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TECHNICAL MEMORANDUM

July 2004

UPDATE AND SUMMARY OF THE TECHNICAL REVIEW OF THE 1999 U.S. EPA AMMONIA WATER QUALITY CRITERIA DOCUMENT

Chadwick Ecological Consultants, Inc. (CEC) was asked by the Colorado Wastewater Utility Council (Council) to conduct a technical review of the 1999 Ammonia Water Quality Criteria document (USEPA 1999). This request was due in large part to the ambiguities regarding acute and chronic model development and the lack of "new" data included in the revision.

Acute Ammonia Toxicity

To explain the relationship between acute ammonia toxicity ($LC50_{TA}$) and pH the EPA derived an empirical "S-shaped" model, using the disassociation characteristics of Total Ammonia (TA) as the basis for the "S-shape:"

$$LC50_{TA} = \left(\frac{LC50_{TA,8}}{\frac{R}{1+10^{pH_{TA}-8}} + \frac{1}{1+10^{8-pH_{TA}}}} \right) \times \left(\frac{R}{1+10^{pH_{TA}-pH}} + \frac{1}{1+10^{pH-pH_{TA}}} \right) \qquad \text{Eq. 1}$$

where R is the slope of the disassociation curve, pH_{TA} is the inflection point at low pH values, and $LC50_{t,8}$ is the acute toxicity value adjusted to a pH = 8. Both R and pH_{TA} are parameterized values based on the nonlinear relationship between $LC50_{TA}$ and pH for a pooled group of organisms. The pooled dataset consisted of four studies that evaluated ammonia toxicity over a broad range of pH (6.5-9) for various freshwater species.

Substitution of the parameterized values, R (0.00704) and pH_{TA} (7.204), into equation one results in the formulation of the EPA's Acute Value model (AV_t) describing pH dependence of acute toxicity. By rearranging the equation one can convert LC50s to an equivalent value at pH = 8 ($AV_{t,8}$) – i.e., normalize all data to pH 8. Note that $LC50_{TA}$ and AV_{TA} are synonymous.

$$AV_{TA} = AV_{TA,8} \times \left(\frac{0.0489}{1+10^{7.204\text{-pH}}} + \frac{6.95}{1+10^{\text{pH-}7.204}} \right) \qquad \text{Eq. 2}$$

Using this normalized value ($AV_{t,8}$) for each species, the geometric mean acute values were calculated for each Genus (GMAV) and Species (SMAV) following EPA guidelines described in Stephan et al. (1985). The GMAV values were ranked from 1 to n, with number 1 being the lowest value. The GMAVs contained within the 5th percentile were used to calculate the Final Acute Value (FAV), which is ultimately used in the development of the Criterion Maximum Concentration (CMC) for TA at a given pH. One additional step taken by the EPA was to calculate a modified SMAV for *Oncorhynchus mykiss* (11.23 mg N/L) based on single study by Thurston and Russo (1983).

The original calculated FAV was then recalculated minus the salmonids genera and became the basis for the "salmonids absent" equation, and the modified SMAV for rainbow trout became the basis for the final acute equation as "salmonids present" in the 1999 EPA document (see equations below).

Salmonids present:

$$\text{CMC} = \frac{0.275}{1+10^{7.204\text{-pH}}} + \frac{39.0}{1+10^{\text{pH-}7.204}} \qquad \text{Eq. 3}$$

Salmonids absent:

$$\text{CMC} = \frac{0.411}{1+10^{7.204\text{-pH}}} + \frac{58.4}{1+10^{\text{pH-}7.204}} \qquad \text{Eq. 4}$$

Reanalysis of pH Dependence of Acute Ammonia Toxicity

CEC was asked by the Council to evaluate potential revisions to these models based on available data acquired by CEC as part of a literature review for studies published through 2003. (See Appendix A for a complete list of toxicity literature used in this analysis.)

Following the guidelines for the inclusion of data in the development of numerical water quality criteria (Stephan et al. 1985), we added 15 new genera to the 34 genera present in the 1999 revision document. We did use one deviation from the guidelines in our revision of this database. Specifically, all data reported as “greater than” or “less than” values were removed from the database. Given the size of the database for ammonia toxicity, these uncertain data become superfluous. For example, even with deletion of these data, the new dataset represents species from five Phyla, nine Classes, 21 Orders and 29 Families, 49 Genera, and 67 Species (Appendix B). The most noteworthy additions were mussels in the Family Unionidae, which recent publications have shown to be extremely sensitive to ammonia toxicity.

Although the dataset doubled in terms of total species, there were only a few studies that evaluated ammonia toxicity over a range of pH (6.5-9) suitable to develop water quality criteria. In addition, there was a concern of developing criteria based on studies that had relatively small sample sizes. Therefore, a decision was made to again use a selected group of studies for “curve-fitting” purposes. CEC was unsure of the four datasets used by the EPA to develop their acute toxicity model, therefore, model validation and parameterization were quite difficult. For our analysis, we used data from Broderius et al. 1985 (n = 70), DeGraeve et al. 1987 (n = 80), Reinbold and Pescitelli 1982 (n = 32), and Thurston et al. 1986 (n = 40) to evaluate the fit of simple linear and multiple regression models to individual and a pooled datasets.

We first re-analyzed the TA vs pH relationship and found we could not specifically fit EPA's model to the available toxicity data. It was clear that linear models showed very weak relationships between $\log_{10}$TA and temperature for the selected data, with stronger relationships observed between $\log_{10}$TA and pH. Linear models were able to account for 63% of the variation observed between $\log_{10}$TA and pH in the Broderius et al. (1985) data. Similarly, 28-51% of the variation observed in the remaining datasets could be accounted for using linear models.

Although pH relationships were more robust than the temperature relationships, the linear model approach still has shortcomings when trying to set CMC values. For example, at lower pHs (6-6.5) the residual error of the linear models increased, exhibiting a poorer fit to potential ammonia toxicity (and EPA's curves) within this pH range (Fig. 1). Theoretically, within this lower pH range, ammonia toxicity might be expected to reach an asymptotic level based on the chemical speciation of ammonia (NH_3) and ammonium ion (NH_4^+) – and this is the basis for EPA's "S-shaped" curves.

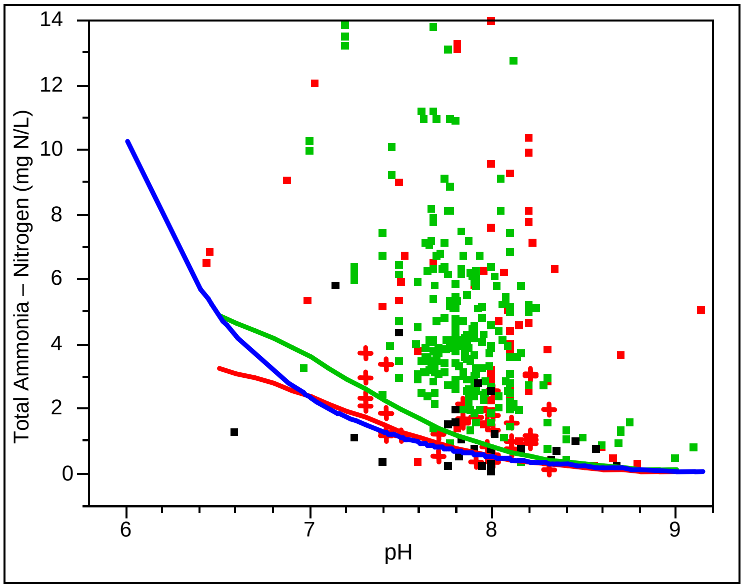

Figure 1. pH dependency of acute ammonia toxicity models. The red line is the EPA CMC with salmonids present; green line is EPA CMC with salmonids absent; blue line is the CEC best fit regression model representing the 5th percentile of the data.

Given the shortcomings of the linear model approach for developing ammonia toxicity criteria and the potential problems with developing such a different curve from the EPA versions, we were directed by the Council to turn back to the non-linear models; i.e., the "salmonids present" and "salmonids absent" curves developed by the EPA (1999) - but apply that approach to our updated database.

Before adjusting the "salmonids present or absent" curves with the new data, it was necessary to address outstanding issues in the EPA acute equations. Specifically, there was a concern with the way EPA decided to use a modified SMAV based on "large" rainbow trout, *Oncorhynchus mykiss,* in the development of their "salmonids present" equation. Thurston and Russo (1983) examined the response of various age-class rainbow trout (<1d to 4yr old) to acute toxicity and found that the tolerance to ammonia toxicity increased through larval development stages, peaking at the juvenile-yearling stage and decreasing in older fish. One caveat of their study is that age-class conclusions were based on regression results from fish that were <1d to 302 days old from the same egg lot, but applied to fish that were 4 years old from a different egg lot.

Based on Thurston and Russo's (1983) conclusions, the EPA lowered the SMAV for *Oncorhynchus mykiss* from 21.95 mg N/L to 11.23 mg N/L. In our review of the Thurston and Russo (1983) results we were unable to duplicate the 11.23 mg N/L geometric mean of LC50 values for "large" rainbow trout that the EPA determined and used to develop the "salmonids present" acute equation.

This size class relationship to acute ammonia has not been observed in other studies of rainbow trout, and the EPA did not clearly define "large" (i.e., provide a size class based on weight) rainbow trout. Therefore, we have developed an alternative and perhaps more defensible approach to account for potential different sensitivities of warm-water and cold-water biota to ammonia. We decided to re-categorize our database as either cold-water or warm-water species. This method alleviates the undocumented preferential treatment given to one age-class of a single species when setting national, or even regional, criteria. This does not mean that sensitive age-classes of a species should not be protected, but rather that the ammonia criteria should be based on more robust scientific results. This is potentially an area where further age-class studies are needed to support a size class relationship to acute ammonia toxicity.

Due to the various data reporting methods, LC50 results for ammonia toxicity were converted to Total Ammonia Nitrogen (TA-N) and normalized to pH 8, as described earlier. Toxicity values that were published as "greater than" or "less than" values were not used. No temperature adjustment was made, consistent with the EPA document. The geometric mean of the normalized pH 8 acute values (AV) were computed for each species (SMAV). Similarly, the Genus Mean Acute Values (GMAV) were computed for each genera (GMAV = geometric mean of SMAV). The database was then split into two lists of species (i.e., cold or warm water), based on habitat type (Appendix C). *Species commonly found in both habitat types were included in each data subset*. Once divided, each database still met the requirements for data inclusion in criteria development (i.e., the "eight family rule"), with the understandable exception that the warm-water database did not include a representative from the Salmonidae family. For each habitat category, the GMAVs were ranked from the highest (n) to lowest (1) value with a cumulative probability assigned to each value (Stephan et al. 1985). The four lowest GMAVs were used to calculate the Final Acute Value (FAV) for each data subset.

Within the cold-water species database (29 genera), the four most sensitive genera were the trout and salmon genera, *Salmo* (23.7 mg TA-N/L) and *Oncorhynchus* (22.9 mg TA-N/L), the cladoceran *Ceriodaphnia* (16.3 mg TA-N/L), and the mountain whitefish, *Prosopium* (12.1 mg TA-N/L). Using these data, the FAV was 14.4 mg TA-N/L for cold-water species; a value slightly higher than the 11.23 mg TA-N/L EPA used for "salmonids present" (Appendix D).

For the warm-water database (44 genera), the four most sensitive genera were *Pyganodon* (4.7 mg TA-N/L), *Medionidus* (4.5 mg TA-N/L), *Lasmigona* (2.8 mg TA-N/L), and *Fusconaia* (1.3 mg TA-N/L). The resulting FAV was 2.8 mg TA-N/L for the warm-water database (Appendix E). These four genera are all mussels from the Unionidae family, representing new data not available for the 1999 Update. In fact, representatives from the unionid family comprised the 8 most sensitive genera within the updated warm-water database. Inclusion of these unionid ammonia toxicity data would lead to a significant reduction in the CMC for warm-water biota, when compared to the "salmonid absent" category of the EPA document (1999).

Given the uncertainty of the unionid distribution within the State of Colorado (Wu and Brandauer, 1978) – plus the apparent potential for further EPA technical review of these studies (per Mark Pifher, WQCD, Summary of State/EPA Water Quality Standards Workshop, memo dated April 22, 2004), we also analyzed the warm-water database <u>minus</u> the Unionidae family.

This modified warm-water database still contained 36 genera, with the darter *Etheostoma* (18.1 mg TA-N/L), the cladoceran *Ceriodaphnia* (16.3 mg TA-N/L), the mosquitofish *Gambusia* (15.3 mg TA-N/L), and the shiner *Notemigonus* (14.7 mg TA-N/L) being the four most sensitive genera. The FAV for this warm-water database minus unionid clams was 15.4 mg TA-N/L (Appendix F).

The FAV value for each database (e.g. cold-water, warm-water, warm-water minus Unionidae) was then used to calculate the Criterion Maximum Concentration (CMC) for each habitat type. Substitution of one-half the FAV into equation two for $AV_{t,8}$ provided the CMC at pH 8. Using the updated databases, and recalculated FAVs, the three resulting acute (CMC) equations for 1) cold-water, 2) warm-water, and 3) warm-water without the family Unionidae, with respect to pH, are:

Cold-water Ammonia Acute Criterion:

$$\mathrm{CMC_{Cold}} = \frac{0.347}{1+10^{7.204\text{-pH}}} + \frac{49.3}{1+10^{\text{pH-}7.204}} \qquad \text{Eq. 5}$$

Warm-water Ammonia Acute Criterion:

$$\mathrm{CMC_{Warm}} = \frac{0.069}{1+10^{7.204\text{-pH}}} + \frac{9.87}{1+10^{\text{pH-}7.204}} \qquad \text{Eq. 6}$$

Warm-water without Unionidae Ammonia Acute Criterion:

$$\mathrm{CMC_{Warm\ without\ Unionidae}} = \frac{0.378}{1+10^{7.204\text{-pH}}} + \frac{53.7}{1+10^{\text{pH-}7.204}} \qquad \text{Eq. 7}$$

Each equation was solved for an acute criterion given a range of pHs (6.5-9), producing an ammonia concentration that "at most" should be lethal to a small fraction of individuals in the 5th percentile (Table 1). These values were then compared to the existing "salmonids present" and "salmonids absent" acute ammonia equations in the EPA 1999 document (Fig. 2).

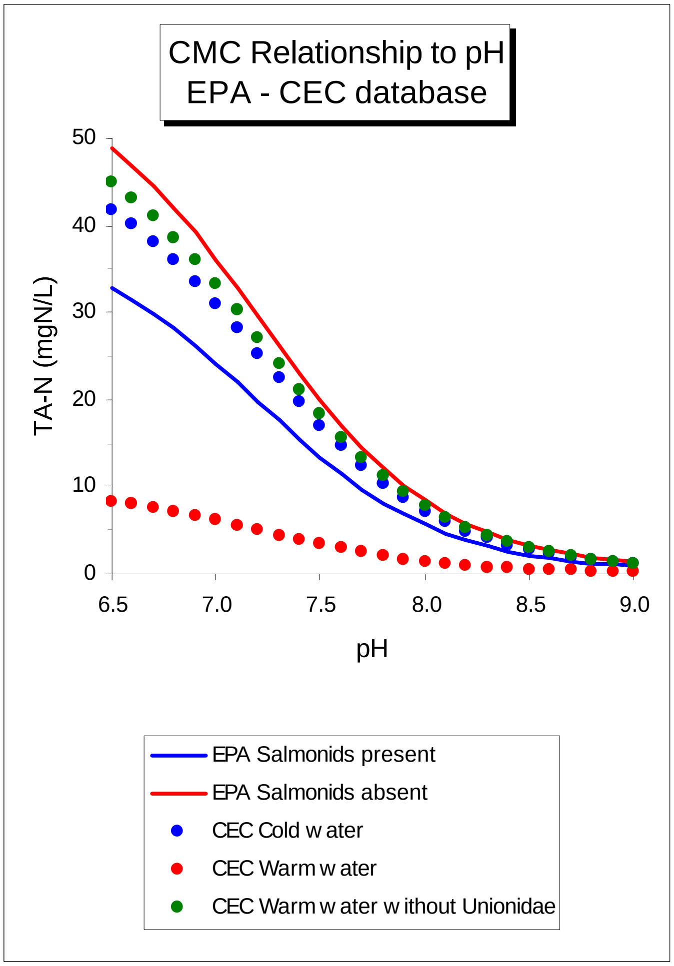

Figure 2. Comparison of EPA 1999 and CEC 2004 Criterion Maximum Concentrations for TA-N given pH.

The notable differences between the EPA acute equations and our revised and updated equations are the slight upward shift for the new "cold-water" acute values as compared to the "salmonids present" acute values in the EPA document, and the 5 fold decrease in the new "warm-water" acute values as compared to the "salmonids absent" acute values from EPA. This substantial decrease is solely due to the inclusion of data for warm-water mussels in the family Unionidae.

When these organisms are removed from the database, the resulting “warm-water without Unionidae” curve is comparable to the EPA “salmonids absent” curve, with only a slight downward shift in the CMC (i.e., the revised warm-water curve is slightly more restrictive than the EPA “salmonids absent” curve).

Table 1. Comparative TA-N concentrations at a given pH for EPA (1999) acute criteria and the proposed updated acute criteria.

Comparison of acute ammonia values for aquatic life

	EPA 1999 Acute Criteria		Potential Revised and Updated Acute Criteria		
pH	Salmonids present	Salmonids absent	Cold-water Biota	Warm-water Biota	Warm-water Biota without Unionidae
	(TA-N mg/L)	(TA-N mg/L)	(TA-N mg/L)	(TA-N mg/L)	(TA-N mg/L)
6.5	32.69	48.83	41.22	8.25	44.90
6.6	31.36	46.84	39.54	7.92	43.07
6.7	29.84	44.57	37.62	7.53	40.98
6.8	28.12	42.00	35.45	7.10	38.62
6.9	26.22	39.16	33.06	6.62	36.01
7.0	24.16	36.09	30.47	6.10	33.19
7.1	22.00	32.86	27.74	5.55	30.22
7.2	19.78	29.54	24.94	4.99	27.16
7.3	17.55	26.21	22.13	4.43	24.10
7.4	15.38	22.97	19.39	3.88	21.12
7.5	13.32	19.89	16.79	3.36	18.29
7.6	11.40	17.03	14.38	2.88	15.66
7.7	9.67	14.44	12.19	2.44	13.28
7.8	8.13	12.14	10.25	2.05	11.16
7.9	6.78	10.13	8.55	1.71	9.32
8.0	5.63	8.41	7.10	1.42	7.73
8.1	4.65	6.95	5.87	1.17	6.39
8.2	3.83	5.73	4.83	0.97	5.27
8.3	3.16	4.71	3.98	0.80	4.34
8.4	2.60	3.88	3.28	0.66	3.57
8.5	2.14	3.20	2.70	0.54	2.95
8.6	1.77	2.65	2.24	0.45	2.44
8.7	1.48	2.20	1.86	0.37	2.03
8.8	1.23	1.84	1.56	0.31	1.70
8.9	1.04	1.56	1.31	0.26	1.43
9.0	0.89	1.32	1.12	0.22	1.22

Summary of Acute Ammonia Criteria

Although verification of the EPA's acute value model (AV_{TA}) remains somewhat questionable (i.e., lack of specifics regarding empirical data) CEC generally accepts their formulation of CMC with a few notable exceptions. The EPA's use of a modified *O. mykiss* SMAV combined with the decision not to include the most current data available resulted in the development of biased ammonia criteria. Therefore, CEC believes an alternate, scientifically sound, approach to developing acute ammonia criteria would be to amend the EPA database by excluding questionable data and including the most current data available, and further excluding the preferential age-class SMAV for *O. mykiss*. The "new" database should then be split based on habitat types (i.e., cold, warm, and warm-water without Unionidae), with "new" FAVs being calculated for each habitat type. These values are the basis for the proposed cold, warm, and warm-water without Unionidae CMC equations using the EPA's pH dependent acute equations.

Chronic Ammonia Toxicity

Owing to the paucity of chronic ammonia studies and stringent experimental protocols (i.e., duration, dissolved oxygen, and life stage) only 15 studies (representing 9 Genera) were considered acceptable by the EPA for the development of chronic ammonia criteria. Our review of the literature did not change this finding appreciably (we removed some data, added some data – with the final chronic database remaining basically the same size) (Appendix G).

With this small number of genera, the chronic database does not meet the "eight family rule" for the development of national water quality criteria (Stephan et al., 1985). In fact, three of the eight required families are not represented - the family Salmonidae, a family in the class Insecta, and a second family from Insecta or a non-represented Phylum. This major shortcoming of the database constrained the EPA's use of the criterion derivation 5th percentile approach to set the Criterion Continuous Concentration (CCC) – constrained, but it did not stop them from developing a chronic criterion separate from the acute equations.

In addition, because the CCC is derived from a variety of toxicological responses in fish (i.e., mortality, embryo production, embryo hatchability, biomass) and not solely based on survival, the EPA believed an effect due to seasonality could or should be included in model development. Ideally, using this assumption, the seasonal component would protect a range of physiological responses of various age-class organisms to chronic ammonia toxicity. Therefore, a temperature component was included in the model development as a surrogate for seasonality and life stage development.

Although the 5th percentile approach was severely constrained by the lack of chronic data, the EPA still used the 5th percentile genus mean chronic values (GMCVs) in their chronic model development. The GMCVs were based on EC20 total ammonia (mg N/L) results for each genera that had been normalized to pH 8 ($CV_{t,8}$) using a similar approach as in the acute database, but in addition, normalized to 25°C. Note that unlike the acute analysis, EPA determined that temperature should be included in the chronic criteria. Interestingly enough, linear regression analysis of <u>acute toxicity</u> data presented by Arthur et al. (1987) for five fish and nine invertebrates was used to derive these temperature dependent <u>chronic</u> ammonia toxicity equations. It is particularly important to note that the Arthur et al. (1987) study was not specifically designed to find temperature effects – rather it was an ammonia toxicity study conducted in outdoor streams during the four seasons (winter, spring, summer, and fall), with no controls on light or temperature. Furthermore, Arthur et al. (1987) reported, “our results do not clearly demonstrate a relationship between ammonia toxicity and temperature” - a finding that supported the exclusion of temperature in the acute ammonia equations.

Nonetheless, the EPA used the Arthur et al. (1987) <u>acute ammonia toxicity</u> study to develop a temperature dependent <u>chronic ammonia toxicity</u> model. Regression analysis of the $\log_{10}$ LC50 and temperature values for a subset of Arthur et al. (1987) data that included *Physa*, *Crangonyx*, and *Musculium* resulted in an invertebrate slope of -0.044. The slope for the pooled fish dataset was not significantly different from zero, thus no temperature dependent relationship was observed for fish. Because the EPA found no significant temperature response for fish, they assumed that the difference between acute and chronic slopes would be the same for fish and invertebrates. Therefore, they modified the acute invertebrate slope (-0.044) by subtracting a fish acute to chronic ratio slope (-0.016), that resulted in the adjusted invertebrate slope of -0.028.

The EPA used the adjusted temperature slope = -0.028 of the three invertebrate LC50 response values to normalize $CV_{t,8}$ of both fish and invertebrates to 25°C for comparative baseline purposes. The reason for choosing 25°C was because the only chronic value for the most sensitive species (*Hyalella azteca*) was experimentally determined at 25°C. In addition, other "acceptable" chronic ammonia toxicity studies were performed at temperatures within 3 degrees of 25°C. The EPA chose not to include the available studies of *Oncorhynchus* species because the data are extremely variable and presented as either greater than, less than or a range of EC20 values.

The four most sensitive species in the limited chronic database in order of decreasing sensitivity were the amphipod *Hyalella* (1.45 mg N/L), the fingernail clam *Musculium* (2.26 mg N/L), the bluegill *Lepomis* (2.52 mg N/L), and minnow *Pimphales* (3.03 mg N/L). However, of the 28 chronic EC20 values presented in Table 5 of the EPA (1999) document, 21 were mistakenly **not** normalized to 25°C. This slightly affects the EPA model output because their empirical model was based on the GMCV pH8 (2.85 mg N/L) for *Lepomis* early life stages instead of the temperature adjusted (25°C) value of 2.52 mg N/L. Also, the *Hyalella* and *Musculium* chronic data are suspect due to poor control organism performance in both studies.

The EPA developed their CCC model around only two genera - *Lepomis* and *Hyalella*, the most sensitive early life (ELS) stage fish and invertebrate to chronic toxicity, respectively. To account for the various fish life stages, the EPA derived two functions, one for *early life stage present* and another for *early life stage absent*. Although the "early life stage present or absent" is obviously related specifically to fish, fish ammonia toxicity data did not show a temperature dependency. Therefore, the model developed by EPA follows the invertebrate response to temperature - although it cannot exceed 85.4% of the lowest fish GMCV.

When *early life stage fish are present* the CCC incorporates the following temperature based function:

$$\mathrm{CCC}_{\text{Early life stage present}} = 0.854 \times \mathrm{MIN}\left(2.85, 1.45 \times 10^{-0.028(25-T)}\right) \quad \text{Eq. 8}$$

where 2.85 is the GMCV value for *Lepomis* early life stage, 1.45 is the GMCV value for *Hyalella*, -0.028 is the invertebrate slope for temperature dependency and T is temperature.

When *early life stage fish are absent* the temperature function is:

$$\mathrm{CCC}_{\text{Early life stage absent}} = 0.854 \times 1.45 \times 10^{-0.028(25-\mathrm{MAX}(T,7))} \quad \text{Eq. 9}$$

which is solely based on *Hyalella*. Neither function is based on either organism's response to temperature. These functions were then substituted into the pH dependency equations that convert chronic effect concentrations from pH 8 to any other pH, resulting in the final EPA CCC equations:

EPA's Early Life Stage Fish Present Equation:

$$\mathrm{CCC}_{\text{Early life stage present}} = \left(\frac{0.0577}{1+10^{7.688-\mathrm{pH}}} + \frac{2.487}{1+10^{\mathrm{pH}-7.688}}\right) \times \left(0.854 \times \mathrm{MIN}\left(2.85, 1.45 \times 10^{-0.028(25-T)}\right)\right)$$

Eq. 10

EPA's Early Life Stage Fish Absent Equation:

$$\mathrm{CCC}_{\text{Early life stage absent}} = \left(\frac{0.0577}{1+10^{7.688-\mathrm{pH}}} + \frac{2.487}{1+10^{\mathrm{pH}-7.688}}\right) \times \left(0.854 \times 1.45 \times 10^{-0.028(25-\mathrm{MAX}(T,7))}\right)$$

Eq. 11

Reanalysis of Temperature and pH Dependence of Chronic Ammonia Toxicity

The EPA's scientific development of the Criterion Continuous Concentration based on temperature and pH has created a variety of concerns.

1. First - the chronic database does not meet the EPA guidelines for deriving numerical national

ambient water quality criteria (Stephan et al., 1985). The database does not contain representatives from the family Salmonidae, class Insecta, or any other Phylum not already present in the database.

2. The temperature dependent chronic toxicity model developed by EPA is based on a single <u>acute toxicity</u> study – a study in which the authors themselves explicitly state that no relationships were observed between acute ammonia toxicity and temperature.
3. The most sensitive organism in the small chronic database, the amphipod *Hyalella azteca* (EC50 <1.45 mg N/L), was used to develop a temperature based function to protect <u>early life stage fish</u>. Obviously, additional studies are needed to understand the response of early life stage fish – but, it is difficult to understand how an amphipod can be used as a substitute.
4. Lastly, the *Hyalella* test (Borgmann 1994) is questionable as a basis for the chronic equations since there was significant control mortality (34%) – much higher than would be allowed for use in development of reliable toxicity data.

These major shortcomings of the EPA chronic ammonia criteria methods seemed insurmountable. We felt a more reasonable approach was the use of acute to chronic ratios (ACR) to adjust the acute equations and simply develop chronic ammonia criteria for cold and warm-water habitats and warm-water habitats without Unionidae.

To calculate ACRs, we used the SMAV and GMAV values from the updated acute database and the pH 8 corrected SMCV and GMCV values from the EPA chronic database (Appendix H). Species mean ACR (SM ACR 4.1) and genus mean ACR (GM ACR 4.9) were calculated from all available matched data. We did not limit our ACR calculations to studies that computed both LC50 and EC20 values for a single species given the same experimental conditions. This approach was too restrictive given the lack of “acceptable” chronic data. Rather, we used the summary statistics (GMAVs and GMCVs) from the available data.

We divided our acute relationships by the genus mean ACR, creating a CCC relationship for cold-water, warm-water and warm water without Unionidae. The resulting chronic equations are listed below:

Cold-water Ammonia Chronic Criterion:

$$\mathrm{CCC}_{\mathrm{Cold}} = \frac{0.071}{1+10^{7.204\text{-pH}}} + \frac{10.06}{1+10^{\text{pH-}7.204}} \qquad \text{Eq. 12}$$

Warm-water Ammonia Chronic Criterion:

$$\mathrm{CCC}_{\mathrm{Warm}} = \frac{0.014}{1+10^{7.204\text{-pH}}} + \frac{2.01}{1+10^{\text{pH-}7.204}} \qquad \text{Eq. 13}$$

Warm-water without Unionidae Ammonia Chronic Criterion:

$$\mathrm{CCC}_{\text{Warm without Unionidae}} = \frac{0.077}{1+10^{7.204\text{-pH}}} + \frac{10.96}{1+10^{\text{pH-}7.204}} \qquad \text{Eq. 14}$$

For comparative purposes, we set the temperature values in the EPA early life stage present/absent equations to 24.6°C and 9°C, with the assumption that these two temperature values would most closely match our warm water, cold-water scenario (see Fig. 3 and Table 3). At temperatures >14.5 °C, the EPA CCC relationship for early life stage fish present or absent are the same, because the *Hyalella* temperature-based function is controlling the CCC (Fig. 3). At temperatures <14.5°C, these two relationships begin to diverge.

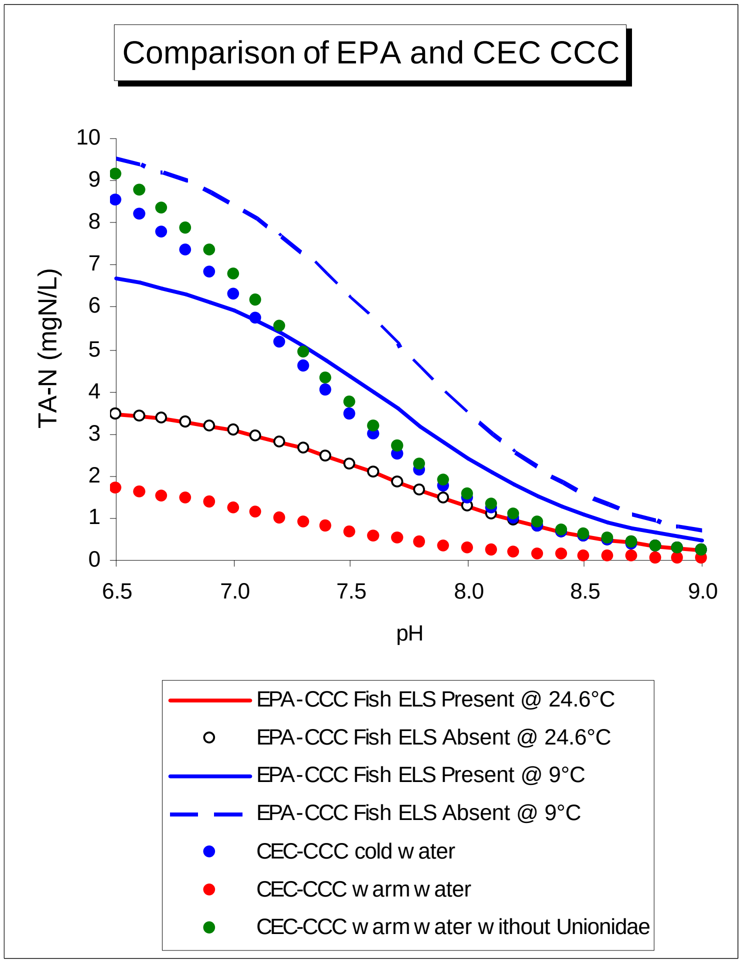

Figure 3. Comparison of the EPA and CEC Criterion Continuous Concentration functions given pH. For comparative purposes the EPA functions were set at 24.6°C and 9°C to closely approximate the CEC cold water, warm water scenario.

Table 2. Comparative TA-N concentrations at a given pH for EPA (1999) chronic criteria and proposed CEC chronic criteria.

Comparison of chronic ammonia values for aquatic life

	EPA Chronic Relationship				CEC Chronic Relationship		
pH	Fish ELS Present @ 24.6°C (TA-N mg/L)	Fish ELS Absent @ 24.6°C (TA-N mg/L)	Fish ELS Present @ 9°C (TA-N mg/L)	Fish ELS Absent @ 9°C (TA-N mg/L)	Cold-water Biota (TA-N mg/L)	Warm-water Biota (TA-N mg/L)	Warm-water Biota without Unionidae (TA-N mg/L)
6.5	3.48	3.48	6.67	9.51	8.41	1.68	9.16
6.6	3.43	3.43	6.56	9.37	8.07	1.62	8.79
6.7	3.36	3.36	6.44	9.20	7.68	1.54	8.36
6.8	3.29	3.29	6.29	8.98	7.23	1.45	7.88
6.9	3.19	3.19	6.12	8.73	6.75	1.35	7.35
7.0	3.08	3.08	5.91	8.43	6.22	1.24	6.77
7.1	2.96	2.96	5.67	8.09	5.66	1.13	6.17
7.2	2.81	2.81	5.39	7.69	5.09	1.02	5.54
7.3	2.65	2.65	5.08	7.25	4.52	0.90	4.92
7.4	2.47	2.47	4.73	6.76	3.96	0.79	4.31
7.5	2.28	2.28	4.36	6.23	3.43	0.69	3.73
7.6	2.08	2.08	3.98	5.67	2.93	0.59	3.20
7.7	1.87	1.87	3.58	5.11	2.49	0.50	2.71
7.8	1.66	1.66	3.18	4.54	2.09	0.42	2.28
7.9	1.46	1.46	2.80	3.99	1.74	0.35	1.90
8.0	1.27	1.27	2.43	3.47	1.45	0.29	1.58
8.1	1.09	1.09	2.10	2.99	1.20	0.24	1.30
8.2	0.94	0.94	1.79	2.56	0.99	0.20	1.08
8.3	0.80	0.80	1.52	2.18	0.81	0.16	0.89
8.4	0.67	0.67	1.29	1.84	0.67	0.13	0.73
8.5	0.57	0.57	1.09	1.55	0.55	0.11	0.60
8.6	0.48	0.48	0.92	1.31	0.46	0.09	0.50
8.7	0.41	0.41	0.78	1.11	0.38	0.08	0.41
8.8	0.35	0.35	0.66	0.94	0.32	0.06	0.35
8.9	0.29	0.29	0.56	0.81	0.27	0.05	0.29
9.0	0.25	0.25	0.49	0.69	0.23	0.04	0.25

Our warm water CCC is approximately two times more restrictive than the EPA's CCC, although this is a bit misleading because total ammonia concentrations are <3.5 mg N/L. Our cold water CCC is less restrictive than the EPA early life stage present at low pHs, although it becomes more restrictive at pH >7.2. The EPA early life stage absent function (cold) is quite a bit less restrictive through the range of pHs than the CEC cold water function. However, it is important to note that at commonly occurring pH ranges 7.5-8.0 the CEC cold water, warm water functions fall within the range of EPA's "cold/warm" early life stage present / absent functions. If unionids are not present in warm water habitats, our CCC is quite a bit less restrictive.

A second approach to developing chronic criteria would be to simply apply the CEC derived GMACR to the existing EPA *salmonids present – absent* equations. This would create a functionally similar CCC as compared to the proposed CEC CCC (Fig. 3 and Table 3). The resulting *salmonids present* CCC is slightly more restrictive than the CEC *cold-water* CCC, and the *salmonids absent* CCC is slightly less restrictive than the CEC *warm-water without Unionidae* CCC (Fig 3).

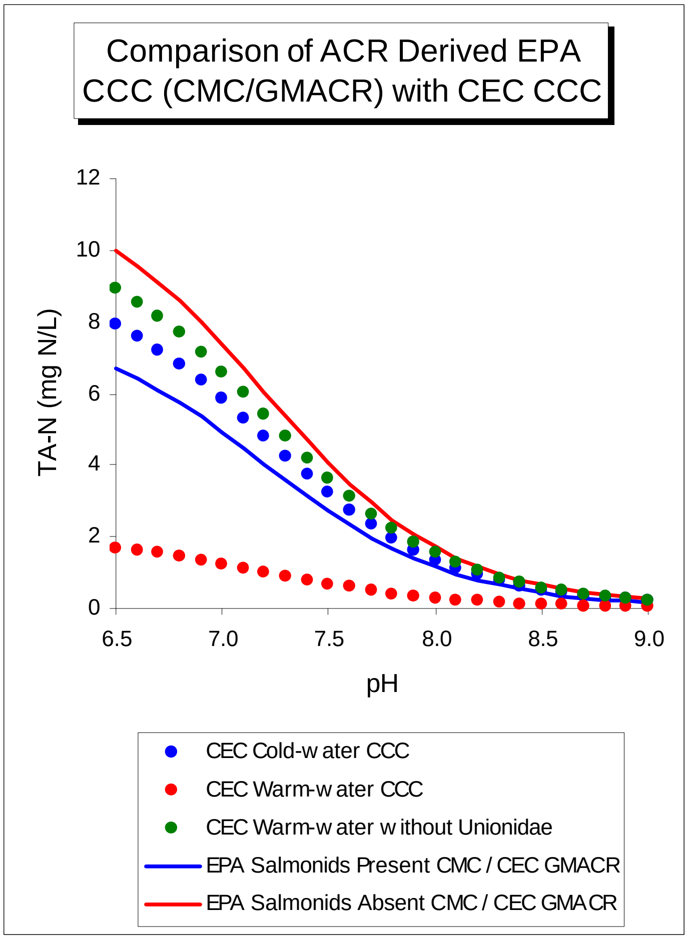

Figure 3. Comparison of the ACR derived EPA CCC using the salmonids present – absent CMC to the CEC CCC relationships for cold, warm, and warm-water without Unionidae.

Table 3. Comparative TA-N concentrations given pH for the proposed ACR derived CCC.

Comparison of the proposed CCC Scenarios

	ACR derived CCC using EPA CMC		ACR derived CCC using CEC CMC		
pH	Salmonids present	Salmonids absent	Cold-water	Warm-water	Warm-water without Unionidae
	(TA-N mg/L)	(TA-N mg/L)	(TA-N mg/L)	(TA-N mg/L)	(TA-N mg/L)
6.5	6.67	9.97	8.41	1.68	9.16
6.6	6.40	9.56	8.07	1.62	8.79
6.7	6.09	9.10	7.68	1.54	8.36
6.8	5.74	8.57	7.23	1.45	7.88
6.9	5.35	7.99	6.75	1.35	7.35
7.0	4.93	7.37	6.22	1.24	6.77
7.1	4.49	6.71	5.66	1.13	6.17
7.2	4.04	6.03	5.09	1.02	5.54
7.3	3.58	5.35	4.52	0.90	4.92
7.4	3.14	4.69	3.96	0.79	4.31
7.5	2.72	4.06	3.43	0.69	3.73
7.6	2.33	3.48	2.93	0.59	3.20
7.7	1.97	2.95	2.49	0.50	2.71
7.8	1.66	2.48	2.09	0.42	2.28
7.9	1.38	2.07	1.74	0.35	1.90
8.0	1.15	1.72	1.45	0.29	1.58
8.1	0.95	1.42	1.20	0.24	1.30
8.2	0.78	1.17	0.99	0.20	1.08
8.3	0.64	0.96	0.81	0.16	0.89
8.4	0.53	0.79	0.67	0.13	0.73
8.5	0.44	0.65	0.55	0.11	0.60
8.6	0.36	0.54	0.46	0.09	0.50
8.7	0.30	0.45	0.38	0.08	0.41
8.8	0.25	0.38	0.32	0.06	0.35
8.9	0.21	0.32	0.27	0.05	0.29
9.0	0.18	0.27	0.23	0.04	0.25

Summary of Chronic Ammonia Criteria

Owing to the lack of chronic ammonia data (not meeting the “8 family rule”), the EPA’s current derivation of chronic ammonia criteria is questionable. Additional data, not as yet developed, are required to support the EPA’s assumption that early life stage fish are more sensitive than juveniles or adults to chronic ammonia toxicity, and that there is a statistically significant temperature dependence chronic toxicity response for biota. As such, we strongly recommend using an ACR modified acute pH-only relationship to set Colorado chronic ammonia criteria.

Either proposed approach of using a GMACR to adjust EPA acute equations or our revised acute equations produces a very similar CCC for habitats with or without salmonids (i.e., cold-water vs. warm-water). The observed differences are primarily due to the questionable use of a modified SMAV for *O. mykiss,* and the non-inclusion of current acute data by the EPA. The ACR approach to developing chronic ammonia criteria provides the most scientifically defensible methodology.

Conclusions and Recommendations for Proposed Ammonia Criteria

We have presented modifications to the national acute and chronic ammonia water quality criteria developed by EPA. We believe these new criteria are more appropriate for the range of aquatic habitats found in Colorado. Firstly, the proposed acute ammonia criterion was based on the most current data available for cold-water (29 genera) and warm-water (44 genera) biota. An acute criterion was derived using the methodology presented by the EPA (1999); however, for reasons stated herein, we created a cold-water and warm-water ammonia criterion. Initially, the categorical databases appeared to circumvent problems associated with the “salmonids” present/absent criteria. However, we quickly realized the cold vs. warm database was not without its concerns. Recent toxicological studies using freshwater mussels (Unionidae) have provided insight about a highly sensitive taxa, one that ultimately dominated the derivation of our warm-water acute ammonia criteria. Given the uncertainty of the distribution of Unionidae in the State of Colorado, we created a sub-category within the warm-water database excluding Unionidae. In light of the recent studies and the declining populations of freshwater mussels, the EPA has recognized that Unionidae should receive further consideration to determine their potential inclusion in the derivation of national water quality criteria. The inclusion of highly sensitive species in national and state water quality criteria may ultimately lead the process to one of site-specific derivation, such that acute and chronic criteria is adjusted accordingly to species present within the ecosystem of interest. As presented, our Criterion Maximum Concentration (CMC), based on three habitat types (cold, warm, warm-water without Unionidae), should protect species along the elevational gradient from high mountainous stream ecosystems to the low prairie stream ecosystems of Colorado. We believe criteria based on habitat categories is scientifically more sound and practical, because it is based on organisms typically found within each habitat type and excludes species not pertinent to the ecosystem. If site-specific criteria becomes a requirement for certain applications, our database provides the most current GMAV values for site-specific derivation. For example, species lists may be compared to our GMAV database, allowing one to rank their species of interest, and compute CMC limits given procedural guidelines found in Stephan et al. (1985) or within the appendices. If selected genera are not present within our database, then Family Mean Acute Values (FMAV) values for genera within the selected family may be substituted (FMAV is the gemometric mean of GMAV). This process may appear to be more laborious given the uncertainties of species distribution in streams of Colorado, but once detailed species lists are generated, site-specific ammonia criteria can easily be derived for the system of interest.

Unfortunately, the paucity of chronic ammonia data creates many procedural inadequacies in the derivation of chronic ammonia criteria. Foremost, the current chronic database does not meet national criteria guidelines for deriving numerical water quality criteria. Therefore, we opted to derive state level Criterion Continuous Concentration limits using acute to chronic ratios for matched species data. We applied the ACR to our CMC limits for each habitat type, creating CCC limits for cold-water, warm-water, and warm-water without Unionidae. This appears to be the most scientifically defensible approach given the limitations. Because our CMC derivation is functionally the same, producing limits similar to the national criteria, we have proposed a second approach to developing state level CCC. We believe the national chronic criteria's temperature dependent and age-class function is weakly supported given the available chronic data. Therefore, in the best interest of the State of Colorado, should our derivation of the state level CMC not be accepted, we strongly recommend that the state level CCC be derived using the ACR and national CMC limits. The ACR derived CCC is the most scientifically defensible and sound criteria given our current knowledge of chronic ammonia toxicity.

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APPENDIX A

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APPENDIX B

Table B-1. Acute ammonia toxicity data used for Criterion Maximum Concentration derivation.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Actinonaias pectorosa [a]	25.0	8.00	0.25	3.76	3.76	Augspurger et al. 2003
Actinonaias pectorosa [a]	25.0	8.00	0.92	14.06	14.05	Augspurger et al. 2003
Arcynopteryx parallela	13.8	7.76	2.06	119.63	77.18	Thurston et al. 1984
Arcynopteryx parallela	13.1	7.81	2.00	109.31	77.03	Thurston et al. 1984
Asellus racovitzai	4.0	8.00	4.95	357.80	357.60	Arthur et al. 1987
Asellus racovitzai	22.0	7.80	5.09	148.83	103.02	Arthur et al. 1987
Asellus racovitzai	11.9	7.81	2.94	176.01	124.02	Thurston et al. 1983a
Baetis rhodani	13.1	8.15	8.20	208.52	277.70	Khatami et al. 1998
Baetis rhodani	13.1	8.15	8.20	208.52	277.70	Khatami et al. 1998
Baetis rhodani	13.1	8.15	0.32	8.14	10.84	Khatami et al. 1998
Callibaetis skokianus	10.8	7.70	3.15	263.55	153.36	Arthur et al. 1987
Callibaetis skokianus	13.3	7.90	4.82	211.66	175.56	Arthur et al. 1987
Callibaetis sp.	11.9	7.81	1.80	107.76	75.93	Thurston et al. 1984
Campostoma anomalum	25.7	7.80	1.72	38.97	26.97	Swigert and Spacie 1983
Catostomus commersoni	3.6	7.80	0.76	89.57	62.00	Arthur et al. 1987
Catostomus commersoni	12.6	8.20	1.73	40.85	59.94	Arthur et al. 1987
Catostomus commersoni	11.3	8.10	1.87	60.86	73.60	Arthur et al. 1987
Catostomus commersoni	15.3	8.20	2.22	43.01	63.10	Arthur et al. 1987
Catostomus commersoni	15.0	8.16	1.40	30.28	41.11	Reinbold and Pescitelli 1982b
Catostomus commersoni	15.4	8.14	1.35	29.65	38.73	Reinbold and Pescitelli 1982b
Catostomus commersoni	22.5	7.80	0.79	22.30	15.44	Swigert and Spacie 1983
Catostomus platyrynchus	11.7	7.73	0.71	51.62	31.62	Thurston and Meyn 1984
Catostomus platyrynchus	12.0	7.67	0.82	66.91	37.02	Thurston and Meyn 1984
Catostomus platyrynchus	13.2	7.69	0.67	47.59	27.23	Thurston and Meyn 1984
Ceriodaphnia acanthina	24.0	7.60	0.70	27.73	13.68	Mount 1982
Ceriodaphnia dubia	25.0	8.00	1.54	23.55	23.54	Bailey et al. 2001
Ceriodaphnia dubia	25.0	8.00	1.36	20.80	20.79	Bailey et al. 2001

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Ceriodaphnia dubia	25.0	8.00	1.22	18.66	18.65	Bailey et al. 2001
Ceriodaphnia dubia	25.0	8.00	1.01	15.45	15.44	Bailey et al. 2001
Ceriodaphnia dubia	25.0	8.00	1.54	23.55	23.54	Bailey et al. 2001
Ceriodaphnia dubia	25.0	8.00	1.22	18.66	18.65	Bailey et al. 2001
Ceriodaphnia dubia	25.0	8.00	1.36	20.80	20.79	Bailey et al. 2001
Ceriodaphnia dubia	25.0	8.00	1.01	15.45	15.44	Bailey et al. 2001
Cottus bardi	12.4	8.02	1.39	49.83	51.73	Thurston and Russo 1981
Crangonyx pseudogracillis	24.9	8.00	1.63	25.10	25.08	Arthur et al. 1987
Crangonyx pseudogracillis	4.0	8.00	2.76	199.50	199.39	Arthur et al. 1987
Crangonyx pseudogracillis	13.3	8.00	3.29	115.32	115.25	Arthur et al. 1987
Crangonyx pseudogracillis	13.0	8.20	3.56	81.60	119.73	Arthur et al. 1987
Crangonyx pseudogracillis	12.1	8.00	5.63	215.97	215.85	Arthur et al. 1987
Crangonyx spp.	12.0	7.68	2.05	163.71	92.10	Diamond et al. 1993
Cyprinodon sp.	12.0	7.68	1.42	113.40	63.79	Diamond et al. 1993
Daphnia magna	19.6	7.68	1.17	53.24	29.95	Diamond et al. 1993
Daphnia magna	19.7	8.34	4.94	51.92	100.02	Reinbold and Pescitelli 1982a
Daphnia magna	25.0	8.20	2.08	20.71	30.38	Russo et. al 1985
Daphnia magna	22.0	7.95	2.45	51.30	46.68	Russo et. al 1985
Daphnia magna	19.6	8.07	2.69	51.09	58.33	Russo et. al 1985
Daphnia magna	20.9	8.09	2.50	41.51	49.25	Russo et. al 1985
Daphnia magna	22.0	8.15	2.77	37.44	49.86	Russo et. al 1985
Daphnia magna	22.8	8.04	2.38	38.70	41.73	Russo et. al 1985
Daphnia magna	20.1	7.51	0.75	48.32	20.72	Russo et. al 1985
Daphnia magna	20.1	7.53	0.90	55.41	24.49	Russo et. al 1985
Daphnia magna	20.6	7.40	0.53	42.31	15.48	Russo et. al 1985
Daphnia magna	20.3	7.50	0.67	43.52	18.39	Russo et. al 1985
Daphnia pulicaria	14.0	8.10	1.16	30.85	37.31	DeGraeve et al. 1980
Dendrocoelom lacteum	18.0	8.20	1.40	22.37	32.82	Stammer 1953
Ephemerella grandis	12.8	7.84	4.96	259.07	192.64	Thurston et al. 1984
Ephemerella grandis	12.0	7.85	5.88	319.03	241.54	Thurston et al. 1984
Ephemerella grandis	13.2	7.84	3.86	195.62	145.46	Thurston et al. 1984

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Erythromma najas	25.0	7.52	10.42	463.98	202.02	Beketov 2002
Erythromma najas	25.0	8.70	37.80	140.28	534.71	Beketov 2002
Erythromma najas	25.0	9.14	22.14	41.44	323.90	Beketov 2002
Erythromma najas	25.0	7.43	12.45	679.66	259.28	Beketov 2002
Etheostoma spectabile	21.0	8.04	0.90	16.56	17.86	Hazel et al. 1979
Etheostoma spectabile	22.0	8.40	1.07	8.52	18.44	Hazel et al. 1979
Fusconaia masoni [a]	25.0	7.60	0.07	2.71	1.34	Black 2001
Gambusia affinis	26.8	7.25	0.72	52.41	15.80	Sangli and Kanabur 2001
Gambusia affinis	26.8	7.25	0.70	50.95	15.36	Sangli and Kanabur 2001
Gambusia affinis	26.8	7.25	0.69	50.22	15.14	Sangli and Kanabur 2001
Gambusia affinis	26.8	7.25	0.67	48.77	14.70	Sangli and Kanabur 2001
Helisoma trivolvis	22.0	7.90	2.04	47.73	39.58	Arthur et al. 1987
Helisoma trivolvis	12.9	8.20	2.76	63.73	93.52	Arthur et al. 1987
Ictalurus punctatus	3.5	8.00	0.50	37.64	37.61	Arthur et al. 1987
Ictalurus punctatus	14.6	8.10	0.98	24.94	30.16	Arthur et al. 1987
Ictalurus punctatus	19.6	7.80	1.29	44.71	30.95	Arthur et al. 1987
Ictalurus punctatus	17.0	8.10	1.91	40.83	49.38	Arthur et al. 1987
Ictalurus punctatus	26.0	8.00	2.26	32.34	32.32	Arthur et al. 1987
Ictalurus punctatus	22.0	8.70	2.40	10.56	40.26	Colt and Tchobanoglous 1976
Ictalurus punctatus	26.0	8.70	2.90	10.19	38.85	Colt and Tchobanoglous 1976
Ictalurus punctatus	30.0	8.70	3.80	10.88	41.47	Colt and Tchobanoglous 1976
Ictalurus punctatus	28.0	8.40	1.95	10.71	23.19	Colt and Tchobanoglous 1978
Ictalurus punctatus	23.8	7.98	1.76	30.49	29.35	Reinbold and Pescitelli 1982c
Ictalurus punctatus	23.8	7.94	1.75	33.10	29.57	Reinbold and Pescitelli 1982c
Ictalurus punctatus	22.0	8.09	2.10	32.33	38.36	Roseboom and Richey 1977
Ictalurus punctatus	28.0	8.08	4.20	44.44	51.72	Roseboom and Richey 1977
Ictalurus punctatus	25.7	7.80	1.45	32.85	22.74	Swigert and Spacie 1983
Ictalurus punctatus	23.0	8.00	1.82	31.87	31.85	Tomasso et al. 1980
Ictalurus punctatus	23.0	7.00	1.39	233.07	54.26	Tomasso et al. 1980
Ictalurus punctatus	23.0	9.00	1.49	3.71	23.57	Tomasso et al. 1980
Ictalurus punctatus	23.0	7.00	1.79	300.14	69.88	Tomasso et al. 1980

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Lampsilis cardium[a]	20.5	8.20	1.86	25.01	36.69	Newton et al. 2003
Lampsilis cardium[a]	21.2	8.20	1.94	24.79	36.38	Newton et al. 2003
Lampsilis cardium[a]	21.3	8.10	0.80	12.67	15.32	Newton et al. 2003
Lampsilis cardium[a]	21.0	7.90	0.56	14.16	11.75	Newton et al. 2003
Lampsilis fasciola[a]	12.6	7.83	0.32	17.38	12.69	Mummert et al. 2003
Lampsilis fasciola[a]	12.6	7.83	0.24	13.26	9.68	Mummert et al. 2003
Lampsilis fasciola[a]	12.6	7.83	0.23	12.68	9.26	Mummert et al. 2003
Lampsilis fasciola[a]	12.6	7.83	0.25	13.59	9.92	Mummert et al. 2003
Lampsilis fasciola[a]	20.6	7.96	0.54	12.27	11.38	Mummert et al. 2003
Lampsilis fasciola[a]	20.6	7.96	0.28	6.37	5.91	Mummert et al. 2003
Lampsilis siliquoidea[a]	24.0	8.30	0.09	0.78	1.39	Myers-Kinzie 1998
Lampsilis siliquoidea[a]	24.0	8.30	0.28	2.39	4.26	Myers-Kinzie 1998
Lasmigona subvirdis[a]	24.0	7.70	0.13	4.28	2.49	Black 2001
Lasmigona subvirdis[a]	24.0	7.70	0.13	4.28	2.49	Black 2001
Lasmigona subvirdis[a]	25.0	8.00	0.24	3.61	3.61	Black 2001
Lepomis cyanellus	12.3	7.84	0.61	33.09	24.61	Jude 1973
Lepomis cyanellus	22.4	6.61	0.61	260.12	46.87	McCormick et al. 1984
Lepomis cyanellus	22.4	7.20	1.29	142.53	40.55	McCormick et al. 1984
Lepomis cyanellus	22.4	7.72	1.63	55.35	33.32	McCormick et al. 1984
Lepomis cyanellus	22.4	8.69	2.10	9.20	34.44	McCormick et al. 1984
Lepomis cyanellus	26.2	8.28	1.08	8.43	14.45	Reinbold and Pescitelli 1982a
Lepomis gibbosus	12.0	7.77	0.14	9.11	5.98	Jude 1973
Lepomis gibbosus	14.5	7.77	0.78	42.02	27.59	Thurston 1981
Lepomis gibbosus	14.0	7.77	0.86	48.09	31.58	Thurston 1981
Lepomis gibbosus	15.7	7.71	0.61	34.43	20.38	Thurston 1981
Lepomis machrochirus	20.0	7.68	1.00	44.14	24.83	Diamond et al. 1993
Lepomis machrochirus	12.0	7.68	0.65	51.91	29.20	Diamond et al. 1993
Lepomis machrochirus	18.5	8.11	0.89	16.73	20.62	Emery and Welch 1969
Lepomis machrochirus	18.5	8.24	2.97	42.01	66.62	Emery and Welch 1969
Lepomis machrochirus	18.5	8.75	2.57	12.70	52.95	Emery and Welch 1969
Lepomis machrochirus	22.0	8.10	1.06	15.97	19.31	Mayes et al. 1986

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Lepomis machrochirus	22.0	8.07	0.55	8.85	10.10	Roseboom and Richey 1977
Lepomis machrochirus	22.0	8.00	0.68	12.75	12.74	Roseboom and Richey 1977
Lepomis machrochirus	22.0	7.93	1.10	24.08	21.11	Roseboom and Richey 1977
Lepomis machrochirus	28.0	8.20	1.80	14.81	21.72	Roseboom and Richey 1977
Lepomis machrochirus	21.7	7.60	0.94	44.03	21.72	Smith et al. 1984
Lepomis machrochirus	24.2	7.80	1.35	33.88	23.45	Swigert and Spacie 1983
Lepomis machrochirus	26.5	7.60	1.75	58.69	28.95	Swigert and Spacie 1983
Lepomis machrochirus	26.6	7.80	1.76	37.52	25.97	Swigert and Spacie 1983
Lestes sponsa	25.0	7.54	7.30	310.69	139.48	Beketov 2002
Medionidus conradicus [a]	25.0	8.00	0.29	4.48	4.47	Augspurger et al. 2003
Micropterus dolomieui	22.3	6.53	0.69	359.93	62.67	Broderius et al. 1985
Micropterus dolomieui	22.3	7.16	1.00	122.21	33.26	Broderius et al. 1985
Micropterus dolomieui	22.3	7.74	1.20	39.30	24.49	Broderius et al. 1985
Micropterus dolomieui	22.3	7.74	1.78	58.30	36.33	Broderius et al. 1985
Micropterus salmoides	22.0	7.96	1.00	20.48	18.99	Roseboom and Richey 1977
Micropterus salmoides	28.0	8.04	1.70	19.59	21.12	Roseboom and Richey 1977
Morone americana	16.0	6.00	0.15	418.44	63.94	Stevenson 1977
Morone americana	16.0	8.00	0.52	14.93	14.92	Stevenson 1977
Musculium transversum	5.4	8.20	0.93	38.18	56.02	Arthur et al. 1987
Musculium transversum	20.5	8.60	1.10	6.43	20.38	Arthur et al. 1987
Musculium transversum	14.6	8.10	1.29	32.83	39.70	Arthur et al. 1987
Notemigonus chrysoleucas	24.5	7.50	0.72	34.73	14.67	Swigert and Spacie 1983
Notropis lutrensis	24.0	8.30	2.83	24.37	43.43	Hazel et al. 1979
Notropis lutrensis	24.0	9.10	3.16	6.50	47.99	Hazel et al. 1979
Notropis spilopterus	26.5	7.95	1.20	18.52	16.85	Rosage et al. 1979
Notropis spilopterus	26.5	8.15	1.62	16.27	21.67	Rosage et al. 1979
Notropis spilopterus	25.7	7.90	1.35	24.52	20.34	Swigert and Spacie 1983
Notropis whipplei	25.7	7.90	1.25	22.71	18.83	Swigert and Spacie 1983
Oncorhynchus aquabonita	13.2	8.60	0.76	7.16	22.71	Thurston and Russo 1981
Oncorhynchus clarki	13.1	7.81	0.80	43.72	30.81	Thurston et al. 1978
Oncorhynchus clarki	12.8	7.80	0.66	37.75	26.13	Thurston et al. 1978

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Oncorhynchus clarki	12.4	7.80	0.62	36.55	25.30	Thurston et al. 1978
Oncorhynchus clarki	12.2	7.78	0.52	32.57	21.76	Thurston et al. 1978
Oncorhynchus gorbuscha	4.3	6.40	0.08	230.47	38.33	Rice and Bailey 1980
Oncorhynchus gorbuscha	4.3	6.40	0.10	277.68	46.18	Rice and Bailey 1980
Oncorhynchus kisutch	15.0	7.00	0.27	82.02	19.10	Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	15.0	7.00	0.28	84.43	19.66	Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	15.0	7.50	0.55	52.76	22.29	Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	15.0	7.50	0.53	50.65	21.40	Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	15.0	8.00	0.17	5.31	5.31	Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	15.0	8.00	0.70	21.63	21.62	Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	15.0	8.50	0.88	9.09	23.86	Robinson-Wilson and Seim 1975
Oncorhynchus kisutch	17.2	8.10	0.55	11.59	14.02	Robinson-Wilson and Seim 1975
Oncorhynchus mykiss	3.6	7.70	0.26	38.52	22.41	Arthur et al. 1987
Oncorhynchus mykiss	16.2	7.90	0.43	15.23	12.63	Arthur et al. 1987
Oncorhynchus mykiss	11.3	7.90	0.59	30.15	25.01	Arthur et al. 1987
Oncorhynchus mykiss	9.8	7.70	0.61	55.15	32.09	Arthur et al. 1987
Oncorhynchus mykiss	18.7	8.30	1.04	12.75	22.72	Arthur et al. 1987
Oncorhynchus mykiss	10.0	7.95	0.70	35.14	31.97	Broderius and Smith 1979
Oncorhynchus mykiss	14.5	7.40	0.49	60.83	22.25	Calamari et al. 1981
Oncorhynchus mykiss	14.5	7.40	0.16	20.03	7.33	Calamari et al. 1981
Oncorhynchus mykiss	14.5	7.40	0.44	55.07	20.15	Calamari et al. 1981
Oncorhynchus mykiss	14.0	8.10	0.77	20.48	24.77	DeGraeve et al. 1980
Oncorhynchus mykiss	15.0	7.50	0.40	38.37	16.21	Holt & Malcolm 1979
Oncorhynchus mykiss	14.1	7.86	0.77	34.95	26.94	Thurston and Russo 1983
Oncorhynchus mykiss	13.8	7.84	0.68	33.09	24.60	Thurston and Russo 1983
Oncorhynchus mykiss	13.9	8.10	0.68	18.14	21.94	Thurston and Russo 1983
Oncorhynchus mykiss	13.6	8.12	0.66	17.34	21.80	Thurston and Russo 1983
Oncorhynchus mykiss	12.8	7.94	0.64	26.49	23.66	Thurston and Russo 1983
Oncorhynchus mykiss	12.5	7.98	0.69	27.02	26.01	Thurston and Russo 1983
Oncorhynchus mykiss	12.4	7.89	0.76	36.73	29.91	Thurston and Russo 1983
Oncorhynchus mykiss	12.5	7.94	0.92	39.25	35.05	Thurston and Russo 1983

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Oncorhynchus mykiss	13.1	7.85	0.64	31.75	24.04	Thurston and Russo 1983
Oncorhynchus mykiss	11.9	7.90	0.46	22.65	18.79	Thurston and Russo 1983
Oncorhynchus mykiss	13.0	7.90	0.83	37.41	31.03	Thurston and Russo 1983
Oncorhynchus mykiss	13.0	7.90	0.80	35.75	29.65	Thurston and Russo 1983
Oncorhynchus mykiss	9.8	7.66	0.26	25.95	14.12	Thurston and Russo 1983
Oncorhynchus mykiss	10.0	7.64	0.31	31.85	16.77	Thurston and Russo 1983
Oncorhynchus mykiss	12.7	7.90	0.44	20.03	16.61	Thurston and Russo 1983
Oncorhynchus mykiss	13.4	7.90	0.45	19.44	16.12	Thurston and Russo 1983
Oncorhynchus mykiss	13.0	7.91	0.48	20.99	17.73	Thurston and Russo 1983
Oncorhynchus mykiss	13.1	7.91	0.29	12.68	10.71	Thurston and Russo 1983
Oncorhynchus mykiss	12.8	7.88	0.23	11.07	8.85	Thurston and Russo 1983
Oncorhynchus mykiss	12.9	7.88	0.34	15.91	12.72	Thurston and Russo 1983
Oncorhynchus mykiss	12.9	7.87	0.35	16.81	13.19	Thurston and Russo 1983
Oncorhynchus mykiss	12.5	7.95	0.47	19.75	17.97	Thurston and Russo 1983
Oncorhynchus mykiss	13.0	7.87	0.44	21.15	16.61	Thurston and Russo 1983
Oncorhynchus mykiss	12.9	7.87	0.39	18.99	14.91	Thurston and Russo 1983
Oncorhynchus mykiss	13.4	7.88	0.43	19.43	15.53	Thurston and Russo 1983
Oncorhynchus mykiss	13.1	7.87	0.40	19.08	14.98	Thurston and Russo 1983
Oncorhynchus mykiss	13.4	7.86	0.50	23.71	18.28	Thurston and Russo 1983
Oncorhynchus mykiss	13.0	7.86	0.42	20.70	15.96	Thurston and Russo 1983
Oncorhynchus mykiss	12.8	8.08	0.76	23.05	26.82	Thurston and Russo 1983
Oncorhynchus mykiss	12.7	7.86	0.57	28.77	22.18	Thurston and Russo 1983
Oncorhynchus mykiss	12.5	7.85	0.57	29.77	22.54	Thurston and Russo 1983
Oncorhynchus mykiss	13.1	7.85	0.67	33.59	25.44	Thurston and Russo 1983
Oncorhynchus mykiss	13.2	8.06	1.09	33.64	37.68	Thurston and Russo 1983
Oncorhynchus mykiss	12.3	7.85	0.64	33.99	25.74	Thurston and Russo 1983
Oncorhynchus mykiss	12.4	7.79	0.70	41.97	28.55	Thurston and Russo 1983
Oncorhynchus mykiss	14.1	7.86	0.77	34.95	26.94	Thurston and Russo 1983
Oncorhynchus mykiss	13.8	7.84	0.68	33.09	24.60	Thurston and Russo 1983
Oncorhynchus mykiss	12.4	7.80	0.81	47.87	33.14	Thurston and Russo 1983
Oncorhynchus mykiss	13.1	7.85	0.63	31.55	23.89	Thurston and Russo 1983

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Oncorhynchus mykiss	12.1	7.87	0.62	31.80	24.97	Thurston and Russo 1983
Oncorhynchus mykiss	11.4	7.71	0.41	32.02	18.95	Thurston and Russo 1983
Oncorhynchus mykiss	11.5	7.71	0.39	30.22	17.89	Thurston and Russo 1983
Oncorhynchus mykiss	13.0	7.84	0.75	38.69	28.77	Thurston and Russo 1983
Oncorhynchus mykiss	13.5	7.83	0.66	33.55	24.50	Thurston and Russo 1983
Oncorhynchus mykiss	13.3	7.80	0.76	42.02	29.09	Thurston and Russo 1983
Oncorhynchus mykiss	12.8	7.44	0.25	32.49	12.57	Thurston and Russo 1983
Oncorhynchus mykiss	12.2	7.84	0.45	24.54	18.25	Thurston and Russo 1983
Oncorhynchus mykiss	12.2	7.87	0.39	20.02	15.72	Thurston and Russo 1983
Oncorhynchus mykiss	11.9	7.90	0.46	22.65	18.79	Thurston and Russo 1983
Oncorhynchus mykiss	14.5	7.50	0.24	24.20	10.22	Thurston and Russo 1983
Oncorhynchus mykiss	13.2	7.82	0.64	33.67	24.15	Thurston and Russo 1983
Oncorhynchus mykiss	12.3	7.75	0.51	33.94	21.52	Thurston and Russo 1983
Oncorhynchus mykiss	12.9	7.84	0.62	32.30	24.01	Thurston and Russo 1983
Oncorhynchus mykiss	13.0	7.90	0.83	37.41	31.03	Thurston and Russo 1983
Oncorhynchus mykiss	13.9	7.70	0.43	28.54	16.60	Thurston and Russo 1983
Oncorhynchus mykiss	13.0	7.90	0.80	35.75	29.65	Thurston and Russo 1983
Oncorhynchus mykiss	13.0	7.87	0.71	34.32	26.95	Thurston and Russo 1983
Oncorhynchus mykiss	9.7	7.80	0.33	23.65	16.37	Thurston and Russo 1983
Oncorhynchus mykiss	14.3	7.65	0.40	29.02	15.53	Thurston and Russo 1983
Oncorhynchus mykiss	14.0	7.67	0.39	27.30	15.11	Thurston and Russo 1983
Oncorhynchus mykiss	14.4	7.62	0.38	28.62	14.58	Thurston and Russo 1983
Oncorhynchus mykiss	13.1	7.64	0.36	29.28	15.42	Thurston and Russo 1983
Oncorhynchus mykiss	13.6	7.66	0.38	28.27	15.38	Thurston and Russo 1983
Oncorhynchus mykiss	13.2	7.65	0.37	28.64	15.33	Thurston and Russo 1983
Oncorhynchus mykiss	13.4	7.69	0.39	27.51	15.74	Thurston and Russo 1983
Oncorhynchus mykiss	12.9	7.60	0.28	25.14	12.40	Thurston and Russo 1983
Oncorhynchus mykiss	11.8	7.75	0.46	31.53	19.99	Thurston and Russo 1983
Oncorhynchus mykiss	12.8	7.66	0.43	33.97	18.48	Thurston and Russo 1983
Oncorhynchus mykiss	13.0	7.60	0.27	23.80	11.74	Thurston and Russo 1983
Oncorhynchus mykiss	12.9	7.63	0.31	25.65	13.29	Thurston and Russo 1983

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Oncorhynchus mykiss	12.7	7.59	0.35	32.62	15.84	Thurston and Russo 1983
Oncorhynchus mykiss	13.0	7.68	0.45	33.15	18.65	Thurston and Russo 1983
Oncorhynchus mykiss	13.6	7.77	0.55	31.81	20.89	Thurston and Russo 1983
Oncorhynchus mykiss	10.2	7.86	0.58	35.31	27.23	Thurston and Russo 1983
Oncorhynchus mykiss	10.0	7.88	0.48	28.60	22.87	Thurston and Russo 1983
Oncorhynchus mykiss	10.7	7.69	0.30	25.62	14.66	Thurston and Russo 1983
Oncorhynchus mykiss	10.4	7.74	0.33	25.76	16.05	Thurston and Russo 1983
Oncorhynchus mykiss	10.0	7.76	0.29	22.44	14.47	Thurston and Russo 1983
Oncorhynchus mykiss	9.8	7.66	0.26	25.95	14.12	Thurston and Russo 1983
Oncorhynchus mykiss	10.0	7.64	0.31	31.85	16.77	Thurston and Russo 1983
Oncorhynchus mykiss	10.4	7.69	0.20	17.75	10.15	Thurston and Russo 1983
Oncorhynchus mykiss	10.7	7.69	0.23	20.18	11.55	Thurston and Russo 1983
Oncorhynchus mykiss	9.8	7.64	0.25	25.82	13.59	Thurston and Russo 1983
Oncorhynchus mykiss	9.8	7.65	0.19	19.46	10.41	Thurston and Russo 1983
Oncorhynchus mykiss	7.9	7.62	0.16	20.53	10.46	Thurston and Russo 1983
Oncorhynchus mykiss	16.1	7.85	0.86	34.17	25.87	Thurston and Russo 1983
Oncorhynchus mykiss	16.7	7.88	0.80	28.60	22.87	Thurston and Russo 1983
Oncorhynchus mykiss	19.0	7.91	0.90	25.36	21.42	Thurston and Russo 1983
Oncorhynchus mykiss	19.1	7.91	0.94	26.44	22.34	Thurston and Russo 1983
Oncorhynchus mykiss	19.2	7.96	0.93	23.21	21.52	Thurston and Russo 1983
Oncorhynchus mykiss	9.7	7.86	0.50	31.64	24.40	Thurston et al. 1981
Oncorhynchus mykiss	8.1	7.74	0.30	27.90	17.39	Thurston et al. 1981
Oncorhynchus mykiss	7.9	7.62	0.16	20.53	10.46	Thurston et al. 1981
Oncorhynchus mykiss	10.0	7.20	0.40	111.18	31.63	Wicks and Randall 2002
Oncorhynchus mykiss	10.0	7.20	0.54	152.35	43.34	Wicks and Randall 2002
Oncorhynchus mykiss	10.0	7.20	0.42	117.76	33.50	Wicks and Randall 2002
Oncorhynchus mykiss	10.0	7.20	0.52	145.76	41.47	Wicks and Randall 2002
Oncorhynchus mykiss	10.0	7.20	0.39	108.71	30.92	Wicks and Randall 2002
Oncorhynchus mykiss	10.0	7.20	0.41	114.47	32.56	Wicks and Randall 2002
Oncorhynchus mykiss	10.0	7.20	0.41	113.65	32.33	Wicks and Randall 2002
Oncorhynchus mykiss	10.0	7.20	0.42	116.12	33.03	Wicks and Randall 2002

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Oncorhynchus mykiss	10.0	7.20	0.51	143.29	40.76	Wicks and Randall 2002
Oncorhynchus mykiss	16.6	6.97	0.72	207.00	46.97	Wicks et al. 2002
Oncorhynchus mykiss	16.6	6.97	0.11	32.38	7.35	Wicks et al. 2002
Oncorhynchus tshawytscha	13.5	7.87	0.40	18.47	14.50	Thurston and Meyn 1984
Oncorhynchus tshawytscha	12.2	7.82	0.48	27.23	19.53	Thurston and Meyn 1984
Oncorhynchus tshawytscha	12.3	7.84	0.46	24.74	18.39	Thurston and Meyn 1984
Orconectes immunis	17.1	7.90	14.72	488.07	404.82	Arthur et al. 1987
Orconectes immunis	4.6	8.20	22.84	999.38	1466.35	Arthur et al. 1988
Orconectes naias	26.5	8.30	3.15	23.15	41.27	Evans 1979
Philarctus quaeris	21.9	7.80	10.07	296.51	205.25	Arthur et al. 1987
Philarctus quaeris	13.3	7.80	10.17	560.07	387.70	Arthur et al. 1987
Physa gyrina	4.0	8.00	1.59	114.93	114.87	Arthur et al. 1987
Physa gyrina	24.9	8.00	1.71	26.33	26.32	Arthur et al. 1987
Physa gyrina	13.3	8.00	1.78	62.39	62.36	Arthur et al. 1987
Physa gyrina	5.5	8.20	2.09	85.13	124.90	Arthur et al. 1987
Physa gyrina	12.8	8.00	2.16	78.60	78.56	Arthur et al. 1987
Physa gyrina	12.1	8.10	2.49	76.29	92.27	Arthur et al. 1987
Pimephales promelas	12.1	8.10	1.83	56.07	67.81	Arthur et al. 1987
Pimephales promelas	17.1	8.00	1.97	52.22	52.19	Arthur et al. 1987
Pimephales promelas	3.4	7.90	2.41	229.72	190.54	Arthur et al. 1987
Pimephales promelas	26.1	8.10	2.55	29.23	35.35	Arthur et al. 1987
Pimephales promelas	14.0	8.10	1.59	42.29	51.14	DeGraeve et al. 1980
Pimephales promelas	19.6	7.68	0.25	11.36	6.39	Diamond et al. 1993
Pimephales promelas	22.0	8.10	1.50	22.60	27.33	Mayes et al. 1986
Pimephales promelas	25.9	7.78	1.75	40.89	27.32	Swigert and Spacie 1983
Pimephales promelas	25.6	7.80	1.87	42.65	29.53	Swigert and Spacie 1983
Pimephales promelas	16.3	7.91	1.50	51.55	43.55	Thurston et al. 1983
Pimephales promelas	13.1	7.89	1.10	50.16	40.85	Thurston et al. 1983
Pimephales promelas	13.6	7.64	0.75	58.40	30.74	Thurston et al. 1983
Pimephales promelas	13.5	7.68	0.91	64.69	36.40	Thurston et al. 1983
Pimephales promelas	22.1	8.03	2.73	47.60	50.35	Thurston et al. 1983

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Pimephales promelas	22.0	8.06	2.59	42.58	47.69	Thurston et al. 1983
Pimephales promelas	13.9	7.67	0.83	58.84	32.55	Thurston et al. 1983
Pimephales promelas	13.0	8.05	2.33	74.65	82.04	Thurston et al. 1983
Pimephales promelas	13.6	8.05	2.17	66.48	73.06	Thurston et al. 1983
Pimephales promelas	19.1	7.94	1.61	42.26	37.75	Thurston et al. 1983
Pimephales promelas	19.0	7.76	1.27	50.28	32.44	Thurston et al. 1983
Pimephales promelas	13.4	7.66	0.78	58.23	31.68	Thurston et al. 1983
Pimephales promelas	15.8	7.87	1.51	58.91	46.25	Thurston et al. 1983
Pimephales promelas	22.0	7.83	1.85	50.58	36.94	Thurston et al. 1983
Pimephales promelas	18.9	7.91	1.73	49.26	41.62	Thurston et al. 1983
Pimephales promelas	14.3	7.77	1.22	66.71	43.80	Thurston et al. 1983
Pimephales promelas	14.1	7.77	1.31	72.71	47.74	Thurston et al. 1983
Pimephales promelas	22.4	8.04	2.16	36.09	38.92	Thurston et al. 1983
Pimephales promelas	21.4	8.08	2.73	44.76	52.10	Thurston et al. 1983
Pimephales promelas	21.4	8.16	3.44	47.39	64.35	Thurston et al. 1983
Pimephales promelas	21.7	7.88	2.04	50.95	40.74	Thurston et al. 1983
Pimephales promelas	12.9	7.68	1.23	91.71	51.60	Thurston et al. 1983
Pimephales promelas	12.3	7.74	1.10	74.89	46.67	Thurston et al. 1983
Pimephales promelas	13.2	7.63	1.10	89.85	46.53	Thurston et al. 1983
Pimephales promelas	11.7	7.62	0.98	92.10	46.93	Thurston et al. 1983
Pimephales promelas	13.6	7.93	1.37	54.97	48.19	Thurston et al. 1983
Pimephales promelas	12.6	7.77	1.45	90.13	59.18	Thurston et al. 1983
Pimephales promelas	12.5	7.83	1.12	61.22	44.71	Thurston et al. 1983
Pimephales promelas	12.9	7.76	1.73	107.53	69.38	Thurston et al. 1983
Pimephales promelas	21.7	7.84	2.03	55.43	41.22	Thurston et al. 1983
Pimephales promelas	16.0	7.90	0.95	34.21	28.37	Thurston et al. 1983
Pimephales promelas	15.5	7.92	1.18	42.05	36.19	Thurston et al. 1983
Pimephales promelas	13.1	7.76	1.09	66.73	43.05	Thurston et al. 1983
Pimephales promelas	12.8	7.74	0.80	52.17	32.51	Thurston et al. 1983
Pimephales promelas	15.9	7.91	1.34	47.43	40.07	Thurston et al. 1983
Poecilia reticulata	25.0	7.22	1.47	129.40	37.66	Rubin and Elmaraghy 1976, 1977

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Poecilia reticulata	25.0	7.45	1.59	82.95	32.56	Rubin and Elmaraghy 1976, 1977
Poecilia reticulata	25.0	7.45	1.45	75.65	29.69	Rubin and Elmaraghy 1976, 1977
Procamberus clarkii	20.0	7.68	1.21	53.41	30.05	Diamond et al. 1993
Prosopium williamsoni	12.3	7.80	0.36	21.27	14.72	Thurston and Meyn 1984
Prosopium williamsoni	12.1	7.68	0.14	11.33	6.38	Thurston and Meyn 1984
Prosopium williamsoni	12.4	7.84	0.47	25.47	18.94	Thurston and Meyn 1984
Pyganodon grandis [a]	25.0	7.50	0.20	9.19	3.88	Scheller 1997
Pyganodon grandis [a]	25.0	7.70	0.33	9.79	5.70	Scheller 1997
Rana pipiens	20.0	7.68	1.44	63.56	35.76	Diamond et al. 1993
Rana pipiens	12.0	7.68	0.42	33.54	18.87	Diamond et al. 1993
Salmo trutta	13.2	7.85	0.60	29.58	22.39	Thurston and Meyn 1984
Salmo trutta	13.8	7.86	0.70	32.46	25.02	Thurston and Meyn 1984
Salmo trutta	14.2	7.82	0.68	33.30	23.89	Thurston and Meyn 1984
Salvelinus fontinalis	13.8	7.83	1.05	52.03	38.00	Thurston and Meyn 1984
Salvelinus fontinalis	13.6	7.86	0.96	45.21	34.86	Thurston and Meyn 1984
Simocephalus vetulus	20.4	8.10	1.27	21.36	25.83	Arthur et al. 1987
Simocephalus vetulus	17.0	8.30	2.29	31.58	56.29	Arthur et al. 1987
Stenelmis sexlineata	25.0	8.70	8.00	29.69	113.17	Hazel et al. 1979
Stizostedion vitreum	19.0	8.30	0.51	6.12	10.91	Arthur et al. 1987
Stizostedion vitreum	3.7	7.90	0.52	48.37	40.12	Arthur et al. 1987
Stizostedion vitreum	11.1	7.70	1.10	89.93	52.33	Arthur et al. 1987
Stizostedion vitreum	21.5	8.10	1.04	16.21	19.61	Mayes et al. 1986
Sympetrum flaveolum	25.0	6.96	1.72	274.34	61.73	Beketov 2002
Sympetrum flaveolum	25.0	7.44	3.41	181.98	70.42	Beketov 2002
Sympetrum flaveolum	25.0	8.22	6.11	58.31	88.95	Beketov 2002
Sympetrum flaveolum	25.0	7.42	12.56	701.39	263.82	Beketov 2002
Tubifex tubifex	12.0	8.20	2.70	66.67	97.82	Stammer 1953
Utterbackia imbecellis [a]	25.0	8.10	0.64	7.87	9.52	Augspurger et al. 2003
Utterbackia imbecellis [a]	25.0	8.00	1.36	20.76	20.75	Augspurger et al. 2003
Utterbackia imbecellis [a]	25.0	8.00	0.72	11.00	10.99	Black 2001
Utterbackia imbecellis [a]	25.0	8.00	0.16	2.51	2.51	Black 2001

Table B-1 cont.

Species	Temp. (°C)	pH	Un-Ionized Ammonia (mg NH_3/L)	Total Ammonia-Nitrogen (mg N/L)	Total Ammonia-Nitrogen pH = 8 (mg N/L)	Source
Utterbackia imbecellis [a]	25.0	8.00	0.22	3.33	3.32	Black 2001
Utterbackia imbecellis [a]	25.0	8.00	0.19	2.88	2.88	Black 2001
Utterbackia imbecellis [a]	25.0	8.30	2.02	16.28	29.01	Black 2001
Utterbackia imbecellis [a]	25.0	8.20	0.85	8.43	12.37	Black 2001
Utterbackia imbecellis [a]	25.0	8.20	0.75	7.51	11.03	Black 2001
Villosa iris [a]	22.0	8.10	0.36	5.46	6.60	Goudreau et al. 1993
Villosa iris [a]	12.5	7.30	0.17	30.31	9.71	Mummert et al. 2003
Villosa iris [a]	12.5	7.30	0.13	24.38	7.81	Mummert et al. 2003
Villosa iris [a]	12.5	7.30	0.10	18.78	6.02	Mummert et al. 2003
Villosa iris [a]	12.5	7.30	0.09	16.96	5.44	Mummert et al. 2003
Villosa iris [a]	20.6	7.41	0.35	27.51	10.20	Mummert et al. 2003
Villosa iris [a]	20.6	7.41	0.19	14.99	5.56	Mummert et al. 2003
Villosa iris [a]	20.6	7.41	0.13	10.29	3.82	Mummert et al. 2003
Villosa iris [a]	20.6	7.41	0.12	9.39	3.48	Mummert et al. 2003
Villosa iris [a]	20.0	7.90	0.10	2.56	2.12	Scheller 1997
Villosa iris [a]	25.0	8.20	0.96	9.58	14.06	Scheller 1997
Villosa iris [a]	25.0	8.20	0.87	8.65	12.70	Scheller 1997
Villosa iris [a]	25.0	8.10	0.48	5.95	7.20	Scheller 1997

[a] Unionidae

APPENDIX C.

Table C-1. Ranked GMAV and SMAV for acute database.

Rank	Genus Mean Acute Value[a]	Species	Species Mean Acute Value[a]	Habitat Type[b]
49	308.62	Damselfly, Erythromma najas	308.62	1, 2
48	282.09	Crayfish, *Philarctus quaeris*	282.09	1, 2
47	189.16	Mayfly, *Ephemerella grandis*	189.16	1, 2
46	178.31	Crayfish, *Orconectes immunis*	770.46	1, 2
		Crayfish, *Orconectes naias*	41.27	1, 2
45	165.94	Isopod, *Asellus racovitzai*	165.94	1, 2
44	139.48	Dragonfly, *Lestes sponsa*	139.48	1, 2
43	126.92	Mayfly, *Callibaetis skokianus*	164.08	1, 2
		Mayfly, *Callibaetis* sp.	75.93	1, 2
42	113.17	Beetle, *Stenelmis sexlineata*	113.17	1, 2
41	100.50	Dragonfly, *Sympetrum flaveolum*	100.50	1, 2
40	99.87	Amphipod, *Crangonyx pseudogracillis*	108.30	1, 2
		Amphipod, *Crangonyx* sp.	92.10	1, 2
39	97.82	Tubificid worm, *Tubifex tubifex*	97.82	1, 2
38	94.19	Mayfly, *Baetis rhodani*	94.19	1, 2
37	77.10	Stonefly, *Arcynopteryx parallela*	77.10	1, 2
36	74.48	Snail, *Physa gyrina*	74.48	1, 2
35	63.79	Minnow, *Cyprinodon* sp.	63.79	2
34	60.84	Snail, *Helisoma trivolvis*	60.84	1, 2
33	51.83	Crayfish, *Procamberus clarkii*	51.83	1, 2
32	51.73	Mottled Sculpin, *Cottus bardi*	51.73	1
31	42.69	Fathead minnow, *Pimephales promelas*	42.69	2
30	38.13	Cladoceran, *Simocephalus vetulus*	38.13	1, 2
29	38.12	White sucker, *Catostomus commersoni*	45.82	1, 2

Table C-1. cont.

Rank	Genus Mean Acute Value[a]	Species	Species Mean Acute Value[a]	Habitat Type[b]
		Mountain sucker, *Catostomus platyrynchus*	31.71	1, 2
28	36.39	Brook trout, *Salvelinus fontinalis*	36.39	1, 2
27	36.26	Cladoceran, *Daphnia magna*	35.24	1, 2
		Cladoceran, *Daphnia pulicaria*	37.31	1, 2
26	35.65	Fingernail clam, *Musculium transversum*	35.65	1, 2
25	34.48	Channel catfish, *Ictalurus punctatus*	35.81	2
24	33.15	Guppy, *Poecilia reticulata*	33.15	2
23	32.82	Flatworm, *Dendrocoelom lacteum*	32.82	1, 2
22	30.89	White perch, *Morone americana*	30.89	2
21	27.18	Smallmouth bass, *Micropterus dolomieui*	36.90	2
		Largemouth bass, *Micropterus salmoides*	20.03	2
20	26.97	Central stoneroller, *Campostoma anomalum*	26.97	2
19	25.97	Northern leopard frog, *Rana pipiens*	25.97	1, 2
18	25.89	Walleye, *Stizostedion vitreum*	25.89	2
17	25.60	Red shiner, *Notropis lutrensis*	45.65	2
		Spotfin shiner, *Notropis spilopterus*	19.51	2
		Steelcolor shiner, *Notropis whipplei*	18.83	2
16	23.74	Brown trout, *Salmo trutta*	23.74	1
15	23.64	Green sunfish, *Lepomis cyanellus*	30.31	2
		Pumpkinseed, *Lepomis gibbosus*	18.05	2
		Bluegill, *Lepomis machrochirus*	24.16	2
14	22.91	Golden trout, *Oncorhynchus aquabonita*	22.71	1
		Cutthroat trout, *Oncorhynchus clarki*	25.80	1
		Pink salmon, *Oncorhynchus gorbuscha*	42.07	1
		Coho salmon, *Oncorhynchus kisutch*	16.97	1

Table C-1. cont.

Rank	Genus Mean Acute Value[a]	Species	Species Mean Acute Value[a]	Habitat Type[b]
		Rainbow trout, *Oncorhynchus mykiss*	19.94	1
		Chinook salmon, *Oncorhynchus tshawytscha*	17.34	1
13	18.14	Orangethroat darter, *Etheostoma spectabile*	18.14	2
12	16.28	Cladoceran, *Ceriodaphnia acanthina*	13.68	1, 2
		Cladoceran, *Ceriodaphnia dubia*	19.38	1, 2
11	15.25	Mosquitofish, *Gambusia affinis*	15.25	2
10	14.67	Golden shiner, *Notemigonus chrysoleucas*	14.67	2
9	12.11	Mountain whitefish, *Prosopium williamsoni*	12.11	1
8	8.39	Paper pondshell mussel, *Utterbackia imbecellis*	8.39	2[c]
7	8.01	Plain pocketbook mussel, *Lampsilis cardium*	22.14	2[c]
		Wavy-rayed lampmussel, *Lampsilis fasciola*	9.55	2[c]
		Fatmucket mussel, *Lampsilis siliquoidea*	2.43	2[c]
6	7.67	Pheasantshell mussel, *Actinonaias pectorosa*	7.67	2[c]
5	6.45	Rainbow mussel, *Villosa iris*	6.45	2[c]
4	4.70	Giant floater mussel, *Pyganodon grandis*	4.70	2[c]
3	4.47	Cumberland moccasinshell mussel, *Medionidus conradicus*	4.47	2[c]
2	2.82	Green floater mussel, *Lasmigona subvirdis*	2.82	2[c]
1	1.34	Atlantic pigtoe mussel, *Fusconaia masoni*	1.34	2[c]

[a] GMAV and SMAV are reported as total ammonia nitrogen at pH = 8, mg N/L
[b] 1 = cold water, 2 = warm water
[c] Unionidae

APPENDIX D

Table D-1. Recalculation of the cold-water Criterion Maximum Concentration for ammonia using the updated acute database. N = 29 genera, R = sensitivity rank in database, P = rank / N+1.

Rank	Genus	GMAV	ln GMAV	(ln GMAV)^2	P = R/(N+1)	vP
4	*Salmo*	23.74	3.1673	10.0318	0.1379	0.3714
3	*Oncorhynchus*	22.91	3.1315	9.8063	0.1034	0.3216
2	*Ceriodaphnia*	16.28	2.7901	7.7847	0.0690	0.2626
1	*Prosopium*	12.11	2.4943	6.2215	0.0345	0.1857
		sum	11.5832	33.8443	0.3448	1.1413

$$S^2 = \frac{\sum(\ln \mathrm{GMAV})^2 - \left(\sum \ln \mathrm{GMAV}\right)^2/4}{\sum P - \left(\sum \sqrt{P}\right)^2/4} = \frac{33.8443 - (11.5832)^2/4}{0.3448 - (1.1413)^2/4} = 15.7233$$

$$S = 3.9653$$

$$L = \left[\sum \ln\mathrm{GMAV} - S\left(\sum\sqrt{P}\right)\right]/4 = [11.5832 - 3.9653(1.1413)]/4 = 1.7644$$

$$A = S\left(\sqrt{0.05}\right) + L = 3.9653(0.2236) + 1.7644 = 2.6511$$

$$\mathrm{FAV} = e^A = e^{2.6511} = 14.17$$

$$\mathrm{AV}_t = \mathrm{AV}_{t,8}\left[\frac{0.0489}{1+10^{7.204-\mathrm{pH}}} + \frac{6.95}{1+10^{\mathrm{pH}-7.204}}\right]$$

$$\mathrm{AV}_{t,8} = \frac{\mathrm{FAV}}{2} = \frac{14.17}{2} = 7.09\ \mathrm{mg\ N/L}$$

$$\mathrm{AV}_t = 7.09\left[\frac{0.0489}{1+10^{7.204-\mathrm{pH}}} + \frac{6.95}{1+10^{\mathrm{pH}-7.204}}\right]$$

$$\mathrm{CMC}_{\mathrm{cold}} = \frac{0.347}{1+10^{7.204-\mathrm{pH}}} + \frac{49.3}{1+10^{\mathrm{pH}-7.204}}$$

APPENDIX E

Table E-1. Recalculation of the warm-water with Unionidae CMC for ammonia using the updated acute database. N = 44 genera, R = sensitivity rank in database, P = rank / N+1.

Rank	Genus	GMAV	ln GMAV	$(\ln \mathrm{GMAV})^2$	P = R/(N+1)	vP
4	*Pyganodon*	4.70	1.5483	2.3972	0.0889	0.2981
3	*Medionidus*	4.47	1.4982	2.2446	0.0667	0.2582
2	*Lasmigona*	2.82	1.0364	1.0741	0.0444	0.2108
1	*Fusconaia*	1.34	0.2894	0.0838	0.0222	0.1491
		sum	4.3723	5.7997	0.2222	0.9162

$$\mathrm{S}^2 = \frac{\sum(\ln\mathrm{GMAV})^2 - \left(\sum \ln\mathrm{GMAV}\right)^2/4}{\sum \mathrm{P} - \left(\sum\sqrt{\mathrm{P}}\right)^2/4} = \frac{5.7997-(4.3723)^2/4}{0.2222-(0.9162)^2/4} = 82.5164$$

$$\mathrm{S} = 9.0839$$

$$\mathrm{L} = \left[\sum \ln\mathrm{GMAV} - \mathrm{S}\left(\sum\sqrt{\mathrm{P}}\right)\right]/4 = \left[4.3723 - 9.0839(0.9162)\right]/4 = -0.9876$$

$$\mathrm{A} = \mathrm{S}\left(\sqrt{0.05}\right) + \mathrm{L} = 9.0839(0.2236) - 0.9876 = 1.0436$$

$$\mathrm{FAV} = e^{A} = e^{1.0436} = 2.84$$

$$\mathrm{AV_t} = \mathrm{AV_{t,8}}\left[\frac{0.0489}{1+10^{7.204-\mathrm{pH}}} + \frac{6.95}{1+10^{\mathrm{pH}-7.204}}\right]$$

$$\mathrm{AV_{t,8}} = \frac{\mathrm{FAV}}{2} = \frac{2.84}{2} = 1.42 \text{ mg N/L}$$

$$\mathrm{AV_t} = 1.42\left[\frac{0.0489}{1+10^{7.204-\mathrm{pH}}} + \frac{6.95}{1+10^{\mathrm{pH}-7.204}}\right]$$

$$\mathrm{CMC_{warm}} = \frac{0.069}{1+10^{7.204-\mathrm{pH}}} + \frac{9.87}{1+10^{\mathrm{pH}-7.204}}$$

APPENDIX F

Table F-1. Recalculation of the warm-water without Unionidae CMC for ammonia using the updated acute database. N = 36 genera, R = sensitivity rank in database, P = rank / N+1.

Rank	Genus	GMAV	ln GMAV	(ln GMAV)^2	P = R/(N+1)	vP
4	*Etheostoma*	18.14	2.8984	8.4007	0.1081	0.3288
3	*Ceriodaphnia*	16.28	2.7901	7.7847	0.0811	0.2847
2	*Gambusia*	15.25	2.7243	7.4218	0.0541	0.2325
1	*Notemigonus*	14.67	2.6860	7.2146	0.0270	0.1644
		sum	11.0988	30.8218	0.2703	1.0104

$$S^2 = \frac{\sum (\ln GMAV)^2 - \left(\sum \ln GMAV\right)^2/4}{\sum P - \left(\sum \sqrt{P}\right)^2/4} = \frac{30.8218 - (11.0988)^2/4}{0.2703 - (1.0104)^2/4} = 1.7257$$

$$S = 1.3136$$

$$L = \left[\sum \ln GMAV - S\left(\sum \sqrt{P}\right)\right]/4 = [11.0988 - 1.3136(0.9484)]/4 = 2.4429$$

$$A = S\left(\sqrt{0.05}\right) + L = 1.3136(0.2236) + 2.4429 = 2.7366$$

$$FAV = e^A = e^{2.7366} = 15.43$$

$$AV_t = AV_{t,8}\left[\frac{0.0489}{1+10^{7.204-pH}} + \frac{6.95}{1+10^{pH-7.204}}\right]$$

$$AV_{t,8} = \frac{FAV}{2} = \frac{15.43}{2} = 7.72 \text{ mg N/L}$$

$$AV_t = 7.72\left[\frac{0.0489}{1+10^{7.204-pH}} + \frac{6.95}{1+10^{pH-7.204}}\right]$$

$$CMC_{\text{warm without Unionidae}} = \frac{0.378}{1+10^{7.204-pH}} + \frac{53.7}{1+10^{pH-7.204}}$$

APPENDIX G

Table G-1. Chronic ammonia toxicity database.

Species	Temp. (°C)	pH	Total Ammonia-Nitrogen EC20 @ test pH & Temp (mg N/L)	Total Ammonia-Nitrogen EC20 @ pH=8 (mg N/L)	Total Ammonia-Nitrogen EC20 @ pH=8 & 25°C (mg N/L)	Source
Ceriodaphnia acanthina	24.50	7.15	44.90	19.77	19.14	Mount 1982
Ceriodaphnia dubia	26.00	8.57	5.80	14.60	15.57	Willingham 1987
Ceriodaphnia dubia	25.00	7.80	15.20	11.63	11.63	Nimmo et al. 1989
Daphnia magna	19.80	8.45	7.37	15.14	10.83	Gersich et al. 1985
Daphnia magna	20.10	7.92	21.70	19.41	14.15	Reinbold and Pescitelli 1982a
Ictalurus punctatus	26.90	7.76	11.50	8.39	9.48	Swigert and Spacie 1983
Ictalurus punctatus	25.80	7.80	12.20	9.34	9.83	Reinbold and Pescitelli 1982a
Lasmigona subviridis	22.00	8.00	0.56	0.56	0.46	Black 2001
Lepomis cyanellus	25.40	8.16	5.84	7.44	7.64	Reinbold and Pescitelli 1982a
Lepomis cyanellus	22.00	7.90	5.61	4.88	4.03	McCormick et al. 1983
Lepomis macrochirus	22.50	7.76	1.85	1.35	1.15	Smith et al. 1984
Micropterus dolomeiu	22.30	6.60	9.61	3.57	3.00	Broderius et al. 1985
Micropterus dolomeiu	22.30	7.25	8.62	4.01	3.37	Broderius et al. 1985
Micropterus dolomeiu	22.30	7.83	8.18	6.50	5.46	Broderius et al. 1985
Micropterus dolomeiu	22.30	8.68	1.54	4.66	3.92	Broderius et al. 1985
Musculium transversum	23.50	8.15	5.82	7.30	6.63	Anderson et al. 1978
Musculium transversum	21.80	7.80	1.23	0.94	0.77	Sparks and Sandusky 1981
Pimephales promelas	24.20	8.00	1.97	1.97	1.87	Thurston et al. 1986
Pimephales promelas	25.10	7.82	3.73	2.93	2.95	Swigert and Spacie 1983
Pimephales promelas	24.80	8.00	5.12	5.12	5.06	Mayes et al. 1986
Salvelinus namayacush	11.60	8.02	9.13	9.40	3.96	Beamish and Tandler 1990

APPENDIX H

Table H-1. Acute to chronic ratios for paired data used in the derivation of CCC limits.

Species	Acute		Chronic		Acute:Chronic	
	SMAV TA-N at pH8 (mg N/L)	GMAV TA-N at pH8 (mg N/L)	SMCV TA-N at pH8 (mg N/L)	GMCV TA-N at pH8 (mg N/L)	SM ACR	GM ACR
Ceriodaphnia acanthina	13.68	16.28	19.77	16.05	0.7	1.0
Ceriodaphnia dubia	19.38		13.03		1.5	
Daphnia magna	35.24	36.26	17.14	17.14	2.1	2.1
Ictalurus punctatus	35.81	35.81	8.85	8.85	4.0	4.0
Lasmigona subviridis	2.82	2.82	0.56	0.56	5.0	5.0
Lepomis cyanellus	30.31	23.64	6.03	2.85	5.0	8.3
Lepomis macrochirus	24.16		1.35			
Micropterus dolomeiu	36.90	27.18	4.56	4.56	8.1	6.0
Musculium transversum	35.65	35.65	2.62	2.62	13.6	13.6
Pimephales promelas	42.69	42.69	3.09	3.09	13.8	13.8
Salvelinus namayacush	36.39	36.39	9.40	9.40	3.9	3.9
Geometric mean					4.1	4.9

$$\mathrm{CMC}_{\mathrm{Cold}} = \frac{\dfrac{0.347}{1+10^{7.204\text{-pH}}}+\dfrac{49.3}{1+10^{\text{pH-}7.204}}}{4.9}$$

$$\mathrm{CCC}_{\mathrm{Cold}} = \frac{0.071}{1+10^{7.204\text{-pH}}}+\frac{10.06}{1+10^{\text{pH-}7.204}}$$

$$\mathrm{CMC}_{\mathrm{Warm}} = \frac{\dfrac{0.069}{1+10^{7.204\text{-pH}}}+\dfrac{9.87}{1+10^{\text{pH-}7.204}}}{4.9}$$

$$\mathrm{CCC}_{\mathrm{Warm}} = \frac{0.014}{1+10^{7.204\text{-pH}}}+\frac{2.01}{1+10^{\text{pH-}7.204}}$$

$$\mathrm{CMC}_{\mathrm{Warm\ without\ Unionidae}} = \frac{\dfrac{0.378}{1+10^{7.204\text{-pH}}}+\dfrac{53.7}{1+10^{\text{pH-}7.204}}}{4.9}$$

$$\mathrm{CCC}_{\mathrm{Warm\ without\ Unionidae}} = \frac{0.077}{1+10^{7.204\text{-pH}}}+\frac{10.96}{1+10^{\text{pH-}7.204}}$$