated Chronic Cadmium Criterion = $e^{0.7998\,[\ln(\text{hardness})]\,-4.4255}$ @ Hardness 100 = 0.476 µg/L

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5.0 Summary

EPA methods for criteria derivation were followed to calculate an updated FAV/FCV for Cd and provide updates to the corresponding equations. This produced a revised FAV (2.785 µg/L) that is higher than the FAV reported in the 2001 document (2.763 µg/L). The revised FCV (0.273 g/L) was also higher than the FCV from the 2001 document (0.162 µg/L). In both cases, the changes are a result of the literature review, additional data on new and existing species in the toxicity databases, and reduced variability in the four most sensitive species. The resulting equations, including application of the EPA conversion factors, would be:

$$\text{Acute Cd} = 1.136672-[(\ln(\text{hardness})*(0.041838)]\ e^{0.9151[\ln(\text{hardness})]-3.2488}$$

$$\text{Acute}_{(\text{trout})}\text{ Cd} = 1.136672-[(\ln(\text{hardness})*(0.041838)]\ e^{0.9151[\ln(\text{hardness})]-3.6236}$$

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On behalf of the SARDA members and L.A. County Sanitation District, we recommend adoption of these updated final acute and chronic equations for Cd water quality objectives. Table 12 summarizes the calculated acute and chronic concentrations at different hardnesses, with comparisons to the outdated 2001 values, including application of conversion factors for total to dissolved objectives.

Table 12: Summary of acute objectives and chronic objectives at various hardness values for Cd. All values are reported in µg/L.

Equations	Hardness (mg/L)									
	25	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
2001 EPA Update										
CMC $= 1.136672-[(\ln(\text{hardness})*(0.041838)]\ e^{1.0166[\ln(\text{hardness})]-3.924}$	0.52	1.03	1.52	2.01	2.99	3.95	4.90	5.85	6.80	7.74
CCC $= 1.101672-[(\ln(\text{hardness})*(0.041838)]\ e^{0.7409[\ln(\text{hardness})]-4.719}$	0.09	0.15	0.20	0.25	0.33	0.40	0.46	0.53	0.59	0.64
GEI Revision/Update										
CMC $= 1.136672-[(\ln(\text{hardness})*(0.041838)]\ e^{0.9151[\ln(\text{hardness})]-3.2488}$	0.74	1.35	1.93	2.48	3.53	4.53	5.50	6.44	7.37	8.27
CMC[a] $= 1.136672-[(\ln(\text{hardness})*(0.041838)]\ e^{0.9151[\ln(\text{hardness})]-3.6236}$	0.51	0.93	1.33	1.70	2.43	3.11	3.78	4.43	5.06	5.69
CCC $= 1.101672-[(\ln(\text{hardness})*(0.041838)]\ e^{0.7998[\ln(\text{hardness})]-4.4255}$	0.15	0.26	0.35	0.43	0.59	0.73	0.86	0.99	1.11	1.23

[a] FAV lower to protect a commercially important species.

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