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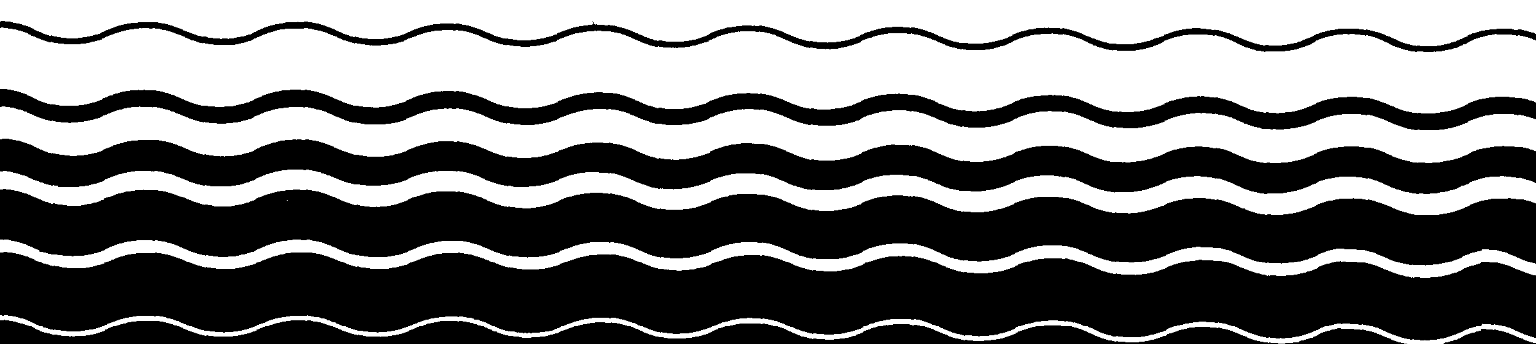
# Copper - 1984



# AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR

# COPPER

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# FOREWORD

Section 304(a)(1) of the Clean Water Act of 1977 (P.L. 95-217) requires the Administrator of the Environmental Protection Agency to publish criteria for water quality accurately reflecting the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare which may be expected from the presence of pollutants in any body of water, including ground water. This document is a revision of proposed criteria based upon a consideration of comments received from other Federal agencies, State agencies, special interest groups, and individual scientists. The criteria contained in this document replace any previously published EPA aquatic life criteria.

The term "water quality criteria" is used in two sections of the Clean Water Act, section 304(a)(1) and section 303(c)(2). The term has a different program impact in each section. In section 304, the term represents a non-regulatory, scientific assessment of ecological effects. The criteria presented in this publication are such scientific assessments. Such water quality criteria associated with specific stream uses when adopted as State water quality standards under section 303 become enforceable maximum acceptable levels of a pollutant in ambient waters. The water quality criteria adopted in the State water quality standards could have the same numerical limits as the criteria developed under section 304. However, in many situations States may want to adjust water quality criteria developed under section 304 to reflect local environmental conditions and human exposure patterns before incorporation into water quality standards. It is not until their adoption as part of the State water quality standards that the criteria become regulatory.

Guidelines to assist the States in the modification of criteria presented in this document, in the development of water quality standards, and in other water-related programs of this Agency, have been developed by EPA.

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## Introduction*

Copper, which occurs in natural waters primarily as the divalent cupric ion in free and complexed forms (Callahan, et al. 1979), is a minor nutrient for both plants and animals at low concentrations but is toxic to aquatic life at concentrations only slightly higher. Concentrations of 1 to 10 μg/l are usually reported for unpolluted surface waters in the United States (Boyle, 1979), but concentrations in the vicinity of municipal and industrial effluents, particularly from smelting, refining, or metal plating industries, may be much higher (Harrison and Bishop, 1984; Hutchinson, 1979).

A two-volume review of various aspects of "Copper in the Environment" (Nriagu, 1979) contains several chapters on the effects of copper on both freshwater and saltwater species. Reviews by Black, et al. (1976), Demayo, et al. (1982), and Spear and Pierce (1979a) summarize most of the available data on the aquatic toxicology of copper through 1982. These reviews form the scientific basis for Canadian environmental quality criteria for copper. Harrison and Bishop (1984) reviewed the potential impact of copper in power plant cooling waters on freshwater environments. Rai, et al. (1981) and Sprague (1985) reviewed effects of water quality parameters on copper toxicity.

The toxicity of copper to aquatic life has been shown to be related primarily to activity of the cupric ($Cu^{2+}$) ion, and possibly to some of

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*An understanding of the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" (Stephan, et al. 1985), hereafter referred to as the Guidelines, is necessary in order to understand the following text, tables, and calculations.

the hydroxy complexes (Andrew, et al. 1977; Chakoumakos, et al. 1979; Dodge and Theis, 1979; Howarth and Sprague, 1978; Pagenkopf, 1983; Petersen, 1982; Rueter, 1983). The cupric ion is highly reactive and forms moderate to strong complexes and precipitates with many inorganic and organic constituents of natural waters, e.g., carbonate, phosphate, amino acids, and humates, and is readily sorbed onto surfaces of suspended solids. The proportion of copper present as the free cupric ion is generally low and may be less than 1 percent in eutrophic waters where complexation predominates. Most organic and inorganic copper complexes and precipitates appear to be much less toxic than free cupric ion and tend to reduce toxicity attributable to total copper (Andrew, 1976; Borgmann and Ralph, 1983). This greatly complicates the interpretation and application of available toxicity data, because the proportion of free cupric ion present is highly variable and is difficult to measure except under laboratory conditions. Except for bacteria and plankton, few toxicity data have been reported using measurements other than total or dissolved copper.

Because a majority of the reported test results (Tables 1 and 2) have been conducted in waters having relatively low complexing capacities, the criteria derived herein may be at or below ambient total copper concentrations in some surface waters of the United States. Seasonally and locally, toxicity in these waters may be mitigated by the presence of naturally occurring complexing and precipitating agents. In addition, removal from the water column may be rapid due to settling of solids and normal growth of aquatic organisms. The various forms of copper are in dynamic equilibrium and any change in chemical conditions, e.g., pH, can rapidly alter the proportion of the various forms present and, therefore, toxicity.

In most natural waters, alkalinity and pH increase with water hardness and the relative influence of these parameters on toxicity is not easily determined. Because increasing calcium hardness and associated carbonate alkalinity are both known to reduce the acute toxicity of copper, expression of the criteria as a function of hardness allows adjustment for these water quality effects. This results in a much better fit with the available toxicity data, i.e., the criteria are higher at high hardness to reflect calcium antagonism and carbonate complexation. A similar approach, i.e., expressing acute toxicity as an exponential function of hardness, was used by Spear and Pierce (1979a) as a basis for the Canadian criteria. Some data on the relationship of toxicity to other factors, i.e., temperature, pH, alkalinity, size of organism, and total organic carbon, are available for a limited number of species and will be discussed later.

Because of the variety of forms of copper (Callahan, et al. 1979) and lack of definitive information about their relative toxicities, no available analytical measurement is known to be ideal for expressing aquatic life criteria for copper. Previous aquatic life criteria for copper (U.S. EPA, 1980) were expressed in terms of total recoverable copper (U.S. EPA, 1983a), but this measurement is probably too rigorous in some situations. Acid-soluble copper (operationally defined as the copper that passes through a 0.45 μm membrane filter after the sample is acidified to pH = 1.5 to 2.0 with nitric acid) is probably the best measurement at the present for the following reasons:

1. This measurement is compatible with nearly all available data concerning toxicity of copper to, and bioaccumulation of copper by, aquatic organisms. Very few test results were rejected just because it was likely that they would have been substantially different if they had been reported in terms of acid-soluble copper. For example, results reported

in terms of dissolved copper were not used if the concentration of precipitated copper was substantial.

2. On samples of ambient water, measurement of acid-soluble copper should measure all forms of copper that are toxic to aquatic life or can be readily converted to toxic forms under natural conditions. In addition, this measurement should not measure several forms, such as copper that is occluded in minerals, clays, and sand or is strongly sorbed to particulate matter, that are not toxic and are not likely to become toxic under natural conditions. Although this measurement (and many others) will measure soluble, complexed forms of copper, such as the EDTA complex of copper, that probably have low toxicities to aquatic life, concentrations of these forms probably are negligible in most ambient water.
3. Although water quality criteria apply to ambient water, the measurement used to express criteria is likely to be used to measure copper in aqueous effluents. Measurement of acid-soluble copper should be applicable to effluents because it will measure precipitates, such as carbonate and hydroxide precipitates of copper, that might exist in an effluent and dissolve when the effluent is diluted with receiving water. If desired, dilution of effluent with receiving water before measurement of acid-soluble copper might be used to determine whether the receiving water can decrease the concentration of acid-soluble copper because of sorption.
4. The acid-soluble measurement should be useful for most metals, thus minimizing the number of samples and procedures that are necessary.
5. The acid-soluble measurement does not require filtration at the time of collection, as does the dissolved measurement.

6. The only treatment required at the time of collection is preservation by acidification to pH = 1.5 to 2.0, similar to that required for the total recoverable measurement.
7. Durations of 10 minutes to 24 hours between acidification and filtration probably will not affect the result substantially.
8. The carbonate system has a much higher buffer capacity from pH = 1.5 to 2.0 than it does from pH = 4 to 9 (Weber and Stumm, 1963).
9. Differences in pH within the range of 1.5 to 2.0 probably will not affect the result substantially.
10. The acid-soluble measurement does not require a digestion step, as does the total recoverable measurement.
11. After acidification and filtration of the sample to isolate the acid-soluble copper, the analysis can be performed using either atomic absorption spectroscopy or ICP-emission spectroscopy (U.S. EPA, 1983a), as with the total recoverable measurement.

Thus, expressing aquatic life criteria for copper in terms of the acid-soluble measurement has both toxicological and practical advantages. On the other hand, because no measurement is known to be ideal for expressing aquatic life criteria for copper or for measuring copper in ambient water or aqueous effluents, measurement of both acid-soluble copper and total recoverable copper in ambient water or effluent or both might be useful. For example, there might be cause for concern if total recoverable copper is much above an applicable limit, even though acid-soluble copper is below the limit.

Unless otherwise noted, all concentrations reported herein are expected to be essentially equivalent to acid-soluble copper concentrations. All concentrations are expressed as copper, not as the chemical tested. The criteria presented herein supersede previous aquatic life water quality criteria for copper (U.S. EPA, 1976, 1980) because these new criteria were derived using improved procedures and additional information. Whenever adequately justified, a national criterion may be replaced by a site-specific criterion (U.S. EPA, 1983b), which may include not only site-specific criterion concentrations (U.S. EPA, 1983c), but also site-specific durations of averaging periods and site-specific frequencies of allowed exceedences (U.S. EPA, 1985). The latest literature search for information for this document was conducted in May, 1984; some newer information was also used.

## Acute Toxicity to Aquatic Animals

Most of the available tests on the toxicity of copper to freshwater animals have been conducted with four salmonid species, fathead and bluntnose minnows, and the bluegill. Acute values range from 6.5 µg/L for *Daphnia magna* in hard water to 10,200 µg/L for the bluegill in hard water. The majority of tests conducted since about 1970 have been flow-through tests with measurements of both total and dissolved copper. Many recent tests have included measurement or calculation of cupric ion activity (Andrew, 1977; McKnight and Morel, 1979; Petersen, 1982; Rueter, 1983; Sunda and Gillespie, 1979; Zevenhuizen, et al. 1979). All the values in Table 1 are for total copper, except that the values obtained by Howarth and Sprague (1978) were dissolved copper. These are included in Table 1 because Chakoumakos, et al. (1979) showed that at low hardness in this water almost all the copper is dissolved. Values obtained by Howarth and Sprague (1978) in hard water are in Table 6.

Acute tests by Cairns, et al. (1978) indicate that daphnids are more resistant to copper at low than at high temperatures (Table 6). Because such data are not available for other species or for longer tests, no generalizations can be made for criteria derivation. Chakoumakos, et al. (1979) and Howarth and Sprague (1978) (Tables 1 and 6) have reported that larger (10 to 30 g) rainbow trout are approximately 2.5 to 3.0 times more resistant to copper than juveniles. Tsai and Chang (1981, 1984) showed a similar size effect for the guppy and the bluegill. This factor is obviously a source of variation in Table 1. However, insufficient data are available for other species to allow adjustment of test results or on which to base criteria. An additional complicating factor is the general lack of knowledge of the range of sensitivity of various life stages of most invertebrate species, or the effects on susceptibility of starvation and other stresses under natural conditions.

Lind, et al. (Manuscript) and Brown, et al. (1974) demonstrated quantitative relationships between the acute toxicity of copper and naturally occurring organic complexing agents (Tables 1 and 6). Although these relationships have been shown for only a few species (Daphnia pulicaria, fathead minnow, and rainbow trout), the effects should be generalizable through chemical effects on cupric ion activity and bioavailability. Lind, et al. (Manuscript) measured the toxicity of copper to Daphnia pulicaria in a variety of surface waters and found that total organic carbon (TOC) is a more important variable than hardness, with acute values varying approximately 30-fold over the range of TOC covered. Similar results were obtained with the fathead minnow. This indicates that criteria should be adjusted upward for surface waters with TOC significantly above the 2 to 3 mg/L usually found in waters used for toxicity tests. Results obtained by Lind, et al. (Manuscript) in waters with low TOC are in Table 1; values obtained in water with high TOC are in Table 6. Rehwoldt, et al. (1971, 1972, 1973) obtained substantially higher acute values than other investigators did with an amphipod, the common carp, striped bass, and pumpkinseed. This may have been an effect of water quality on toxicity.

To account for the apparent relationship of copper toxicity to hardness, an analysis of covariance (Dixon and Brown, 1979; Neter and Wasserman, 1974) was performed using the natural logarithm of the acute value as the dependent variable, species as the treatment or grouping variable, and the natural logarithm of hardness as the covariate or independent variable. This analysis of covariance model was fit to the data in Table 1 for the eight species for which acute values are available over a range of hardness such that the highest hardness is at least three times the lowest and the highest is also at least 100 mg/L higher than the lowest. Seven of the slopes ranged from 0.6092 to 1.3639 (Table 1). The slope for Daphnia magna was 0.4666 with wide confidence limits if all the data for this species were used, but the slope was 1.0438 with narrower confidence limits if the value from Dave (1984) was not used. Therefore, this value was not used. An F-test showed that, under the assumption of equality of slopes, the probability of obtaining eight slopes as dissimilar as these is P=0.11. This was interpreted as indicating that it is not unreasonable to assume that the slopes for all eight species are the same. The pooled slope of 0.9422 is close to the slope of 1.0 that is expected on the basis that copper, calcium, magnesium, and carbonate all have a charge of two.

The pooled slope of 0.9422 was fitted through the geometric mean toxicity value and hardness for each species to obtain Species Mean Acute Values at a hardness of 50 mg/L (Table 1), which were used to calculate Genus

Mean Acute Values (Table 3). Of the 41 genera for which acute values are available, the most sensitive, Ptychocheilus, is 610 times more sensitive than the most resistant, Acroneuria. The seven most sensitive genera are within a factor of 3 and both fishes and invertebrates are among the most sensitive and most resistant genera. Acute values are available for more than one species in each of nine genera, and the range of Species Mean Acute Values within each genus is less than a factor of 6.6. A freshwater Final Acute Value of 18.46 μg/L (at a hardness of 50 mg/L) was obtained for copper using the Genus Mean Acute Values in Table 3 and the calculation procedure described in the Guidelines. Thus, the freshwater Criterion Maximum Concentration (in μg/L) = $e^{(0.9422[\ln(\text{hardness})]-1.464)}$.

Embryos of the blue mussel and Pacific oyster are the most sensitive saltwater animal species tested with acute values of 5.8 and 7.8 μg/L, respectively (Table 1). Differences in life-stage sensitivity with the Pacific oyster are clearly evident because the adults of this species studied in a flow-through test had an LC50 of 560 μg/L, which is about two orders of magnitude greater than the values for the embryos. This suggests that embryos may be the most sensitive life stage of these two species. Eisler (1977) demonstrated that copper toxicity to Mya arenaria varied according to the seasonal temperature, being at least 100 times more toxic at 22 C than at 4 C. The calanoid copepods, Acartia tonsa and Acartia clausi, were the most sensitive crustacean species tested with LC50s in the range of 17 to 55 μg/L. Sosnowski, et al. (1979) showed that the sensitivity of field populations of A. tonsa to copper was strongly correlated with population density and food ration (Table 6), whereas cultured A. tonsa manifested a reproducible toxicological response to copper (Table 1) through six generations (Sosnowski and Gentile, 1978). Life-stage sensitivity differences also occurred with crustaceans as evidenced by the acute values of 100 µg/L for lobster adults (McLeese, 1974) and 48 µg/L for larvae (Johnson and Gentile, 1979). The range of crustacean sensitivity to copper is further highlighted by larvae of the green crab, Carcinus maenus, whose LC50 of 600 µg/L is the highest of all reported saltwater acute values. Adult Neanthes arenaceodentata had a range of acute values from 77 to 200 µg/L (Pesch and Morgan, 1978) and adult Nereis diversicolor acute values ranged from 200 to 480 µg/L over a salinity range of 5 to 34 g/kg, respectively (Jones, et al. 1976).

Acute values for saltwater fishes ranged from 13.93 to 411.7 µg/L and as with invertebrates, the lowest value was obtained in a test with embryos. In addition, tests with embryos of Atlantic cod resulted in a 14-day LC50 of 10 µg/L (Table 6). Birdsong and Avavit (1971) found that copper may be more toxic to adult pompano at a salinity of 10 g/kg than at 30 g/kg. A number of anadromous species, such as the coho salmon, have been exposed to copper in fresh water. These data were utilized in deriving the freshwater, but not the saltwater, criterion.

The 19 available saltwater Genus Mean Acute Values ranged from 5.8 µg/L for Mytilus to 7,694 µg/L for Rangia for a factor of over 1,000. Acute values are available for more than one species in each of five genera and the range of Species Mean Acute Values within each genus is less than a factor of 3.7. A saltwater Final Acute Value of 5.832 µg/L was obtained using the Genus Mean Acute Values in Table 3 and the calculation procedure described in the Guidelines. This is close to the acute value of 5.8 µg/L for the blue mussel and the value of 7.807 µg/L for the Pacific oyster.

## Chronic Toxicity to Aquatic Animals

Chronic toxicity tests have been conducted on copper in fresh water with five invertebrate and ten fish species (Table 2). In addition, results of seven life-cycle tests with daphnids are listed in Table 6, because the copper concentrations were not measured during the tests. Winner (1984a,b) demonstrated that both humic acid and selenium decreased the chronic toxicity of copper to *Daphnia pulex*. A life-cycle test with the fathead minnow was conducted in a stream water of variable quality (Brungs, et al. 1976). This result is in Table 6, because the dilution water for the test was obtained downstream of a sewage treatment plant and contained varying, high concentrations of organic material, phosphates, etc. Long-term tests by Seim, et al. (1984) with rainbow trout and by Nebeker, et al. (1984) with the midge, *Chironomus tentans*, are also in Table 6, because the studies did not include reproductive effects. Seim, et al. (1984) and McKim, et al. (1978) obtained nearly identical results with the trout at slightly different hardnesses. The 20-day EC50 for the midge, *Chironomus tentans*, indicates that this species is slightly more resistant to copper than other invertebrates in long-term tests.

The fifteen chronic values for the ten fish species range from 3.873 µg/L in an early life-stage test with brook trout to 60.36 µg/L in an early life-stage test with northern pike (Table 2). The seven values for the five invertebrate species range from 6.066 to 29.33 µg/L. The range for fishes is greater than the range for invertebrates, but this is largely due to the fact that the three chronic values for brook trout range from 3.873 to 31.15 µg/L. The only fish species with a chronic value greater than 31.15 µg/L is the northern pike at 60.36 µg/L. Although 22 chronic tests have been conducted on copper with freshwater species (Table 2), comparable acute values are not available for eight of the chronic tests, and one additional chronic test did not actually produce a chronic value.

The range of the thirteen acute-chronic ratios that can actually be calculated is 153, and the range of the thirteen individual acute values is a factor of 85. However, the range of the thirteen chronic values is only a factor of 4.8, indicating that for copper, the chronic values, rather than the acute-chronic ratio, is nearly constant across species. Most of the range in the acute-chronic ratio is obviously due to the range in the acute values, and the correlation coefficient (r) between the logarithm of the acute-chronic ratio and the logarithm of the acute value is 0.94. The increase in the acute-chronic ratio for resistant species might be due to an increase in precipitation of copper in acute tests as the sensitivity of the species to copper decreases. If the chronic tests for these same species are generally conducted at concentrations below the solubility limit of the common hydroxy-carbonates, the ratio would be increased when precipitation occurs in the acute tests.

Because the Final Acute-Chronic Ratio is meant to be used to calculate a Final Chronic Value from the Final Acute Value and because the Species Mean Acute Values for Daphnia magna and Gammarus pseudolimnaeus (Table 3) are only slightly higher than the Final Acute Value, it seems reasonable to use the geometric mean of the Species Mean Acute-Chronic Ratios for these two species as the Final Acute-Chronic Ratio. Division of the Final Acute Value by the Final Acute-Chronic Ratio of 2.823 results in a Final Chronic Value of 6.539 µg/L at a hardness of 50 mg/L.

The available information concerning the effect of hardness on the chronic toxicity of copper is inconclusive. The four chronic tests with the fathead minnow show a consistent relationship, and the slope of 0.2646 is much lower than the pooled slope of 0.9422 for the effect of hardness on acute toxicity. On the other hand, in tests with Daphnia magna Chapman, et al. (Manuscript) found a slope of 1.075 when hardness was increased from 51 to 104 mg/L, but a very negative slope when hardness was increased from 104 to 211 mg/L. It seems reasonable to assume that chronic toxicity decreases as hardness increases for two reasons. First, the available data seem to suggest it. Second, the small acute-chronic ratio and the strong effect of hardness on acute toxicity require an effect of hardness on chronic toxicity if the Final Chronic Value is to be below the Criterion Maximum Concentration at very low hardnesses. On the other hand, if the chronic slope is assumed to be equal to the acute slope of 0.9422, the Final Chronic Value would be 24 µg/L at a hardness of 200 mg/L. This seems a little high based on the chronic values at high hardness in Table 2. The combination of a chronic intercept of -1.465 and a chronic slope of 0.8545 provides the lowest chronic slope that will keep the Final Chronic Value below the Criterion Maximum Concentration down to a hardness of 1 mg/L and will result in a Final Chronic Value of 6.539 µg/L at a hardness of 50 mg/L. This combination results in a Final Chronic Value of 21 µg/L at a hardness of 200 mg/L, which seems more appropriate than the value of 24 µg/L.

The only saltwater chronic value available is for the mysid, Mysidopsis bahia (Table 2). The chronic toxicity of copper to this saltwater invertebrate was determined in a flow-through life-cycle test in which the concentrations of copper were measured by atomic absorption spectroscopy. Survival was reduced at 140 µg/L, and the number of spawns recorded at 77 µg/L was significantly ($P<0.05$) fewer than at 38 µg/L. The number of spawns at 24 and 38 μg/L was not significantly different from the number of spawns in the controls. Brood size was significantly ($P<0.05$) reduced at 77 μg/L, but not at lower concentrations, and no effects on growth were detected at any of the copper concentrations. Based upon reproductive data, unacceptable effects were observed at 77 μg/L, but not at 38 μg/L, resulting in a chronic value of 54.09 μg/L. Using the acute value of 181 μg/L, the acute-chronic ratio for this species is 3.346 (Table 2).

Use of 3.346 as the saltwater Final Acute-Chronic Ratio does not seem reasonable because Mysidopsis bahia is relatively acutely insensitive to copper. The lowest saltwater acute values are from tests with embryos and larvae of molluscs and embryos of summer flounder, which are possibly the most sensitive life stages of these species. It seems likely that concentrations that do not cause acute lethality to these life stages of these species will not cause chronic toxicity either. Thus, for salt water the Final Chronic Value for copper is equal to the Criterion Maximum Concentration of 2.916 μg/L (Table 3).

Several recent studies have attempted to test the validity of the "two-number" basis of the 1980 copper criteria (U.S. EPA, 1980). Ingersoll and Winner (1982) and Seim, et al. (1984) tested the effects of daily pulses at the copper LC50 to Daphnia pulex and rainbow trout, respectively. Both studies maintained the "average concentration" at or below the "no effect" concentration of a comparable long-term test with continuous exposure. Ingersoll and Winner (1982) observed a reduction in brood size and decreased survival of daphnids in the pulsed exposure. Similarly, Seim, et al. (1984) noted decreases in both survival and growth of trout with pulsed exposures. Buckley, et al. (1982) exposed coho salmon continuously to copper levels of

1/4 and 1/2 the LC50, while periodically testing acute toxicity (168-hr LC50), which is equivalent to short "pulses" above the long-term average concentration. Both groups of fish acclimated to the long-term copper exposure, and increased tolerance to acute exposures. At the end of 16 weeks the 168-hr LC50 of fish exposed at 1/2 the original LC50 increased 2.5 fold. Exposure to 1/4 the LC50 increased the 168-hr LC50 by 40%. These results were shown to be related to storage of copper in the liver and the induction of metallothionein or other hepatoproteins (Dixon and Sprague, 1981b; McCarter and Roch, 1984; McCarter, et al. 1982).

Acclimation to chronic exposure to copper is a protective mechanism, as is the induction of chelate excretion by algae (McKnight and Morel, 1979) and the development of copper-resistant strains of phytoplankton (Foster, 1982). All of the above studies indicate, however, that acclimation of either individuals, species, or populations requires sublethal exposures of several days or weeks duration, and that rapid excursions to near-lethal levels are more harmful than continuous low-level exposure.

LaPoint, et al. (1984) conducted field studies of effects of metal concentrations on benthic communities in 15 streams impacted to varying degrees by mining and industrial wastes. Their results at each sampling site were compared to hardness-related criteria calculated for each metal based on the 1980 criteria documents (U.S. EPA, 1980). This comparison indicated that "for the relatively simple metal pollution problems ..... the resident fauna responds in a predictable and indicative manner". In these cases, where only one or two metals were found, impacts on the benthos corresponded to areas of the stream exceeding the criteria. In a majority of cases, however, the complexity of the waste and the physical habitat or the influence of nutrient-rich effluents made the "community structural response ..... less readily predictable". In general, these studies tend to support the calculated criteria in those cases where the area impacted by the metals was defineable and valid upstream-downstream comparisons could be made. This report also points up the enormous difficulty of attempting to extrapolate from laboratory results to complex field situations.

Toxicity to Aquatic Plants

Copper has been widely used as an algicide and herbicide for nuisance aquatic plants (McKnight, et al. 1983). Although it is known as an inhibitor of photosynthesis and plant growth, toxicity data on individual species (Table 4; see also Rai, et al. 1981; Spear and Pierce, 1979a) are not numerous.

The relationship of copper toxicity to the complexing capacity of the water or the culture medium is now widely recognized (Gachter, et al. 1973; Petersen, 1982) and several recent studies have used algae to "assay" the copper complexing capacity of both fresh and salt waters (Allen, et al. 1983; Lumsden and Florence, 1983; Rueter, 1983). It has also been shown that algae are capable of excreting complexing substances in response to copper stress (McKnight and Morel, 1979; Swallow, et al. 1978; Van den Berg, et al. 1979). Foster (1982) and Stokes and Hutchinson (1976) have identified resistant strains and/or species of algae from copper (or other metal) impacted environments. A portion of this resistance probably results from induction of the chelate-excretion mechanism. Chelate-excretion by algae may also serve as a protective mechanism for other aquatic organisms in eutrophic waters, i.e., where algae are capable of maintaining free copper activities below harmful concentrations.

Copper concentrations from 1 to 8,000 µg/L have been shown to inhibit growth of various plant species. Several of the values are near or below the chronic values for fish and invertebrate species, but most are much higher. No Final Plant Value can be obtained because none of the plant values were based on tests with important species in which the concentrations of copper were measured in the test solutions.

Data are available on the toxicity of copper in salt water to two species of macroalgae and ten species of microalgae (Table 4). A copper concentration of 100 µg/L caused a 50% decrease in photosynthesis in the giant kelp, Macrocystis pyrefera (Clendenning and North, 1959). Growth reduction in the red alga, Champia parvula, occurred in both the tetrasporophyte and female plants exposed to copper concentrations of 4.6 and 4.7 µg/L (Steele and Thursby, 1983). Microalgae were equally sensitive to copper. The growth rates of Thalassiosira pseudonana and Scrippsiella faeroense were reduced by 50% after exposure to 5.0 ug/L for three and five days, respectively. Thus, saltwater plant species show similar sensitivity to copper as animal species, and water quality criteria that protect saltwater animals should also protect saltwater plants.

## Bioaccumulation

Bioconcentration factors (BCFs) in fresh water ranged from zero for the bluegill to 2,000 for the alga, Chlorella regularis (Table 5). In salt water the polychaete worm, Neanthes arenaceodentata, bioconcentrated copper 2,550 times (Pesch and Morgan, 1978), whereas in a series of measurements with algae by Riley and Roth (1971) the highest reported BCF was 617 for Heteromastix longifillis. The highest saltwater BCFs were obtained with bivalve molluscs. Shuster and Pringle (1969) found that the eastern oyster could concentrate copper 28,200 times during a 140-day continuous exposure to 50 µg/L. Even though the tissue of the oyster became bluish-green, mortalities were only slightly higher than in the controls. This amount of copper is not known to be harmful to man, but the color would undoubtedly adversely affect the marketability of oysters. Because no maximum permissible tissue concentration exists, neither a freshwater nor a saltwater Final Residue Value can be calculated for copper.

## Other Data

Many of the data in Table 6 are acute values for durations other than 96 hours with the same species reported in Table 1, with some exposures lasting up to 30 days. Acute values for test durations less than 96 hours are available for several species not shown in Table 1, and these species have approximately the same sensitivities to copper as species in the same families listed in Table 1. For example, Anderson, et al. (1980) report a 10-day value for the midge, Tanytarsus dissimilis, of 16.3 µg/L in soft water. This compares with the 96-hr LC50 of 30 µg/L for Chironomus at a hardness of 50 mg/L (Rehwoldt, et al. 1973). Reported LC50s at 200 hours for chinook salmon and rainbow trout (Chapman, 1978) differ only slightly from 96-hr LC50s reported for these same species in the same water.

Many of the other acute tests in Table 6 were conducted in dilution waters which were known to contain materials which would significantly reduce the toxicity of copper. These reductions were different from those caused by hardness, but not enough data exist to account for these in the derivation of criteria. For example, Lind, et al. (Manuscript) conducted tests with

Daphnia pulicaria and the fathead minnow in waters with concentrations of TOC ranging up to 34 mg/L. Similarly, Brungs, et al. (1976) and Geckler, et al. (1976) conducted tests with many species in stream water which contained a large amount of effluent from a sewage treatment plant. Wallen, et al. (1957) tested mosquitofish in a turbid pond water. Until chemical measurements which correlate well with the toxicity of copper in a wide variety of waters are identified and widely used, results of tests in unusual dilution waters, such as those in Table 6, will not be very useful for deriving water quality criteria.

Table 6 also includes tests based on physiological effects, e.g., changes in growth, appetite, blood parameters, stamina, etc. These were included in Table 6, because they could not be directly interpreted for derivation of criteria. Only avoidance of 0.1 µg/L by rainbow trout fry (Folmar, 1976) appeared to be substantially lower than other acute and chronic effects listed in Tables 1 and 2. Geckler, et al. (1976) also mention avoidance of copper at 120 µg/L as a significant factor in their studies on stream populations. Such results cannot be translated into criteria, because of the paucity of available data and the number of poorly understood factors involved in application of the results, e.g., acclimation, mixing zones, species specificity, etc.

Waiwood and Beamish (1978) studied the effect of copper on growth of rainbow trout at different pHs. Baker, et al. (1983), Hetrick, et al. (1979), and Knittel (1981) found that exposure to copper increased the susceptibility of rainbow trout and chinook salmon to diseases. Ewing, et al. (1982) found little change in the infection rate of channel catfish following sublethal exposure to copper.

Most noteworthy among saltwater organisms are the values reported for the bay scallop, Argopecten irradiens, which suffered mortality and reduced growth when chronically exposed to concentrations of 5 and 5.8 µg/L, respectively (Table 6). Also, the 14-day LC50 of 10 µg/L for Atlantic cod embryos further substantiates that this life stage is particularly sensitive. These results and those from similar studies support the need for a saltwater Final Chronic Value no greater than 2.9 µg/L.

## Unused Data

Some data on the effects of copper on aquatic organisms were not used because the studies were conducted with species that are not resident in North America, e.g., Ahsanullah, et al. (1981), Bougis (1965), Collvin (1984), Cosson and Martin (1981), Heslinga (1976), Karbe (1972), Majori and Petronio (1973), Mishra and Srivastava (1980), Negilski, et al. (1981), Pant, et al. (1980), Saward, et al. (1975), Solbe and Cooper (1976), Verriopoulos and Moraitou-Apostolopoulou (1982), and White and Rainbow (1982). Data were not used if copper was a component of a mixture (Wong, et al. 1982). Reviews by Chapman, et al. (1968), Eisler (1981), Eisler, et al. (1979), Phillips and Russo (1978), Spear and Pierce (1979b), and Thompson et al. (1972) only contain data that have been published elsewhere.

Ferreira (1978), Ferreira, et al. (1979), Leland (1983), Lett, et al. (1976), Ozoh and Jacobson (1979), and Waiwood (1980) investigated effects of copper on various physiological parameters of aquatic animals, but the reports do not contain any interpretable concentration-time relationships useful for deriving criteria. de March (1979) and Wong, et al. (1977) presented no useful data on copper. The results of Riedel (1983) and

Sanders, et al. (1983) were not used because they could not be interpreted in terms of acid-soluble copper.

Papers by Borgmann (1981), Filbin and Hough (1979), Frey, et al. (1978), Gillespie and Vaccaro (1978), Guy and Kean (1980), Jennett, et al. (1982), Maloney and Palmer (1956), Nakajima, et al. (1979), Sunda and Lewis (1978), Swallow, et al. (1978), Van den Berg (1979), and Wagemann and Barica (1979) report on studies of various aspects of copper complexation on uptake, growth inhibition, or toxicity to various algae, bacteria, and plankton. Most of these report data on relative effects, usually in artificial media, and do not contain useable toxicological data for surface waters. Chelating agents were used in the tests by Gavis, et al. (1981), Hawkins and Griffith (1982), Lee and Ku (1984), Reed and Moffat (1983), Rueter, et al. (1981), Schenck (1984), Sullivan, et al. (1983), and Wikfors and Ukeles (1982).

Papers that dealt with the selection, adaptation, or acclimation of organisms for increased resistance to copper were not used, e.g., Fisher (1981), Fisher and Fabris (1982), Hall (1980), Harrison and Lam (1983), Harrison, et al. (1983), Lumaden and Florence (1983), Lumoa, et al. (1983), Myint and Tyler (1982), Neuhoff (1983), Parker (1984), Phelps, et al. (1983), Ray, et al. (1981), Sander (1982), Scarfe, et al. (1982), Schmidt (1978a,b), Sheffrin, et al. (1984), Steele (1983), Viarengo, et al. (1981a,b), and Wood (1983).

Abbe (1982), Bouquegmean and Martoja (1982), Gibbs, et al. (1981), Gordon, et al. (1980), Howard and Brown (1983), Mackey (1983), Martin, et al. (1984), Pophan and D'Auria (1981), Smith, et al. (1981), and Strong and Luoma (1981) did not report sufficient measurements of copper concentrations in water to allow use of their field studies. Finlayson and Ashuckian (1979), Labat, et al. (1977), McIntosh and Kevern (1974), McKnight (1980), and Taylor

(1978) reported the results of various field studies with poorly defined or experimentally confounded exposure conditions. Papers by Baudouin and Scoppa (1974), Dodge and Theis (1979), Evans (1980), Furmanska (1979), Muramoto (1980, 1982), and Verma, et al. (1980) contain too few experimental details to allow interpretation of the results. Bringmann and Kuhn (1982) cultured Daphnia magna in one water and conducted tests in another water. Smith and Heath (1979) only reported results graphically. Shcherban (1977) did not report usable results, and Brkovic-Popovic and Popovic (1977a,b) used questionable dilution water. Data were not used if mortality in the controls was too high (Ho and Zubkoff, 1982; Huilsom, 1983; Watling, 1981, 1982, 1983). High control mortalities occurred in all except one test reported by Sauter, et al. (1976). Control mortality exceeded 10% in one test by Mount and Norberg (1984). The 96-hr values reported by Buikema, et al. (1974a,b) were subject to error because of possible reproductive interactions (Buikema, et al. 1977). Bioconcentration factors could not be calculated from the data of Anderson and Spear (1980a).

## Summary

Acute toxicity data are available for species in 41 genera of freshwater animals. At a hardness of 50 mg/L the genera range in sensitivity from 16.74 µg/L for Ptychocheilus to 10,240 µg/L for Acroneuria. Data for eight species indicate that acute toxicity decreases as hardness increases. Additional data for several species indicate that toxicity also decreases with increases in alkalinity and total organic carbon.

Chronic values are available for fifteen freshwater species and range from 3.873 µg/L for brook trout to 60.36 µg/L for northern pike. Fish and invertebrate species seem to be about equally sensitive to the chronic toxicity of copper.

Toxicity tests have been conducted on copper with a wide range of freshwater plants and the sensitivities are similar to those of animals. Complexing effects of the test media and a lack of good analytical data make interpretation and application of these results difficult. Protection of animal species, however, appears to offer adequate protection of plants. Copper does not appear to bioconcentrate very much in the edible portion of freshwater aquatic species.

The acute sensitivities of saltwater animals to copper range from 5.8 µg/L for the blue mussel to 600 µg/L for the green crab. A chronic life-cycle test has been conducted with a mysid, and adverse effects were observed at 77 µg/L but not at 38 µg/L, which resulted in an acute-chronic ratio of 3.346. Several saltwater algal species have been tested, and effects were observed between 5 and 100 µg/L. Oysters can bioaccumulate copper up to 28,200 times, and become bluish-green, apparently without significant mortality. In long-term exposures, the bay scallop was killed at 5 µg/L.

## National Criteria

The procedures described in the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" indicate that, except possibly where a locally important species is very sensitive, freshwater aquatic organisms and their uses should not be affected unacceptably if the four-day average concentration (in µg/L) of copper does not exceed the numerical value given by $e^{(0.8545[\ln(\text{hardness})]-1.465)}$ more than once every three years on the average and if the one-hour average concentration (in μg/L) does not exceed the numerical value given by $e^{(0.9422[\ln(\text{hardness})]-1.464)}$ more than once every three years on the average. For example, at hardnesses of 50, 100, and 200 mg/L as $CaCO_3$ the four-day average concentrations of copper are 6.5, 12, and 21 μg/L, respectively, and the one-hour average concentrations are 9.2, 18, and 34 ug/L.

The procedures described in the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" indicate that, except possibly where a locally important species is very sensitive, saltwater aquatic organisms and their uses should not be affected unacceptably if the one-hour average concentration of copper does not exceed 2.9 μg/L more than once every three years on the average.

EPA believes that a measurement such as "acid-soluble" would provide a more scientifically correct basis upon which to establish criteria for metals. The criteria were developed on this basis. However, at this time, no EPA approved methods for such a measurement are available to implement the criteria through the regulatory programs of the Agency and the States. The Agency is considering development and approval of methods for a measurement such as "acid-soluble". Until available, however, EPA recommends applying the criteria using the total recoverable method. This has two impacts: (1) certain species of some metals cannot be analyzed directly because the total recoverable method does not distinguish between individual oxidation states, and (2) these criteria may be overly protective when based on the total recoverable method.

The recommended exceedence frequency of three years is the Agency's best scientific judgment of the average amount of time it will take an unstressed system to recover from a pollution event in which exposure to copper exceeds the criterion. Stressed systems, for example, one in which several outfalls occur in a limited area, would be expected to require more time for recovery. The resilience of ecosystems and their ability to recover differ greatly, however, and site-specific criteria may be established if adequate justification is provided.

The use of criteria in developing waste treatment facilities requires the selection of an appropriate wasteload allocation model. Dynamic models are preferred for the application of these criteria. Limited data or other factors may make their use impractical, in which case one should rely on a steady-state model. The Agency recommends the interim use of 1Q5 or 1Q10 for Criterion Maximum Concentration (CMC) design flow and 7Q5 or 7Q10 for the Criterion Continuous Concentration (CCC) design flow in steady-state models for unstressed and stressed systems respectively. These matters are discussed in more detail in the Technical Support Document for Water Quality-Based Toxics Control (U.S. EPA, 1985).

## Table 1. Acute Toxicity of Copper to Aquatic Animals

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| | | | FRESHWATER SPECIES | | | |
| Worm, *Lumbriculus variegatus* | S, U | Copper sulfate | 30 | 150 | 242.7 | Bailey & Liu, 1980 |
| Tubificid worm, *Limnodrilus hoffmeisteri* | S, U | Copper sulfate | 100 | 102 | 53.08 | Wurtz & Bridges, 1961 |
| Worm, *Nais* sp. | S, M | - | 50 | 90 | 90.00 | Rehwoldt, et al. 1973 |
| Snail, *Campeloma decisum* | FT, M | Copper sulfate | 35-55 | 1,700 | 1,877 | Arthur & Leonard, 1970 |
| Snail (embryo), *Amnicola* sp. | S, M | - | 50 | 9,300**** | - | Rehwoldt, et al. 1973 |
| Snail (adult), *Amnicola* sp. | S, M | - | 50 | 900 | 900.0 | Rehwoldt, et al. 1973 |
| Snail, *Goniobasis livescens* | S, M | Copper sulfate | 154 | 590 | - | Paulson, et al. 1983 |
| Snail, *Goniobasis livescens* | S, M | Copper sulfate | 154 | 390 | 166.2 | Paulson, et al. 1983 |
| Snail, *Gyraulus circumstriatus* | S, U | Copper sulfate | 100 | 108 | 56.21 | Wurtz & Bridges, 1961 |
| Snail, *Physa heterostropha* | S, U | Copper sulfate | 100 | 69 | 35.91 | Wurtz & Bridges, 1961 |
| Snail, *Physa integra* | FT, M | Copper sulfate | 35-55 | 39 | 43.07 | Arthur & Leonard, 1970 |
| Asiatic clam, *Corbicula fluminea* | S, U | Copper sulfate | 64 | 40 | - | Rodgers, et al. 1980 |
| Asiatic clam, *Corbicula fluminea* | FT, U | Copper sulfate | 64 | 490 | ***** | Rodgers, et al. 1980 |
| Cladoceran, *Ceriodaphnia reticulata* | S, U | - | 45 | 17 | 18.77 | Mount and Norberg, 1984 |

**Table 1. (Continued)**

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Cladoceran, *Daphnia magna* | S, U | Copper chloride | - | 12.7 | - | Anderson, 1948 |
| Cladoceran, *Daphnia magna* | S, U | Copper sulfate | 226 | 200 | - | Cabejszek & Stasiak, 1960 |
| Cladoceran, *Daphnia magna* | S, U | Copper chloride | 45.3 | 9.8 | - | Biesinger & Christensen, 1972 |
| Cladoceran, *Daphnia magna* | S, U | Copper chloride | 99 | 85 | - | Adema & Degroot-Van Zijl, 1972 |
| Cladoceran, *Daphnia magna* | S, U | Copper chloride | 99 | 50 | - | Adema & Degroot-Van Zijl, 1972 |
| Cladoceran, *Daphnia magna* | S, M | Copper chloride | 52 | 26 | - | Chapman, et al. Manuscript |
| Cladoceran, *Daphnia magna* | S, M | Copper chloride | 105 | 30 | - | Chapman, et al. Manuscript |
| Cladoceran, *Daphnia magna* | S, M | Copper chloride | 106 | 38 | - | Chapman, et al. Manuscript |
| Cladoceran, *Daphnia magna* | S, M | Copper chloride | 207 | 69 | - | Chapman, et al. Manuscript |
| Cladoceran, *Daphnia magna* | S, U | Copper sulfate | 45 | 10 | - | Cairns, et al. 1978 |
| Cladoceran, *Daphnia magna* | S, M | - | 100 | 31.8 | - | Borgmann & Ralph, 1983 |
| Cladoceran, *Daphnia magna* | S, M | Copper oxide | 143 | 26 | - | Lewis, 1983 |
| Cladoceran, *Daphnia magna* | S, U | Copper sulfate | 250 | 6.5[†] | - | Dave, 1984 |
| Cladoceran, *Daphnia magna* | S, U | - | 45 | 54 | 21.17 | Mount & Norberg, 1984 |

**Table 1. (Continued)**

| Species | Method[*] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[**] | Species Mean Acute Value (µg/L)[***] | Reference |
|---|---|---|---|---|---|---|
| Cladoceran, *Daphnia pulex* | S, U | Copper sulfate | 45 | 10 | - | Cairns, et al. 1978 |
| Cladoceran, *Daphnia pulex* | S, U | - | 45 | 53 | 25.42 | Mount & Norberg, 1984 |
| Cladoceran, *Daphnia pulicaria* | S, M | - | 48 | 11.4 | - | Lind, et al. Manuscript |
| Cladoceran, *Daphnia pulicaria* | S, M | - | 48 | 9.06 | - | Lind, et al. Manuscript |
| Cladoceran, *Daphnia pulicaria* | S, M | - | 48 | 7.24 | - | Lind, et al. Manuscript |
| Cladoceran, *Daphnia pulicaria* | S, M | - | 44 | 10.8 | - | Lind, et al. Manuscript |
| Cladoceran, *Daphnia pulicaria* | S, M | - | 45 | 9.3 | - | Lind, et al. Manuscript |
| Cladoceran, *Daphnia pulicaria* | S, M | - | 95 | 17.8 | - | Lind, et al. Manuscript |
| Cladoceran, *Daphnia pulicaria* | S, M | - | 145 | 23.7 | - | Lind, et al. Manuscript |
| Cladoceran, *Daphnia pulicaria* | S, M | - | 245 | 27.3 | 9.263 | Lind, et al. Manuscript |
| Amphipod, *Gammarus pseudolimnaeus* | FT, M | Copper sulfate | 45 | 20 | 22.09 | Arthur & Leonard, 1970 |
| Amphipod, *Gammarus pulex* | R, U | Copper chloride | 104 | 41 | - | Stephenson, 1983 |
| Amphipod, *Gammarus pulex* | R, U | Copper chloride | 249 | 183 | 28.79 | Stephenson, 1983 |
| Amphipod, *Gammarus* sp. | S, M | - | 50 | 910[††] | - | Rehwoldt, et al. 1973 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Crayfish,<br>*Orconectes limosus* | S, M | Copper chloride | - | 600 | - | Boutet & Chaisemartin, 1973 |
| Crayfish,<br>*Orconectes rusticus* | FT, M | Copper sulfate | 100-125 | 3,000 | 1,397 | Hubschman, 1967 |
| Crayfish (larva),<br>*Procambarus clarkii* | FT, M | - | 17 | 720 | 1,990 | Rice & Harrison, 1983 |
| Damselfly,<br>Unidentified | S, M | - | 50 | 4,600 | 4,600 | Rehwoldt, et al. 1973 |
| Stonefly,<br>*Acroneuria lycorias* | S, M | Copper sulfate | 40 | 8,300 | 10,240 | Warnick & Bell, 1969 |
| Caddisfly,<br>Unidentified | S, M | - | 50 | 6,200 | 6,200 | Rehwoldt, et al. 1973 |
| Midge (1st instar),<br>*Chironomus tentans* | FT, M | Copper chloride | 71-84 | 298 | - | Nebeker, et al. 1984a |
| Midge (2nd instar),<br>*Chironomus tentans* | FT, M | Copper chloride | 71-84 | 773**** | - | Nebeker, et al. 1984a |
| Midge (3rd instar),<br>*Chironomus tentans* | FT, M | Copper chloride | 71-84 | 1,446**** | - | Nebeker, et al. 1984a |
| Midge (4th instar),<br>*Chironomus tentans* | FT, M | Copper chloride | 71-84 | 1,690**** | 197.2 | Nebeker, et al. 1984a |
| Midge,<br>*Chironomus* sp. | S, M | Copper sulfate | 50 | 30 | 30.00 | Rehwoldt, et al. 1973 |
| Bryozoan,<br>*Pectinatella magnifica* | S, U | - | 190-220 | 510 | 135.0 | Pardue & Wood, 1980 |
| Bryozoan,<br>*Lophopodella carteri* | S, U | - | 190-220 | 140 | 37.05 | Pardue & Wood, 1980 |
| Bryozoan,<br>*Plumatella emarginata* | S, U | - | 190-220 | 140 | 37.05 | Pardue & Wood, 1980 |
| American eel,<br>*Anguilla rostrata* | S, M | Copper nitrate | 53 | 6,400 | - | Rehwoldt, et al. 1971 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| American eel, *Anguilla rostrata* | S, M | - | 55 | 6,000 | - | Rehwoldt, et al. 1972 |
| American eel (black eel stage), *Anguilla rostrata* | S, U | Copper sulfate | 40-48 | 3,200 | - | Hinton & Eversole, 1979 |
| American eel (glass eel stage), *Anguilla rostrata* | S, U | Copper sulfate | 40-48 | 2,540 | 4,305 | Hinton & Eversole, 1978 |
| Coho salmon (adult), *Oncorhynchus kisutch* | FT, M | Copper chloride | 20 | 46 | - | Chapman & Stevens, 1978 |
| Coho salmon (parr), *Oncorhynchus kisutch* | FT, M | Copper chloride | 23 | 28-38 | - | Chapman, 1975 |
| Coho salmon (adult), *Oncorhynchus kisutch* | FT, M | Copper chloride | 23 | 42.9 | - | Chapman, 1975 |
| Coho salmon (yearling), *Oncorhynchus kisutch* | S, M | Copper chloride | 89-99 | 74 | - | Lorz & McPherson, 1976 |
| Coho salmon (yearling), *Oncorhynchus kisutch* | S, M | Copper chloride | 89-99 | 70 | - | Lorz & McPherson, 1976 |
| Coho salmon (smolt), *Oncorhynchus kisutch* | S, M | Copper chloride | 89-99 | 60 | - | Lorz & McPherson, 1976 |
| Coho salmon (juvenile), *Oncorhynchus kisutch* | R, M | - | 33 | 164 | 70.25 | Buckley, 1983 |
| Sockeye salmon (smolt), *Oncorhynchus nerka* | R, M | Copper chloride | 36-46 | 240 | - | Davis & Shand, 1978 |
| Sockeye salmon (smolt), *Oncorhynchus nerka* | R, M | Copper chloride | 36-46 | 103 | - | Davis & Shand, 1978 |
| Sockeye salmon (fingerling), *Oncorhynchus nerka* | R, M | Copper chloride | 36-46 | 220 | - | Davis & Shand, 1978 |
| Sockeye salmon (fingerling), *Oncorhynchus nerka* | R, M | Copper chloride | 36-46 | 210 | - | Davis & Shand, 1978 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Sockeye salmon (fingerling), *Oncorhynchus nerka* | R, M | Copper chloride | 36-46 | 240 | 233.8 | Davis & Shand, 1978 |
| Chinook salmon (alevin), *Oncorhynchus tshawytscha* | FT, M | Copper chloride | 23 | 26 | - | Chapman, 1975, 1978 |
| Chinook salmon (swim-up), *Oncorhynchus tshawytscha* | FT, M | Copper chloride | 23 | 19 | - | Chapman, 1975, 1978 |
| Chinook salmon (parr), *Oncorhynchus tshawytscha* | FT, M | Copper chloride | 23 | 38 | - | Chapman, 1975, 1978 |
| Chinook salmon (smolt), *Oncorhynchus tshawytscha* | FT, M | Copper chloride | 23 | 26 | - | Chapman, 1975, 1978 |
| Chinook salmon (juvenile), *Oncorhynchus tshawytscha* | FT, M | Copper chloride | 25 | 33.1 | - | Chapman, 1982 |
| Chinook salmon, *Oncorhynchus tshawytscha* | FT, M | - | 13 | 10 | - | Chapman & McCrady, 1977 |
| Chinook salmon, *Oncorhynchus tshawytscha* | FT, M | - | 46 | 22 | - | Chapman & McCrady, 1977 |
| Chinook salmon, *Oncorhynchus tshawytscha* | FT, M | - | 182 | 85 | - | Chapman & McCrady, 1977 |
| Chinook salmon, *Oncorhynchus tshawytscha* | FT, M | - | 359 | 130 | - | Chapman & McCrady, 1977 |
| Chinook salmon, *Oncorhynchus tshawytscha* | FT, M | Copper sulfate | 21 | 32 | 42.26 | Finlayson & Verrue, 1982 |
| Cutthroat trout, *Salmo clarki* | FT, M | Copper chloride | 205 | 367 | - | Chakoumakos, et al. 1979 |
| Cutthroat trout, *Salmo clarki* | FT, M | Copper chloride | 70 | 186 | - | Chakoumakos, et al. 1979 |
| Cutthroat trout, *Salmo clarki* | FT, M | Copper chloride | 18 | 36.8 | - | Chakoumakos, et al. 1979 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Cutthroat trout, *Salmo clarki* | FT, M | Copper chloride | 204 | 232 | - | Chakoumakos, et al. 1979 |
| Cutthroat trout, *Salmo clarki* | FT, M | Copper chloride | 83 | 162 | - | Chakoumakos, et al. 1979 |
| Cutthroat trout, *Salmo clarki* | FT, M | Copper chloride | 31 | 73.6 | - | Chakoumakos, et al. 1979 |
| Cutthroat trout, *Salmo clarki* | FT, M | Copper chloride | 160 | 91 | - | Chakoumakos, et al. 1979 |
| Cutthroat trout, *Salmo clarki* | FT, M | Copper chloride | 74 | 44.4 | - | Chakoumakos, et al. 1979 |
| Cutthroat trout, *Salmo clarki* | FT, M | Copper chloride | 26 | 15.7 | 66.26 | Chakoumakos, et al. 1979 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 30 | 19.9 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 32 | 22.4 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 31 | 28.9 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 31 | 30 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 30 | 30 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 101 | 176 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 101 | 40 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 99 | 33.1 | - | Howarth & Sprague, 1978 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as CaCO$_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 102 | 30.7 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 101 | 46.3 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 99 | 47.9 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 100 | 48.1 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 100 | 81.1 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 98 | 85.9 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 370 | 232 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 366 | 70 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 371 | 82.2 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 361 | 298 | - | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper chloride | 194 | 169 | - | Chakoumakos, et al. 1979 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper chloride | 194 | 85.3 | - | Chakoumakos, et al. 1979 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper chloride | 194 | 83.3 | - | Chakoumakos, et al. 1979 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper chloride | 194 | 103 | - | Chakoumakos, et al. 1979 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Rainbow trout,<br>*Salmo gairdneri* | FT, M | Copper chloride | 194 | 274 | - | Chakoumakos, et al. 1979 |
| Rainbow trout,<br>*Salmo gairdneri* | FT, M | Copper chloride | 194 | 128 | - | Chakoumakos, et al. 1979 |
| Rainbow trout,<br>*Salmo gairdneri* | FT, M | Copper chloride | 194 | 221 | - | Chakoumakos, et al. 1979 |
| Rainbow trout,<br>*Salmo gairdneri* | FT, M | Copper chloride | 194 | 165 | - | Chakoumakos, et al. 1979 |
| Rainbow trout,<br>*Salmo gairdneri* | FT, M | Copper chloride | 194 | 197 | - | Chakoumakos, et al. 1979 |
| Rainbow trout,<br>*Salmo gairdneri* | FT, M | Copper chloride | 194 | 514 | - | Chakoumakos, et al. 1979 |
| Rainbow trout,<br>*Salmo gairdneri* | FT, M | Copper chloride | 194 | 243 | - | Chakoumakos, et al. 1979 |
| Rainbow trout (alevin),<br>*Salmo gairdneri* | FT, M | Copper chloride | 23 | 28 | - | Chapman, 1975, 1978 |
| Rainbow trout (swim-up),<br>*Salmo gairdneri* | FT, M | Copper chloride | 23 | 17 | - | Chapman, 1975, 1978 |
| Rainbow trout (parr),<br>*Salmo gairdneri* | FT, M | Copper chloride | 23 | 18 | - | Chapman, 1975, 1978 |
| Rainbow trout (smolt),<br>*Salmo gairdneri* | FT, M | Copper chloride | 23 | 29 | - | Chapman, 1975, 1978 |
| Rainbow trout (adult),<br>*Salmo gairdneri* | FT, M | Copper chloride | 42 | 57 | - | Chapman, 1975; Chapmar & Stevens, 1978 |
| Rainbow trout (fry),<br>*Salmo gairdneri* | FT, M | Copper nitrate | - | 253 | - | Hale, 1977 |
| Rainbow trout,<br>*Salmo gairdneri* | FT, M | Copper sulfate | 125 | 200 | - | Spear, 1977; Anderson & Spear, 1980b |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 125 | 190 | - | Spear, 1977; Anderson & Spear, 1980b |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper sulfate | 125 | 210 | - | Spear, 1977; Anderson & Spear, 1980b |
| Rainbow trout, *Salmo gairdneri* | S, M | Copper sulfate | 290 | 890 | - | Calamari & Marchetti, 1973 |
| Rainbow trout, *Salmo gairdneri* | - | - | 90 | 190 | - | Giles & Klaverkamp, 1982 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Copper chloride | 120 | 80 | 42.50 | Seim, et al. 1984 |
| Atlantic salmon, *Salmo salar* | FT, M | Copper sulfate | 20 | 48 | - | Sprague, 1964 |
| Atlantic salmon, *Salmo salar* | S, M | - | 8-10 | 125 | - | Wilson, 1972 |
| Atlantic salmon, *Salmo salar* | FT, M | - | 14 | 32 | 196.6 | Sprague & Ramsey, 1965 |
| Brook trout, *Salvelinus fontinalis* | FT, M | Copper sulfate | 45 | 100 | 110.4 | McKim & Benoit, 1971 |
| Chiselmouth, *Acrocheilus alutaceus* | FT, M | Copper chloride | 52-56 | 143 | 133.0 | Andros & Garton, 1980 |
| Central stoneroller, *Campostoma anomalum* | FT, M | Copper sulfate | 200 | 290 | 78.55 | Geckler, et al. 1976 |
| Goldfish, *Carassius auratus* | S, U | Copper sulfate | 20 | 36 | - | Pickering & Henderson, 1966 |
| Goldfish, *Carassius auratus* | FT, M | Copper sulfate | 52 | 300 | 157.1 | Tsai & McKee, 1978, 1980 |
| Common carp, *Cyprinus carpio* | S, M | Copper nitrate | 53 | 810†† | - | Rehwoldt, et al. 1971 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Common carp, *Cyprinus carpio* | S, M | - | 55 | 800†† | - | Rehwoldt, et al. 1972 |
| Common carp (140 mg), *Cyprinus carpio* | S, U | Copper sulfate | 144-188 | 117.5††† | - | Deshmukh & Marathe, 1980 |
| Common carp (3200 mg), *Cyprinus carpio* | S, U | Copper sulfate | 144-188 | 530††† | - | Deshmukh & Marathe, 1980 |
| Common carp, *Cyprinus carpio* | R, U | Copper sulfate | 19 | 63 | 156.8 | Khangarot, et al. 1983 |
| Striped shiner, *Notropis chrysocephalus* | FT, M | Copper sulfate | 200 | 790 | - | Geckler, et al. 1976 |
| Striped shiner, *Notropis chrysocephalus* | FT, M | Copper sulfate | 200 | 1,900 | 331.8 | Geckler, et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | FT, M | Copper sulfate | 200 | 290 | - | Geckler, et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | FT, M | Copper sulfate | 200 | 260 | - | Geckler, et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | FT, M | Copper sulfate | 200 | 260 | - | Geckler, et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | FT, M | Copper sulfate | 200 | 280 | - | Geckler, et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | FT, M | Copper sulfate | 200 | 340 | - | Geckler, et al. 1976 |
| Bluntnose minnow, *Pimephales notatus* | FT, M | Copper sulfate | 194 | 210 | - | Horning & Neiheisel, 1979 |
| Bluntnose minnow, *Pimephales notatus* | FT, M | Copper sulfate | 194 | 220 | - | Horning & Neiheisel, 1979 |
| Bluntnose minnow, *Pimephales notatus* | FT, M | Copper sulfate | 194 | 270 | 72.16 | Horning & Neiheisel, 1979 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Fathead minnow, *Pimephales promelas* | S, U | Copper sulfate | 20 | 50 | - | Tarzwell & Henderson, 1960 |
| Fathead minnow, *Pimephales promelas* | S, U | Copper sulfate | 400 | 1,400 | - | Tarzwell & Henderson, 1960 |
| Fathead minnow, *Pimephales promelas* | FT, M | Copper sulfate | 202 | 460 | - | Pickering, et al. 1977 |
| Fathead minnow, *Pimephales promelas* | FT, M | Copper sulfate | 202 | 490 | - | Pickering, et al. 1977 |
| Fathead minnow, *Pimephales promelas* | FT, M | - | 200 | 790 | - | Andrew, 1976 |
| Fathead minnow, *Pimephales promelas* | FT, M | - | 45 | 200 | - | Andrew, 1976 |
| Fathead minnow, *Pimephales promelas* | S, U | Copper sulfate | 20 | 25 | - | Pickering & Henderson, 1966 |
| Fathead minnow, *Pimephales promelas* | S, U | Copper sulfate | 20 | 23 | - | Pickering & Henderson, 1966 |
| Fathead minnow, *Pimephales promelas* | S, U | Copper sulfate | 20 | 23 | - | Pickering & Henderson, 1966 |
| Fathead minnow, *Pimephales promelas* | S, U | Copper sulfate | 20 | 22 | - | Pickering & Henderson, 1966 |
| Fathead minnow, *Pimephales promelas* | S, U | Copper sulfate | 360 | 1,760 | - | Pickering & Henderson, 1966 |
| Fathead minnow, *Pimephales promelas* | S, U | Copper sulfate | 360 | 1,140 | - | Pickering & Henderson, 1966 |
| Fathead minnow, *Pimephales promelas* | S, U | Copper sulfate | 200 | 430 | - | Mount, 1968 |
| Fathead minnow, *Pimephales promelas* | FT, M | Copper sulfate | 200 | 470 | - | Mount, 1968 |

**Table 1. (Continued)**

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Fathead minnow, *Pimephales promelas* | S, U | Copper sulfate | 31 | 84 | - | Mount & Stephan, 1969 |
| Fathead minnow, *Pimephales promelas* | FT, M | Copper sulfate | 31 | 75 | - | Mount & Stephan, 1969 |
| Fathead minnow, *Pimephales promelas* | FT, M | Copper sulfate | 200 | 440 | - | Geckler, et al. 1976 |
| Fathead minnow, *Pimephales promelas* | FT, M | Copper sulfate | 200 | 490 | - | Geckler, et al. 1976 |
| Fathead minnow, *Pimephales promelas* | FT, M | - | 48 | 114 | - | Lind, et al. Manuscript |
| Fathead minnow, *Pimephales promelas* | FT, M | - | 45 | 121 | - | Lind, et al. Manuscript |
| Fathead minnow, *Pimephales promelas* | FT, M | - | 46 | 88.5 | - | Lind, et al. Manuscript |
| Fathead minnow (adult), *Pimephales promelas* | S, M | Copper sulfate | 103 | 210 | - | Birge, et al. 1983 |
| Fathead minnow (adult), *Pimephales promelas* | S, M | Copper sulfate | 103 | 310 | - | Birge, et al. 1983 |
| Fathead minnow (adult), *Pimephales promelas* | S, M | Copper sulfate | 103 | 120 | - | Birge, et al. 1983 |
| Fathead minnow (adult), *Pimephales promelas* | S, M | Copper sulfate | 254-271 | 390 | 115.5 | Birge, et al. 1983 |
| Northern squawfish, *Ptychocheilus oregonensis* | FT, M | Copper chloride | 52-56 | 18 | 16.74 | Andros & Garton, 1980 |
| Blacknose dace, *Rhinichthys atratulus* | FT, M | Copper sulfate | 200 | 320 | 86.67 | Geckler, et al. 1976 |
| Creek chub, *Semotilus atromaculatus* | FT, M | Copper sulfate | 200 | 310 | 83.97 | Geckler, et al. 1976 |
| Brown bullhead, *Ictalurus nebulosus* | FT, M | Copper sulfate | 202 | 170 | - | Brungs, et al. 1973 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Brown bullhead, Ictalurus nebulosus | FT, M | Copper sulfate | 202 | 190 | - | Brungs, et al. 1973 |
| Brown bullhead, Ictalurus nebulosus | FT, M | Copper sulfate | 200 | 540 | 69.81 | Geckler, et al. 1976 |
| Banded killifish, Fundulus diaphanus | S, M | Copper nitrate | 53 | 860 | - | Rehwoldt, et al. 1971 |
| Banded killifish, Fundulus diaphanus | S, M | - | 55 | 840 | 790.6 | Rehwoldt, et al. 1972 |
| Mosquitofish (female), Gambusia affinis | S, U | Copper nitrate | 27-41 | 93 | - | Joski & Rege, 1980 |
| Mosquitofish (female), Gambusia affinis | S, U | Copper sulfate | 27-41 | 200 | 196.1 | Joski & Rege, 1980 |
| Guppy, Poecilia reticulata | S, U | Copper sulfate | 20 | 36 | - | Chynoweth, et al. 1976 |
| Guppy, Poecilia reticulata | FT, M | - | 87.5 | 112 | - | Black, 1974;<br>Chynoweth, et al. 1976 |
| Guppy, Poecilia reticulata | FT, M | - | 67.2 | 138 | - | Black, 1974;<br>Chynoweth, et al. 1976 |
| Guppy (6.5 mg), Poecilia reticulata | R, U | Copper sulfate | 144-188 | 160††† | - | Deshmukh & Marathe, 1980 |
| Guppy (63 mg; female), Poecilia reticulata | R, U | Copper sulfate | 144-188 | 275††† | - | Deshmukh & Marathe, 1980 |
| Guppy (60 mg; male), Poecilia reticulata | R, U | Copper sulfate | 144-188 | 210††† | - | Deshmukh & Marathe, 1980 |
| Guppy (340 mg; female), Poecilia reticulata | R, U | Copper sulfate | 144-188 | 480††† | - | Deshmukh & Marathe, 1980 |
| Guppy, Poecilia reticulata | S, U | Copper sulfate | 230 | 1,230 | - | Khangarot, 1981 |
| Guppy, Poecilia reticulata | S, U | Copper sulfate | 240 | 764 | 124.6 | Khangarot, et al. 1981b |

**Table 1. (Continued)**

| Species | Method[*] | Chemical | Hardness (mg/L as CaCO$_3$) | LC50 or EC50 (µg/L)[**] | Species Mean Acute Value (µg/L)[***] | Reference |
|---|---|---|---|---|---|---|
| White perch, *Morone americana* | S, M | Copper nitrate | 53 | 6,200 | - | Rehwoldt, et al. 1971 |
| White perch, *Morone americana* | S, M | - | 55 | 6,400 | 5,860 | Rehwoldt, et al. 1971 |
| Striped bass, *Morone saxatilis* | S, M | Copper nitrate | 53 | 4,300[††] | - | Rehwoldt, et al. 1971 |
| Striped bass, *Morone saxatilis* | S, M | - | 55 | 4,000[††] | - | Rehwoldt, et al. 1972 |
| Striped bass, *Morone saxatilis* | S, U | Copper sulfate | 35 | 620 | - | Wellborn, 1969 |
| Striped bass (larva), *Morone saxatilis* | S, U | Copper chloride | 34.5 | 50 | - | Hughes, 1973 |
| Striped bass (fingerling), *Morone saxatilis* | S, U | Copper chloride | 34.5 | 50 | - | Hughes, 1973 |
| Stripped bass (larva), *Morone saxatilis* | S, U | Copper sulfate | 34.5 | 25 | - | Hughes, 1973 |
| Striped bass (fingerling), *Morone saxatilis* | S, U | Copper sulfate | 34.5 | 38 | ***** | Hughes, 1973 |
| Pumpkinseed, *Lepomis gibbosus* | S, M | Copper nitrate | 53 | 2,400[††] | - | Rehwoldt, et al. 1971 |
| Pumpkinseed, *Lepomis gibbosus* | S, M | - | 55 | 2,700[††] | - | Rehwoldt, et al. 1972 |
| Pumpkinseed, *Lepomis gibbosus* | FT, M | Copper sulfate | 125 | 1,240 | - | Spear, 1977; Anderson & Spear, 1980b |
| Pumpkinseed, *Lepomis gibbosus* | FT, M | Copper sulfate | 125 | 1,300 | - | Spear, 1977; Anderson & Spear, 1980b |
| Pumpkinseed, *Lepomis gibbosus* | FT, M | Copper sulfate | 125 | 1,670 | - | Spear, 1977; Anderson & Spear, 1980b |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Pumpkinseed, *Lepomis gibbosus* | FT, M | Copper sulfate | 125 | 1,940 | - | Spear, 1977; Anderson & Spear, 1980b |
| Pumpkinseed, *Lepomis gibbosus* | FT, M | Copper sulfate | 125 | 1,240 | - | Spear, 1977; Anderson & Spear, 1980b |
| Pumpkinseed, *Lepomis gibbosus* | FT, M | Copper sulfate | 125 | 1,660 | - | Spear, 1977; Anderson & Spear, 1980b |
| Pumpkinseed, *Lepomis gibbosus* | FT, M | Copper sulfate | 125 | 1,740 | 640.9 | Spear, 1977; Anderson & Spear, 1980b |
| Bluegill, *Lepomis macrochirus* | S, U | Copper sulfate | 52 | 400 | - | Inglis & Davis, 1972 |
| Bluegill, *Lepomis macrochirus* | S, U | Copper sulfate | 209 | 680 | - | Inglis & Davis, 1972 |
| Bluegill, *Lepomis macrochirus* | S, U | Copper sulfate | 365 | 1,020 | - | Inglis & Davis, 1972 |
| Bluegill, *Lepomis macrochirus* | FT, M | Copper sulfate | 45 | 1,100 | - | Benoit, 1975 |
| Bluegill, *Lepomis macrochirus* | FT, M | Copper sulfate | 200 | 8,300 | - | Geckler, et al. 1976 |
| Bluegill, *Lepomis macrochirus* | FT, M | Copper sulfate | 200 | 10,000 | - | Geckler, et al. 1976 |
| Bluegill, *Lepomis macrochirus* | S, U | Copper sulfate | 20 | 200 | - | Tarzwell & Henderson, 1960 |
| Bluegill, *Lepomis macrochirus* | S, U | Copper sulfate | 400 | 10,000 | - | Tarzwell & Henderson, 1960 |
| Bluegill, *Lepomis macrochirus* | S, U | Copper sulfate | 43 | 770 | - | Academy of Natural Sciences, 1960 |
| Bluegill, *Lepomis macrochirus* | S, U | Copper chloride | 43 | 1,250 | - | Academy of Natural Sciences, 1960; Patrick, et al. 1968; Cairns & Scheier, 1968 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Bluegill, *Lepomis macrochirus* | S, U | Copper sulfate | 20 | 660 | - | Pickering & Henderson, 1966 |
| Bluegill, *Lepomis macrochirus* | S, U | Copper sulfate | 360 | 10,200 | - | Pickering & Henderson, 1966 |
| Bluegill, *Lepomis macrochirus* | FT, M | Copper sulfate | 35 | 2,400 | - | O'Hara, 1971 |
| Bluegill, *Lepomis macrochirus* | FT, M | Copper chloride | 40 | 1,000 | - | Thompson, et al. 1980 |
| Bluegill, *Lepomis macrochirus* | FT, M | Copper chloride | 26 | 1,000 | 1,017 | Cairns, et al. 1981 |
| Rainbow darter, *Etheostoma caeruleum* | FT, M | Copper sulfate | 200 | 320 | 86.67 | Geckler, et al. 1976 |
| Orangethroat darter, *Etheostoma spectabile* | FT, M | Copper sulfate | 200 | 850 | 230.2 | Geckler, et al. 1976 |
| Mozambique tilapia, *Tilapia mossambica* | S, U | Copper sulfate | 115 | 1,500 | 684.3 | Qureshi & Saksena, 1980 |
| | | | SALTWATER SPECIES | | | |
| Polychaete worm, *Phyllodoce maculata* | S, U | Copper sulfate | - | 120 | 120 | McLusky & Phillips, 1975 |
| Polychaete worm, *Neanthes arenaceodentata* | FT, M | Copper nitrate | - | 77 | - | Pesch & Morgan, 1978 |
| Polychaete worm, *Neanthes arenaceodentata* | FT, M | Copper nitrate | - | 200 | - | Pesch & Morgan, 1978 |
| Polychaete worm, *Neanthes arenaceodentata* | FT, M | Copper nitrate | - | 222 | 150.6 | Pesch & Hoffman, 1982 |
| Polychaete worm, *Nereis diversicolor* | S, U | Copper sulfate | - | 200 | - | Jones, et al. 1976 |
| Polychaete worm, *Nereis diversicolor* | S, U | Copper sulfate | - | 445 | - | Jones, et al. 1976 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Polychaete worm, *Nereis diversicolor* | S, U | Copper sulfate | - | 480 | - | Jones, et al. 1976 |
| Polychaete worm, *Nereis diversicolor* | S, U | Copper sulfate | - | 410 | 363.8 | Jones, et al. 1976 |
| Black abalone, *Haliotis cracherodii* | S, U | Copper sulfate | - | 50 | 50 | Martin, et al. 1977 |
| Red abalone, *Haliotis rufescens* | S, U | Copper sulfate | - | 65 | - | Martin, et al. 1977 |
| Red abalone (larva), *Haliotis rufescens* | S, U | Copper sulfate | - | 114 | 86.08 | Martin, et al. 1977 |
| Blue mussel (embryo), *Mytilus edulis* | S, U | Copper sulfate | - | 5.8 | 5.8 | Martin, et al. 1981 |
| Pacific oyster (embryo), *Crassostrea gigas* | S, U | Copper sulfate | - | 5.3 | - | Martin, et al. 1981 |
| Pacific oyster (embryo), *Crassostrea gigas* | S, U | Copper sulfate | - | 11.5 | - | Coglianese & Martin, 1981 |
| Pacific oyster (adult), *Crassostrea gigas* | FT, M | Copper sulfate | - | 560**** | 7.807 | Okazaki, 1976 |
| Eastern oyster (embryo), *Crassostrea virginica* | S, U | Copper chloride | - | 128 | - | Calabrese, et al. 1973 |
| Eastern oyster (embryo), *Crassostrea virginica* | S, U | Copper chloride | - | 15.1 | - | MacInnes & Calabrese, 1978 |
| Eastern oyster (embryo), *Crassostrea virginica* | S, U | Copper chloride | - | 18.7 | - | MacInnes & Calabrese, 1978 |
| Eastern oyster (embryo), *Crassostrea virginica* | S, U | Copper chloride | - | 18.3 | 28.52 | MacInnes & Calabrese, 1978 |
| Common rangia, *Rangia cuneata* | S, U | - | - | 8,000 | - | Olson & Harrel, 1973 |
| Common rangia, *Rangia cuneata* | S, U | - | - | 7,400 | 7,694 | Olson & Harrel, 1973 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Soft-shell clam, *Mya arenaria* | S, U | Copper chloride | - | 39 | 39 | Eisler, 1977 |
| Copepod, *Pseudodiaptomus coronatus* | S, U | Copper chloride | - | 138 | 138 | Gentile, 1982 |
| Copepod, *Eurytemora affinis* | S, U | Copper chloride | - | 526 | 526 | Gentile, 1982 |
| Copepod, *Acartia clausi* | S, U | Copper chloride | - | 52 | 52 | Gentile, 1982 |
| Copepod, *Acartia tonsa* | S, U | Copper chloride | - | 17 | - | Sosnowski & Gentile, 1978 |
| Copepod, *Acartia tonsa* | S, U | Copper chloride | - | 55 | - | Sosnowski & Gentile, 1978 |
| Copepod, *Acartia tonsa* | S, U | Copper chloride | - | 31 | 30.72 | Sosnowski & Gentile, 1978 |
| Mysid, *Mysidopsis bahia* | FT, M | Copper nitrate | - | 181 | 181 | Lussier, et al. Manuscript |
| Mysid, *Mysidopsis bigelowi* | FT, M | Copper nitrate | - | 141 | 141 | Gentile, 1982 |
| American lobster (larva), *Homarus americanus* | S, U | Copper nitrate | - | 48 | - | Johnson & Gentile, 1979 |
| American lobster (adult), *Homarus americanus* | S, U | Copper sulfate | - | 100 | 69.28 | McLeese, 1974 |
| Dungeness crab (larva), *Cancer magister* | S, U | Copper sulfate | - | 49 | 49 | Martin, et al. 1981 |
| Green crab (larva), *Carcinus maenas* | S, U | Copper sulfate | - | 600 | 600 | Connor, 1972 |
| Sheepshead minnow, *Cyprinodon variegatus* | S, U | Copper nitrate | - | 280 | 280 | Hansen, 1983 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Atlantic silverside (larva), *Menidia menidia* | FT, M | Copper nitrate | - | 66.6 | - | Cardin, 1982 |
| Atlantic silverside (larva), *Menidia menidia* | FT, M | Copper nitrate | - | 216.5 | - | Cardin, 1982 |
| Atlantic silverside (larva), *Menidia menidia* | FT, M | Copper nitrate | - | 101.8 | - | Cardin, 1982 |
| Atlantic silverside (larva), *Menidia menidia* | FT, M | Copper nitrate | - | 97.6 | - | Cardin, 1982 |
| Atlantic silverside (larva), *Menidia menidia* | FT, M | Copper nitrate | - | 155.9 | - | Cardin, 1982 |
| Atlantic silverside (larva), *Menidia menidia* | FT, M | Copper nitrate | - | 197.6 | - | Cardin, 1982 |
| Atlantic silverside (larva), *Menidia menidia* | FT, M | Copper nitrate | - | 190.9 | 135.6 | Cardin, 1982 |
| Tidewater silverside, *Menidia peninsulae* | S, U | Copper nitrate | - | 140 | 140 | Hansen, 1983 |
| Florida pompano, *Trachinotus carolinus* | S, U | Copper sulfate | - | 360 | - | Birdsong & Avavit, 1971 |
| Florida pompano, *Trachinotus carolinus* | S, U | Copper sulfate | - | 380 | - | Birdsong & Avavit, 1971 |
| Florida pompano, *Trachinotus carolinus* | S, U | Copper sulfate | - | 510 | 411.7 | Birdsong & Avavit, 1971 |
| Summer flounder (early cleavage embryo), *Paralichthys dentatus* | FT, M | Copper nitrate | - | 16.3 | - | Cardin, 1982 |
| Summer flounder (early cleavage embryo), *Paralichthys dentatus* | FT, M | Copper nitrate | - | 11.9 | - | Cardin, 1982 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L)*** | Reference |
|---|---|---|---|---|---|---|
| Summer flounder (blastula stage embryo), *Paralichthys dentatus* | FT, M | Copper chloride | - | 111.8**** | 13.93 | Cardin, 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | FT, M | Copper nitrate | - | 77.5 | - | Cardin, 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | FT, M | Copper nitrate | - | 167.3 | - | Cardin, 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | FT, M | Copper nitrate | - | 52.7 | - | Cardin, 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | FT, M | Copper nitrate | - | 158.0 | - | Cardin, 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | FT, M | Copper chloride | - | 173.7 | - | Cardin, 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | FT, M | Copper nitrate | - | 271.0 | - | Cardin, 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | FT, M | Copper chloride | - | 132.8 | - | Cardin, 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | FT, M | Copper nitrate | - | 148.2 | - | Cardin, 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | FT, M | Copper nitrate | - | 98.2 | 128.9 | Cardin, 1982 |

Table 1. (Continued)

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* S = static, FT = flow-through, R = renewal, U = unmeasured, M = measured.

** Results are expressed as copper, not as the chemical.

*** Freshwater Species Mean Acute Values are calculated at a hardness of 50 mg/L using the pooled slope.

**** Not used in calculation of Species Mean Acute Value because data are available for a more sensitive life stage.

***** No Species Mean Acute Value calculated because acute values are too divergent for this species.

† Not used in calculations (see text).

†† Not used in calculations because Rehwoldt, et al. (1971, 1972, 1973) obtained values that appear to be higher than appropriate for a number of species (see text).

††† Not used in calculations because of wide range in hardness.

**Results of Covariance Analysis of Freshwater Acute Toxicity versus Hardness**

| Species | n | Slope | 95% Confidence Limits | Degrees of Freedom |
|---|---|---|---|---|
| *Daphnia magna* | 13 | 0.4666 | -0.5141, 1.4474 | 11 |
| *Daphnia magna* except value from Dave (1984) | 12 | 1.0438 | 0.2906, 1.7970 | 10 |
| *Daphnia pulicaria* | 8 | 0.6952 | 0.4480, 0.9424 | 6 |
| Chinook salmon | 10 | 0.6092 | 0.3530, 0.8654 | 8 |
| Cutthroat trout | 9 | 0.8766 | 0.2560, 1.4972 | 7 |
| Rainbow trout | 40 | 0.8889 | 0.6520, 1.1258 | 38 |
| Fathead minnow | 25 | 1.1949 | 1.0455, 1.3444 | 23 |
| Guppy | 5 | 1.3639 | 0.6289, 2.0990 | 3 |
| Bluegill | 15 | 0.7776 | 0.2848, 1.2703 | 13 |
| All of above | 125 | 0.9177[†] | 0.7886, 1.0468 | 116 |
| All of above except value from Dave (1984) | 124 | 0.9422[††] | 0.8209, 1.0635 | 115 |

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[†] p=0.09 for equality of slopes.

[††] p=0.11 for equality of slopes.

## Table 2. Chronic Toxicity of Copper to Aquatic Animals

| Species | Test* | Chemical | Hardness (mg/L as $CaCO_3$) | Limits (µg/L)** | Chronic Value (µg/L)** | Reference |
|---|---|---|---|---|---|---|
| | | | FRESHWATER SPECIES | | | |
| Snail, *Campeloma decisum* | LC | Copper sulfate | 35-55 | 8-14.8 | 10.88 | Arthur & Leonard, 1970 |
| Snail, *Physa integra* | LC | Copper sulfate | 35-55 | 8-14.8 | 10.88 | Arthur & Leonard, 1970 |
| Cladoceran, *Daphnia magna* | LC | Copper chloride | 51 | 11.4-16.3 | 13.63 | Chapman, et al. Manuscript |
| Cladoceran, *Daphnia magna* | LC | Copper chloride | 104 | 20-43 | 29.33 | Chapman, et al. Manuscript |
| Cladoceran, *Daphnia magna* | LC | Copper chloride | 211 | 7.2-12.6 | 9.525 | Chapman, et al. Manuscript |
| Amphipod, *Gammarus pseudolimnaeus* | LC | Copper sulfate | 45 | 4.6-8 | 6.066 | Arthur & Leonard, 1970 |
| Caddisfly, *Clistornia magnifica* | LC | Copper chloride | 26 | 8.3-13 | 10.39 | Nebeker, et al. 1984 |
| Chinook salmon, *Oncorhynchus tshawytscha* | ELS | Copper chloride | 23 | <7.4*** | <7.4 | Chapman, 1975, 1982 |
| Rainbow trout, *Salmo gairdneri* | ELS | Copper sulfate | 45.4 | 11.4-31.7 | 19.01 | McKim, et al. 1978 |
| Brown trout, *Salmo trutta* | ELS | Copper sulfate | 45.4 | 22.0-43.2 | 30.83 | McKim, et al. 1978 |
| Brook trout, *Salvelinus fontinalis* | LC | Copper sulfate | 45 | 9.5-17.4 | 12.86 | McKim & Benoit, 1971 |
| Brook trout, *Salvelinus fontinalis* | ELS | Copper sulfate | 45.4 | 22.3-43.5 | 31.15 | McKim, et al. 1978 |
| Brook trout, *Salvelinus fontinalis* | ELS | Copper sulfate | 37.5 | 3-5 | 3.873 | Sauter, et al. 1976 |
| Lake trout, *Salvelinus namaycush* | ELS | Copper sulfate | 45.4 | 22.0-42.3 | 30.51 | McKim, et al. 1978 |

**Table 2. (Continued)**

| Species | Test* | Chemical | Hardness (mg/L as $CaCO_3$) | Limits (µg/L)** | Chronic Value (µg/L)** | Reference |
|---|---|---|---|---|---|---|
| Northern pike, <br> *Esox lucius* | ELS | Copper sulfate | 45.4 | 34.9-104.4 | 60.36 | McKim, et al. 1978 |
| Bluntnose minnow, <br> *Pimephales notatus* | LC | Copper sulfate | 194 | 4.3-18 | 8.798 | Horning & Neiheisel, 1979 |
| Fathead minnow, <br> *Pimephales promelas* | LC | Copper sulfate | 198 | 14.5-33 | 21.87 | Mount, 1968 |
| Fathead minnow, <br> *Pimephales promelas* | LC | Copper sulfate | 30 | 10.6-18.4 | 13.97 | Mount & Stephan, 1969 |
| Fathead minnow, <br> *Pimephales promelas* | LC | Copper sulfate | 200 | 24-32 | 27.71 | Pickering, et al. 1977 |
| Fathead minnow, <br> *Pimephales promelas* | ELS | - | 45 | 13.1-26.2 | 18.53 | Lind, et al. Manuscript |
| White sucker, <br> *Catostomus commersoni* | ELS | Copper sulfate | 45.4 | 12.9-33.8 | 20.88 | McKim, et al. 1978 |
| Bluegill, <br> *Lepomis macrochirus* | LC | Copper sulfate | 45 | 21-40 | 28.98 | Benoit, 1975 |
| | | | SALTWATER SPECIES | | | |
| Mysid, <br> *Mysidopsis bahia* | LC | Copper nitrate | - | 38-77 | 54.09 | Lussier, et al. Manuscript |

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* LC = life cycle or partial life cycle; ELS = early life stage.

** Results are expressed as copper, not as the chemical.

***Adverse effects occurred at all concentrations tested.

**Results of Regression Analysis of Freshwater Chronic Toxicity versus Hardness**

| Species | n | Slope | 95% Confidence Limits | Degrees of Freedom |
|---|---|---|---|---|
| *Daphnia magna* | 3 | -0.2508 | -10.03, 9.53 | 1 |
| Fathead minnow | 4 | 0.2646 | -0.10, 0.63 | 2 |

Table 2. (Continued)

## Acute-Chronic Ratios

| Species | Hardness (mg/L as $CaCO_3$) | Acute Value (µg/L) | Chronic Value (µg/L) | Ratio |
|---|---|---|---|---|
| Snail, *Campeloma decisum* | 35-55 | 1,700 | 10.88 | 156.2 |
| Snail, *Physa integra* | 35-55 | 39 | 10.88 | 3.585 |
| Cladoceran, *Daphnia magna* | 51-52 | 26 | 13.63 | 1.908 |
| Cladoceran, *Daphnia magna* | 104-105 | 30 | 29.33 | 1.023 |
| Cladoceran, *Daphnia magna* | 207-211 | 69 | 9.525 | 7.244 |
| Amphipod, *Gammarus pseudolimnaeus* | 35-55 | 20 | 6.066 | 3.297 |
| Chinook salmon, *Oncorhynchus tshawytscha* | 23-25 | 33.1 | <7.4 | >4.473 |
| Brook trout, *Salvelinus fontinalis* | 45 | 100 | 12.86 | 7.776 |
| Bluntnose minnow, *Pimephales notatus* | 194 | 231.9* | 8.798 | 26.36 |
| Fathead minnow, *Pimephales promelas* | 198-200 | 470 | 21.87 | 21.49 |
| Fathead minnow, *Pimephales promelas* | 30-31 | 75 | 13.97 | 5.369 |
| Fathead minnow, *Pimephales promelas* | 200 | 474.8** | 27.71 | 17.13 |
| Fathead minnow, *Pimephales promelas* | 45-48 | 106.9*** | 18.53 | 5.769 |
| Bluegill, *Lepomis macrochirus* | 45 | 1,100 | 28.98 | 37.96 |
| Mysid, *Mysidopsis bahia* | - | 181 | 54.09 | 3.346 |

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* Geometric mean of three values from Horning and Neiheisel (1979) in Table 1.

** Geometric mean of two values from Pickering, et al. (1977) in Table 1.

***Geometric mean of three values from Lind, et al. (Manuscript) in Table 1.

Table 3. Ranked Genus Mean Acute Values with Species Mean Acute-Chronic Ratios

| Rank* | Genus Mean Acute Value (µg/L)** | Species | Species Mean Acute Value (µg/L)** | Species Mean Acute-Chronic Ratio |
|---|---|---|---|---|
| | | FRESHWATER SPECIES | | |
| 41 | 10,240 | Stonefly,<br>*Acroneuria lycorias* | 10,240 | - |
| 40 | 6,200 | Caddisfly,<br>Unidentified | 6,200 | - |
| 39 | 5,860 | White perch,<br>*Morone americanus* | 5,860 | - |
| 38 | 4,600 | Damselfly,<br>Unidentified | 4,600 | - |
| 37 | 4,305 | American eel,<br>*Anguilla rostrata* | 4,305 | - |
| 36 | 1,990 | Crayfish,<br>*Procambarus clarkii* | 1,990 | - |
| 35 | 1,877 | Snail,<br>*Campeloma decisum* | 1,877 | 156.2 |
| 34 | 1,397 | Crayfish,<br>*Orconectes rusticus* | 1,397 | - |
| 33 | 900.0 | Snail,<br>*Amnicola* sp. | 900.0 | - |
| 32 | 807.3 | Pumpkinseed,<br>*Lepomis gibbosus* | 640.9 | - |
| | | Bluegill,<br>*Lepomis macrochirus* | 1,017 | 37.96 |
| 31 | 790.6 | Banded killifish,<br>*Fundulus diaphanus* | 790.6 | - |
| 30 | 684.3 | Mozambique tilapia,<br>*Tilapia mossambica* | 684.3 | - |

Table 3. (Continued)

| Rank* | Genus Mean Acute Value (µg/L)** | Species | Species Mean Acute Value (µg/L)** | Species Mean Acute-Chronic Ratio |
|---|---|---|---|---|
| 29 | 331.8 | Striped shiner, *Notropis chrysocephalus* | 331.8 | - |
| 28 | 242.7 | Worm, *Lumbriculus variegatus* | 242.7 | - |
| 27 | 196.1 | Mosquitofish, *Gambusia affinis* | 196.1 | - |
| 26 | 166.2 | Snail, *Goniobasis livescens* | 166.2 | - |
| 25 | 157.1 | Goldfish, *Carassius auratus* | 157.1 | - |
| 24 | 156.8 | Common carp, *Cyprinus carpio* | 156.8 | - |
| 23 | 141.2 | Rainbow darter, *Etheostoma caeruleum* | 86.67 | - |
|  |  | Orangethroat darter, *Etheostoma spectabile* | 230.2 | - |
| 22 | 135.0 | Bryozoan, *Pectinatella magnifica* | 135.0 | - |
| 21 | 133.0 | Chiselmouth, *Acrocheilus alutaceus* | 133.0 | - |
| 20 | 124.6 | Guppy, *Poecilia reticulata* | 124.6 | - |
| 19 | 110.4 | Brook trout, *Salvelinus fontinalis* | 110.4 | 7.776 |
| 18 | 91.29 | Bluntnose minnow, *Pimephales notatus* | 72.16 | 26.36 |
|  |  | Fathead minnow, *Pimephales promelas* | 115.5 | 10.33*** |

Table 3. (Continued)

| Rank* | Genus Mean Acute Value (µg/L)** | Species | Species Mean Acute Value (µg/L)** | Species Mean Acute-Chronic Ratio |
|---|---|---|---|---|
| 17 | 90.00 | Worm,<br>*Nais* sp. | 90.00 | - |
| 16 | 88.54 | Coho salmon,<br>*Oncorhynchus kisutch* | 70.25 | - |
| | | Sockeye salmon,<br>*Oncorhynchus nerka* | 233.8 | - |
| | | Chinook salmon,<br>*Oncorhynchus tshawytscha* | 42.26 | >4.473 |
| 15 | 86.67 | Blacknose dace,<br>*Rhinichthys atratulus* | 86.67 | - |
| 14 | 83.97 | Creek chub,<br>*Semotilus atromaculatus* | 83.97 | - |
| 13 | 82.11 | Cutthroat trout,<br>*Salmo clarkii* | 66.26 | - |
| | | Rainbow trout,<br>*Salmo gairdneri* | 42.50 | - |
| | | Atlantic salmon,<br>*Salmo salar* | 196.6 | - |
| 12 | 78.55 | Central stoneroller,<br>*Campostoma anomalum* | 78.55 | - |
| 11 | 76.92 | Midge,<br>*Chironomus tentans* | 197.2 | - |
| | | Midge,<br>*Chironomus* sp. | 30.00 | - |
| 10 | 69.81 | Brown bullhead,<br>*Ictalurus nebulosus* | 69.81 | - |

Table 3. (Continued)

| Rank* | Genus Mean Acute Value (µg/L)** | Species | Species Mean Acute Value (µg/L)** | Species Mean Acute-Chronic Ratio |
|---|---|---|---|---|
| 9 | 56.21 | Snail, *Gyraulus circumstriatus* | 56.21 | - |
| 8 | 53.08 | Worm, *Limnodrilus hoffmeisteri* | 53.08 | - |
| 7 | 39.33 | Snail, *Physa heterostropha* | 35.91 | - |
|  |  | Snail, *Physa integra* | 43.07 | 3.585 |
| 6 | 37.05 | Bryozoan, *Lophopodella carteri* | 37.05 | - |
| 5 | 37.05 | Bryozoan, *Plumatella emarginata* | 37.05 | - |
| 4 | 25.22 | Amphipod, *Gammarus pseudolimnaeus* | 22.09 | 3.297 |
|  |  | Amphipod, *Gammarus pulex* | 28.79 | - |
| 3 | 18.77 | Cladoceran, *Ceriodaphnia reticulata* | 18.77 | - |
| 2 | 17.08 | Cladoceran, *Daphnia magna* | 21.17 | 2.418**** |
|  |  | Cladoceran, *Daphnia pulex* | 25.42 | - |
|  |  | Cladoceran, *Daphnia pulicaria* | 9.263 | - |
| 1 | 16.74 | Northern squawfish, *Ptychocheilus oregonensis* | 16.74 | - |

Table 3. (Continued)

| Rank* | Genus Mean Acute Value (µg/L)** | Species | Species Mean Acute Value (µg/L)** | Species Mean Acute-Chronic Ratio |
|---|---|---|---|---|
| | | SALTWATER SPECIES | | |
| 20 | 7,694 | Common rangia, *Rangia cuneata* | 7,694 | - |
| 19 | 600 | Green crab, *Carcinus maenus* | 600 | - |
| 18 | 526 | Copepod, *Eurytemora affinis* | 526 | - |
| 17 | 411.7 | Florida pompano, *Trachinotus carolinus* | 411.7 | - |
| 16 | 363.8 | Polychaete worm, *Nereis diversicolor* | 363.8 | - |
| 15 | 280 | Sheepshead minnow, *Cyprinodon variegatus* | 280 | - |
| 14 | 159.8 | Mysid, *Mysidopsis bahia* | 181 | 3.346 |
| | | Mysid, *Mysidopsis bigelowi* | 141 | - |
| 13 | 150.6 | Polychaete worm, *Neanthes arenaceodentata* | 150.6 | - |
| 12 | 138 | Copepod, *Pseudodiaptomus coronatus* | 138 | - |
| 11 | 137.8 | Atlantic silverside, *Menidia menidia* | 135.6 | - |
| | | Tidewater silverside, *Menidia peninsulae* | 140 | - |
| 10 | 128.9 | Winter flounder, *Pseudopleuronectes americanus* | 128.9 | - |

Table 3. (Continued)

| Rank* | Genus Mean Acute Value (µg/L)** | Species | Species Mean Acute Value (µg/L)** | Species Mean Acute-Chronic Ratio |
|---|---|---|---|---|
| 9 | 120 | Polychaete worm,<br>*Phyllodoce maculata* | 120 | - |
| 8 | 69.28 | American lobster,<br>*Homarus americanus* | 69.28 | - |
| 7 | 65.60 | Black abalone,<br>*Haliotis cracherodii* | 50 | - |
|  |  | Red abalone,<br>*Haliotis rufescens* | 86.08 | - |
| 6 | 49 | Dungeness crab,<br>*Cancer magister* | 49 | - |
| 5 | 39.97 | Copepod,<br>*Acartia clausi* | 52 | - |
|  |  | Copepod,<br>*Acartia tonsa* | 30.72 | - |
| 4 | 39 | Soft-shell clam,<br>*Mya arenaria* | 39 | - |
| 3 | 14.92 | Pacific oyster,<br>*Crassostrea gigas* | 7.807 | - |
|  |  | Eastern oyster,<br>*Crassostrea virginica* | 28.52 | - |
| 2 | 13.93 | Summer flounder,<br>*Paralichthys dentatus* | 13.93 | - |
| 1 | 5.8 | Blue mussel,<br>*Mytilus edulis* | 5.8 | - |

**Table 3. (Continued)**

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* Ranked from most resistant to most sensitive based on Genus Mean Acute Value.

** Freshwater Genus Mean Acute Values and Species Mean Acute Values are at a hardness of 50 mg/L.

*** Geometric mean of four values in Table 2.

****Geometric mean of three values in Table 2.

Fresh water

Final Acute Value = 18.46 μg/L (at a hardness of 50 mg/L)

Criterion Maximum Concentration = (18.46 μg/L) / 2 = 9.230 μg/L (at a hardness of 50 mg/L)

Pooled Slope = 0.9422 (see Table 1)

$\ln(\text{Criterion Maximum Intercept}) = \ln(9.230) - [\text{slope} \times \ln(50)]$

$= 2.222 - (0.9422 \times 3.912) = -1.464$

Criterion Maximum Concentration = $e^{(0.9422[\ln(\text{hardness})]-1.464)}$

Final Acute-Chronic Ratio = 2.823 (see text)

Final Chronic Value = (18.46 μg/L) / 2.823 = 6.539 μg/L (at a hardness of 50 mg/L)

Assumed Chronic Intercept = -1.465 (see text)

Assumed Chronic Slope = 0.8545 (see text)

Final Chronic Value = $e^{(0.8545[\ln(\text{hardness})]-1.465)}$

Salt water

Final Acute Value = 5.832 μg/L

Criterion Maximum Concentration = (5.832 μg/L) / 2 = 2.916 μg/L

Final Chronic Value = 2.916 μg/L (see text)

## Table 4. Toxicity of Copper to Aquatic Plants

| Species | Effect | Result (µg/L) | Reference |
|---|---|---|---|
| | FRESHWATER SPECIES | | |
| Alga, *Anabaena flos-aqua* | 75% growth inhibition | 200 | Young & Lisk, 1972 |
| Alga, *Anabaena variabilis* | Growth inhibition | 100 | Young & Lisk, 1972 |
| Alga, *Anabaena* strain 7120 | Lag in growth | 64 | Laube, et al. 1980 |
| Alga, *Anacystis nidulans* | Growth inhibiton | 100 | Young & Lisk, 1972 |
| Alga, *Ankistrodesmus braunii* | Growth reduction | 640 | Laube, et al. 1980 |
| Alga, *Chlamydomonas* sp. | Growth reduction | 8,000 | Cairns, et al. 1978 |
| Alga, *Chlorella pyrenoidosa* | Lag in growth | 1 | Steeman-Nielsen & Wium-Andersen, 1970 |
| Alga, *Chlorella pyrenoidosa* | Growth inhibition | 100 | Steeman-Nielsen & Kamp-Nielsen, 1970 |
| Alga, *Chlorella regularis* | Lag in growth | 20 | Sakaguchi, et al. 1977 |
| Alga, *Chlorella saccharophila* | 96-hr EC50 | 550 | Rachlin, et al. 1982 |
| Alga, *Chlorella* sp. | Photosynthesis inhibited | 6.3 | Gachter, et al. 1973 |
| Alga, *Chlorella vulgaris* | Growth inhibition | 200 | Young & Lisk, 1972 |
| Alga, *Chlorella vulgaris* | 96-hr IC50 | 62 | Ferard, et al. 1983 |
| Alga, *Chlorella vulgaris* | 33-day EC50 (growth) | 180 | Rosko & Rachlin, 1977 |

Table 4. (Continued)

| Species | Effect | Result (µg/L) | Reference |
|---|---|---|---|
| Alga, *Chlorella vulgaris* | 50% growth reduction | 100-200 | Stokes & Hutchinson, 1976 |
| Alga, *Chroococcus paris* | Growth reduction | 100 | Les & Walker, 1984 |
| Alga, *Cyclotella meneghiniana* | Growth reduction | 8,000 | Cairns, et al. 1978 |
| Alga, *Eudorina californica* | Growth inhibition | 5,000 | Young & Lisk, 1972 |
| Alga, *Scenedesmus acuminatus* | 40% growth reduction | 300 | Stokes & Hutchinson, 1976 |
| Alga, *Scenedesmus quadricauda* | Growth reduction | 8,000 | Cairns, et al. 1978 |
| Algae, Mixed culture | Significant reduction in photosynthesis | 5 | Elder & Horne, 1978 |
| Blue green algae, Mixed culture | 50% reduction in photosynthesis | 25 | Steeman-Nielsen & Bruun-Laursen, 1976 |
| Diatom, *Navicula incerta* | 4-day EC50 | 10,450 | Rachlin, et al. 1983 |
| Diatom, *Nitzschia linearis* | 5-day EC50 | 795-815 | Academy of Natural Sciences, 1960; Patrick, et al. 1968 |
| Diatom, *Nitzschia palea* | Complete growth inhibition | 5 | Steeman-Nielsen & Wium-Anderson, 1970 |
| Duckweed, *Lemna minor* | 7-day EC50 | 119 | Walbridge, 1977 |
| Macrophyte, *Elodea canadensis* | 50% reduction in photosynthetic $O_2$ production | 150 | Brown & Rattigan, 1979 |

Table 4. (Continued)

| Species | Effect | Result (µg/L) | Reference |
|---|---|---|---|
| Eurasian watermilfoil, *Myriophyllum spicatum* | 32-day EC50 (root weight) | 250 | Stanley, 1974 |
| Green alga, *Selenastrum capricornutum* | Growth reduction | 50 | Bartlett, et al. 1974 |
| Green alga, *Selenastrum capricornutum* | 14-day EC50 (cell volume) | 85 | Christensen, et al. 1979 |
| Blue alga, *Microcystis aeruginosa* | Incipient inhibition | 30 | Bringmann, 1975; Bringmann & Kuhn, 1976, 1978a,b |
| Green alga, *Scenedesmus quadricauda* | Incipient inhibition | 1,100 | Bringmann & Kuhn, 1977a, 1978a,b, 1979, 1980b |
| | SALTWATER SPECIES | | |
| Alga, giant kelp, *Macrocystis pyrifera* | 96-hr EC50 (photosynthesis inactivation) | 100 | Clendenning & North, 1959 |
| Alga, *Thalassiosira aestevallis* | Reduced chlorophyll a | 19 | Hollibaugh, et al. 1980 |
| Alga, *Thalassiosira pseudonana* | 72-hr EC50 (growth rate) | 5 | Erickson, 1972 |
| Alga, *Amphidinium carteri* | 14-day EC50 (growth rate) | <50 | Erickson, et al. 1970 |
| Alga, *Olisthodiscus luteus* | 14-day EC50 (growth rate) | <50 | Erickson, et al. 1970 |
| Alga, *Skeletonema costatum* | 14-day EC50 (growth rate) | 50 | Erickson, et al. 1970 |
| Alga, *Nitschia closterium* | 96-hr EC50 (growth rate) | 33 | Rosko & Rachlin, 1975 |
| Alga, *Scrippsiella faeroense* | 5-day EC50 (growth rate) | 5 | Saifullah, 1978 |

Table 4. (Continued)

| Species | Effect | Result (µg/L) | Reference |
|---|---|---|---|
| Alga, *Prorocentrum micans* | 5-day EC50 (growth rate) | 10 | Saifullah, 1978 |
| Alga, *Gymnodinium splendens* | 5-day EC50 (growth rate) | 20 | Saifullah, 1978 |
| Red alga, *Champia parvula* | Reduced tetrasporophyte growth | 4.6 | Steele & Thursby, 1983 |
| Red alga, *Champia parvula* | Reduced tetrasporangia production | 13.3 | Steele & Thursby, 1983 |
| Red alga, *Champia parvula* | Reduced female growth | 4.7 | Steele & Thursby, 1983 |
| Red alga, *Champia parvula* | Stopped sexual reproduction | 7.3 | Steele & Thursby, 1983 |
| Alga, *Chlorella stigmatophora* | 21-day EC50 (cell volume) | 70 | Christensen, et al. 1979 |
| Alga, *Asterionella japonica* | 72-hr EC50 (growth rate) | 12.7 | Fisher & Jones, 1981 |

**Table 5. Bioaccumulation of Copper by Aquatic Organisms**

| Species | Tissue | Duration (days) | Bioconcentration Factor | Reference |
|---|---|---|---|---|
| | | FRESHWATER SPECIES | | |
| Alga, *Chlorella regularis* | - | 20 hrs | 2,000 | Sakaguchi, et al. 1977 |
| Alga, *Chroococcus paris* | - | 10 min | up to 4,000 | Les & Walker, 1984 |
| Asiatic clam, *Corbicula fluminea* | Soft tissue | 28 | 17,700-<br>22,600 | Graney, et al. 1983 |
| Cladoceran, *Daphnia magna* | Whole body | 7 | 471* | Winner, 1984a |
| Stonefly, *Pteronarcys californica* | - | 14 | 203 | Nehring, 1976 |
| Fathead minnow (larva), *Pimephales promelas* | - | 30 | 290 | Lind, et al. Manuscript |
| Bluegill, *Lepomis macrochirus* | Muscle | 660 | 1.0 | Benoit, 1975 |
| | | SALTWATER SPECIES | | |
| Alga, *Dunaliella primolecta* | - | 25 | 153* | Riley & Roth, 1971 |
| Alga, *Dunaliella tertiolecta* | - | 25 | 168* | Riley & Roth, 1971 |
| Alga, *Chlamydomonas* sp. | - | 25 | 135* | Riley & Roth, 1971 |
| Alga, *Chlorella salina* | - | 25 | 74* | Riley & Roth, 1971 |
| Alga, *Stichococcus bacillaris* | - | 25 | 156* | Riley & Roth, 1971 |
| Alga, *Hemiselmis virescens* | - | 25 | 273* | Riley & Roth, 1971 |

Table 5. (Continued)

| Species | Tissue | Duration (days) | Bioconcentration Factor | Reference |
|---|---|---|---|---|
| Alga, *Hemiselmis brunescens* | - | 25 | 553* | Riley & Roth, 1971 |
| Alga, *Olisthodiscus luteus* | - | 25 | 182* | Riley & Roth, 1971 |
| Alga, *Asterionella japonica* | - | 25 | 309* | Riley & Roth, 1971 |
| Alga, *Phaeodactylum tricornutum* | - | 25 | 323* | Riley & Roth, 1971 |
| Alga, *Monochrysis lutheri* | - | 25 | 138* | Riley & Roth, 1971 |
| Alga, *Pseudopedinella pyriformis* | - | 25 | 85* | Riley & Roth, 1971 |
| Alga, *Heteromastix longifillis* | - | 25 | 617* | Riley & Roth, 1971 |
| Alga, *Micromonas squamata* | - | 25 | 279* | Riley & Roth, 1971 |
| Alga, *Tetraselmis tetrathele* | - | 25 | 265* | Riley & Roth, 1971 |
| Polychaete worm, *Phyllodoce maculata* | - | 21 | 1,750* | McLusky & Phillips, 1975 |
| Polychaete worm, *Neanthes arenaceodentata* | - | 28 | 2,550* | Pesch & Morgan, 1978 |
| Polychaete worm, *Nereis diversicolor* | - | 24 | 203* | Jones, et al. 1976 |
| Polychaete worm, *Cirriformia spirabranchia* | - | 24 | 250* | Milanovich, et al. 1976 |
| Polychaete worm, *Eudistylia vancouveri* | - | 33 | 1,006 | Young, et al. 1979 |
| Blue mussel, *Mytilus edulis* | - | 14 | 90 | Phillips, 1976 |

Table 5. (Continued)

| Species | Tissue | Duration (days) | Bioconcentration Factor | Reference |
|---|---|---|---|---|
| Bay scallop, *Argopecten irradians* | - | 112 | 3,310 | Zaroogian & Johnson, 1983 |
| Bay scallop, *Argopecten irradians* | - | 112 | 4,160 | Zaroogian & Johnson, 1983 |
| Eastern oyster, *Crassostrea virginica* | - | 140 | 28,200 | Shuster & Pringle, 1969 |
| Eastern oyster, *Crassostrea virginica* | - | 140 | 20,700 | Shuster & Pringle, 1969 |
| Quahog clam, *Mercenaria mercenaria* | - | 70 | 88 | Shuster & Pringle, 1968 |
| Soft-shell clam, *Mya arenaria* | - | 35 | 3,300 | Shuster & Pringle, 1968 |

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*Bioconcentration factor was converted from dry weight to wet weight basis.

## Table 6. Other Data on Effects of Copper on Aquatic Organisms

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| | | FRESHWATER SPECIES | | |
| Green alga, *Haematococcus* sp. | 96 hrs | Inhibited growth | 50 | Pearlmutter & Buchheim, 1983 |
| Green alga, *Scenedesmus quadricauda* | 96 hrs | Incipient inhibition | 150* | Bringmann & Kuhn, 1959a,b |
| Green alga, *Scenedesmus quadricauda* | 45 min | EC50 inhibition of phosphorus uptake | 5.1 | Peterson, et al. 1984 |
| Alga, *Cladophora glomerata* | 12 mos | Suppressed growth | 120 | Weber & McFarland, 1981 |
| Diatom, *Coreoneis placentula* | 12 mos | Suppressed growth | 120 | Weber & McFarland, 1981 |
| Phytoplankton, Mixed species | 124 hrs | Reduced rate of primary production | 10 | Cote, 1983 |
| Periphyton, Mixed species | 1 yr | Affected species composition; reduced productivity | 2.5 | Leland & Carter, 1984, Manuscript |
| Bacteria, *Escherichia coli* | - | Incipient inhibition | 80 | Bringmann & Kuhn, 1959a |
| Bacteria, *Pseudomonas putida* | 16 hrs | Incipient inhibition | 30 | Bringmann & Kuhn, 1976, 1977a, 1979, 1980b |
| Protozoan, *Entosiphon sulcatum* | 72 hrs | Incipient inhibition | 110 | Bringmann, 1978;<br>Bringmann & Kuhn, 1979, 1980b, 1981 |
| Protozoan, *Microregma heterostoma* | 28 hrs | Incipient inhibition | 50 | Bringmann & Kuhn, 1959b |
| Protozoan, *Chilomonas paramecium* | 48 hrs | Incipient inhibition | 3,200 | Bringmann, et al. 1980, 1981 |
| Protozoan, *Uronema parduezi* | 20 hrs | Incipient inhibition | 140 | Bringmann & Kuhn, 1980a, 1981 |
| Protozoa, Mixed species | 7 days | Reduced colonization rates | 167 | Cairns, et al. 1981 |

Table 6. (Continued)

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Protozoa,<br>Mixed species | 15 days | Reduced colonization rates | 100 | Buikema, et al. 1983 |
| Rotifer,<br>*Keratella* sp. | 24 hrs | EC50 | 101 | Borgmann & Ralph, 1984 |
| Rotifer,<br>*Philodina acuticornis* | 48 hrs | LC50 ( 5 C) | 1,300 | Cairns, et al. 1978 |
| | | (10 C) | 1,200 | |
| | | (15 C) | 1,130 | |
| | | (20 C) | 1,000 | |
| | | (25 C) | 950 | |
| Worm,<br>*Aeolosoma headleyi* | 48 hrs | LC50 (5 C) | 2,600 | Cairns, et al. 1978 |
| | | (10 C) | 2,300 | |
| | | (15 C) | 2,000 | |
| | | (20 C) | 1,650 | |
| | | (25 C) | 1,000 | |
| Snail,<br>*Goniobasis livescens* | 48 hrs | LC50 | 860 | Cairns, et al. 1976 |
| Snail,<br>*Nitrocris* sp. | 48 hrs | LC50 (5 C) | 3,000 | Cairns, et al. 1978 |
| | | (10 C) | 2,400 | |
| | | (15 C) | 1,000 | |
| | | (20 C) | 300 | |
| | | (25 C) | 210 | |
| Snail,<br>*Lymnaea emarginata* | 48 hrs | LC50 | 300 | Cairns, et al. 1976 |
| Asiatic clam (adult),<br>*Corbicula manilensis* | 96 hrs | LC50 | >2,600 | Harrison, et al. 1981, 1984 |
| Asiatic clam (adult),<br>*Corbicula manilensis* | 70 days | ILC | <10 | Harrison, et al. 1981, 1984 |
| Asiatic clam (larva),<br>*Corbicula manilensis* | 24 hrs | 53.1% mortality | 25 | Harrison, et al. 1981, 1984 |
| Cladoceran,<br>*Daphnia ambigua* | 72 hrs | LC50 (fed) | 67.7 | Winner & Farrell, 1976 |
| Cladoceran,<br>*Daphnia ambigua* | Life cycle | Reduced productivity | 49 | Winner & Farrell, 1976 |

Table 6. (Continued)

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Cladoceran, *Daphnia magna* | 16 hrs | EC50 (immobilization) | 38<br>38 | Anderson, 1944 |
| Cladoceran, *Daphnia magna* | 48 hrs | EC50 (fed) (immobilization) | 60 | Biesinger & Christensen, 1972 |
| Cladoceran, *Daphnia magna* | 21 days | Reproductive impairment | 22 | Biesinger & Christensen, 1972 |
| Cladoceran, *Daphnia magna* | 48 hrs | LC50 ( 5 C) | 90 | Cairns, et al. 1978 |
| | | (10 C) | 70 | |
| | | (15 C) | 40 | |
| | | (25 C) | 7 | |
| Cladoceran, *Daphnia magna* | Life cycle | Reduced number of young produced | 10 | Adema & DeGroot Van Zijl, 1972 |
| Cladoceran, *Daphnia magna* | 72 hrs | LC50 | 56-75 | Debelak, 1975 |
| Cladoceran, *Daphnia magna* | 72 hrs | LC50 (fed) | 86.5 | Winner & Farrell, 1976 |
| | | | 88.8 | |
| | | | 85 | |
| | | | 81.5 | |
| | | | 81.4 | |
| | | | 85.3 | |
| Cladoceran, *Daphnia magna* | Life cycle | Reduced productivity | 49 | Winner & Farrell, 1976 |
| Cladoceran, *Daphnia magna* | Life cycle | Reduced productivity | 28.2 | Winner, et al. 1977 |
| Cladoceran, *Daphnia magna* | Life cycle | Reduced number of young produced | 10 | Winner, et al. 1977 |
| Cladoceran, *Daphnia magna* | 29 hrs | Median survival time | 12.7 | Andrew, et al. 1977 |
| Cladoceran, *Daphnia magna* | 48 hrs | EC50 | 100* | Bringmann & Kuhn, 1959a,b |

Table 6. (Continued)

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Cladoceran,<br>*Daphnia magna* | 24 hrs | LC50 | 80 | Bringmann & Kuhn,<br>1977b |
| Cladoceran (3-5 days),<br>*Daphnia magna* | 72 hrs | LC50 (10 C) | 61 | Braginskiy & Shcherban,<br>1978 |
| | | (15 C) | 70 | |
| | | (25 C) | 21 | |
| | | (30 C) | 9.3 | |
| Cladoceran (adult),<br>*Daphnia magna* | 72 hrs | LC50 (30 C) | 0.25 | Braginskiy & Shcherban,<br>1978 |
| Cladoceran,<br>*Daphnia magna* | 24 hrs | EC50<br>(immobilization) | 70 | Bellavere & Gorbi, 1981 |
| Cladoceran,<br>*Daphnia magna* | 48 hrs | EC50 (250 µM Tris) | 254 | Borgmann & Ralph, 1983 |
| | | EC50 (1,000 µM Tris) | 1,239 | |
| Cladoceran,<br>*Daphnia magna* | Life cycle | Reduced longevity | 60 | Winner 1981 |
| Cladoceran,<br>*Daphnia magna* | 48 hrs | LC50 (fed) | 18.5 | Dave, 1984 |
| | 21 days | LC50 (fed) | 1.4 | |
| | Life cycle | Stopped reproduction | 3.2 | |
| Cladoceran,<br>*Daphnia parvula* | 72 hrs | LC50 (fed) | 57<br>72 | Winner & Farrell,<br>1976 |
| Cladoceran,<br>*Daphnia parvula* | Life cycle | Reduced productivity | 49 | Winner & Farrell,<br>1976 |
| Cladoceran,<br>*Daphnia pulex* | 72 hrs | LC50 (fed) | 54<br>86 | Winner & Farrell,<br>1976 |
| Cladoceran,<br>*Daphnia pulex* | Life cycle | Reduced productivity | 49 | Winner & Farrell,<br>1976 |
| Cladoceran,<br>*Daphnia pule* | 48 hrs | LC50 ( 5 C) | 70 | Cairns, et al. 1978 |
| | | (10 C) | 60 | |
| | | (15 C) | 20 | |
| | | (25 C) | 5.6 | |
| Cladoceran,<br>*Daphnia pulex* | 100 min | LC50 (15 day)<br>delayed mortality | 200 | Abel, 1980 |

Table 6. (Continued)

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Cladoceran, *Daphnia pulex* | 48 hrs | LC50 (fed) | 20-31 | Ingersoll & Winner, 1982 |
| Cladoceran, *Daphnia pulex* | 72 hrs | LC50 (fed) | 23-33 | Winner, 1984a |
| Cladoceran, *Daphnia pulicaria* | 48 hrs | LC50 (TOC=14 mg/L) | 55.5 | Lind, et al. Manuscript |
| | | (TOC=13 mg/L) | 55.3 | |
| | | (TOC=13 mg/L) | 53.3 | |
| | | (TOC=28 mg/L) | 97.2 | |
| | | (TOC=34 mg/L) | 199 | |
| | | (TOC=34 mg/L) | 627 | |
| | | (TOC=32 mg/L) | 213 | |
| | | (TOC=32 mg/L) | 165 | |
| | | (TOC=12 mg/L) | 35.5 | |
| | | (TOC=13 mg/L) | 78.8 | |
| | | (TOC=28 mg/L) | 113 | |
| | | (TOC=25 mg/L) | 76.4 | |
| | | (TOC=13 mg/L) | 84.7 | |
| | | (TOC=21 mg/L) | 184 | |
| | | (TOC=34 mg/L) | 240 | |
| Cladoceran, *Simocephalus serrulatus* | 48 hrs | LC50 (TOC=11) | 28.5 | Giesy, et al. 1983 |
| | | (TOC=12.4) | 43.0 | |
| | | (TOC=15.6) | 16.0 | |
| Copepods, *Acanthocyclops* and *Diacyclops* sp. | 7 days | 20% growth reduction | 42 | Borgmann & Ralph, 1984 |
| Amphipod, *Gammarus fasciatus* | 48 hrs | LC50 | 210 | Judy, 1979 |
| Amphipod, *Gammarus lacustris* | 96 hrs | LC50 | 1,500 | Nebeker & Gaufin, 1964 |
| Crayfish, *Orconectes rusticus* | 17 days | Survival of newly hatched young | 125 | Hubschman, 1967 |
| Crayfish (adult), *Procambarus clarkii* | 1,358 hrs | LC50 | 657 | Rice & Harrison, 1983 |

**Table 6. (Continued)**

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Mayfly,<br>*Cloeon dipterum* | 72 hrs | LC50 (10 C) | 193 | Braginskiy & Shcherban, 1978 |
| | | (15 C) | 95.2 | |
| | | (25 C) | 53 | |
| | | (30 C) | 4.8 | |
| Mayfly,<br>*Ephemerella grandis* | 14 days | LC50 | 180-200 | Nehring, 1976 |
| Mayfly,<br>*Ephemerella subvaria* | 48 hrs | LC50 | 320 | Warnick & Bell, 1969 |
| Stonefly,<br>*Pteronarcys californica* | 14 days | LC50 | 10,100-13,900 | Nehring, 1976 |
| Caddisfly,<br>*Hydropsyche betteni* | 14 days | LC50 | 32,000 | Warnick & Bell, 1969 |
| Midge,<br>*Chironomus tentans* | 20 days | EC50 | 77.5 | Nebeker, et al. 1984a |
| Midge,<br>*Tanytarsus dissimilis* | 10 days | LC50 | 16.3 | Anderson, et al. 1980 |
| Midge,<br>Unidentified | 32 wks | Emergence | 30 | Hedtke, 1984 |
| Coho salmon,<br>*Oncorhynchus kisutch* | 96 hrs | Reduced survival when transferred to seawater | 30 | Lorz & McPherson, 1976 |
| Coho salmon,<br>*Oncorhynchus kisutch* | 30 days | LC50 | 360 | Holland, et al. 1960 |

Table 6. (Continued)

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Coho salmon, *Oncorhynchus kisutch* | 72 hrs | LC50 | 280<br>370<br>190<br>480<br>440<br>460<br>480<br>560<br>780<br>510<br>520<br>480 | Holland, et al. 1960 |
| Coho salmon, *Oncorhynchus kisutch* | 96 hrs | LC50 (TOC=7.3) | 286 | Buckley, 1983 |
| Coho salmon, *Oncorhynchus kisutch* | 100 days | Reduced growth rate | 70 | Buckley, et al. 1982 |
| Coho salmon, *Oncorhynchus kisutch* | 168 hrs | LC50 | 275 | McCarter & Roch, 1983 |
| Coho salmon, *Oncorhynchus kisutch* | 168 hrs | LC50 (acclimated to copper for 2 wks) | 325-440 | McCarter & Roch, 1983 |
| Sockeye salmon, *Oncorhynchus nerka* | 24 hrs | Significant change in corticosteriod | 64 | Donaldson & Dye, 1975 |
| Chinook salmon, *Oncorhynchus tshawytscha* | 72 hrs<br>5 days | LC50<br>LC50 | 190<br>178 | Holland, et al. 1960 |
| Chinook salmon, *Oncorhynchus tshawytscha* | 26 days | Reduced survival and growth of sac fry | 21 | Hazel & Meith, 1970 |
| Chinook salmon (alevin), *Oncorhynchus tshawytscha* | 200 hrs | LC50<br>LC10 | 20<br>15 | Chapman, 1978 |
| Chinook salmon (swim-up), *Oncorhynchus tshawytscha* | 200 hrs | LC50<br>LC10 | 19<br>14 | Chapman, 1978 |
| Chinook salmon (parr), *Oncorhynchus tshawytscha* | 200 hrs | LC50<br>LC10 | 30<br>17 | Chapman, 1978 |

Table 6. (Continued)

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Chinook salmon (smolt), *Oncorhynchus tshawytscha* | 200 hrs | LC50<br>LC10 | 26<br>18 | Chapman, 1978 |
| Rainbow trout, *Salmo gairdneri* | 96 hrs | LC50 | 516**<br>309**<br>111** | Howarth & Sprague, 1978 |
| Rainbow trout, *Salmo gairdneri* | 2 hrs | Depressed olfactory response | 8 | Hara, et al. 1976 |
| Rainbow trout, *Salmo gairdneri* | 7 days | LC50 | 44 | Lloyd, 1961 |
| Rainbow trout, *Salmo gairdneri* | 21 days | Median period of survival | 40 | Grande, 1966 |
| Rainbow trout, *Salmo gairdneri* | 10 days | Depressed feeding rate and growth | 75 | Lett, et al. 1976 |
| Rainbow trout, *Salmo gairdneri* | 7 days | Median period of survival | 44 | Lloyd, 1961 |
| Rainbow trout (alevin), *Salmo gairdneri* | 200 hrs | LC50<br>LC10 | 26<br>19 | Chapman, 1978 |
| Rainbow trout (swim-up), *Salmo gairdneri* | 200 hrs | LC50<br>LC10 | 17<br>9 | Chapman, 1978 |
| Rainbow trout (parr), *Salmo gairdneri* | 200 hrs | LC50<br>LC10 | 15<br>8 | Chapman, 1978 |
| Rainbow trout (smolt), *Salmo gairdneri* | 200 hrs | LC50<br>LC10 | 21<br>7 | Chapman, 1978 |
| Rainbow trout (smolt), *Salmo gairdneri* | 96 hrs<br>>10 days | LC50<br>Threshold LC50 | 102**<br>94** | Fogels & Sprague, 1977 |
| Rainbow trout (smolt), *Salmo gairdneri* | 14 days | LC50 | 870 | Calamari & Marchetti, 1973 |

**Table 6. (Continued)**

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Rainbow trout (fry), *Salmo gairdneri* | 1 hr | Avoidance | 0.1 | Folmar, 1976 |
| Rainbow trout (fry), *Salmo gairdneri* | 24 hrs | LC50 (5 C)<br>(15 C)<br>(30 C) | 950<br>430<br>150 | Cairns, et al. 1978; |
| Rainbow trout (fry), *Salmo gairdneri* | 96 hrs | LC50 | 250-680 | Lett, et al. 1976 |
| Rainbow trout (fry), *Salmo gairdneri* | 48 hrs | LC50 (field) | 70 | Calamari & Marchetti, 1975 |
| Rainbow trout (embryo, larva), *Salmo gairdneri* | 28 days | EC50 (death and deformity) | 110 | Birge, et al. 1980,<br>Birge & Black, 1979 |
| Rainbow trout (embryo, larva), *Salmo gairdneri* | 28 days | EC10 (death and deformity) | 16.5 | Birge, et al. 1981 |
| Rainbow trout, *Salmo gairdneri* | 80 min | Avoidance threshold | 74 | Black & Birge, 1980 |
| Rainbow trout (fry), *Salmo gairdneri* | 96 hrs | LC50 | 250 | Goettl, et al. 1972 |
| Rainbow trout (fry), *Salmo gairdneri* | 24 hrs | LC50 | 140<br>130 | Shaw & Brown, 1974 |
| Rainbow trout (fry), *Salmo gairdneri* | 72 hrs | LC50 | 580 | Brown, et al. 1974 |
| Rainbow trout, *Salmo gairdneri* | >15 days | Threshold LC50 | 19<br>54<br>48<br>78<br>18<br>96 | Miller & McKay, 1980 |

Table 6. (Continued)

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Rainbow trout, *Salmo gairdneri* | 48 hrs | LC50 | 500 | Brown, 1968 |
| Rainbow trout, *Salmo gairdneri* | 48 hrs | LC50 | 750 | Brown & Dalton, 1970 |
| Rainbow trout, *Salmo gairdneri* | 48 hrs | LC50 | 150 | Cope, 1966 |
| Rainbow trout, *Salmo gairdneri* | 72 hrs | LC50 | 1,100 | Lloyd, 1961 |
| Rainbow trout, *Salmo gairdneri* | 48 hrs | LC50 | 270 | Herbert & Vandyke, 1964 |
| Rainbow trout, *Salmo gairdneri* | 4 mos | Biochemical and enzyme levels | 30 | Arillo, et al. 1984 |
| Rainbow trout, *Salmo gairdneri* | 96 hrs | LC50 | 185 | Bills, et al. 1981 |
| Rainbow trout, *Salmo gairdneri* | 96 hrs | LC50 | 160 | Daoust, 1981 |
| Rainbow trout, *Salmo gairdneri* | 144 hrs | LC50 (various diets) | 246-408 | Dixon & Hilton, 1981 |
| Rainbow trout, *Salmo gairdneri* | 144 hrs | Incipient lethal level | 274-381 | Dixon & Sprague, 1981a |
| Rainbow trout, *Salmo gairdneri* | 144 hrs | Incipient lethal level '(acclimated at 131-194 µg/L) | 564-717 | Dixon & Sprague, 1981a |
| Rainbow trout, *Salmo gairdneri* | - | Avoidance | 6.4 | Giattina, et al. 1982 |
| Rainbow trout (embryo), *Salmo gairdneri* | 96 hrs | LC50 | 400 | Giles & Klaverkamp, 1982 |
| Rainbow trout, *Salmo gairdneri* | 96 hrs | LC50 (various diets) | 11.3-23.9 | Marking, et al. 1984 |

Table 6. (Continued)

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Rainbow trout, *Salmo gairdneri* | 85 days | Reduced growth (continuous exposure) | 31 | Seim, et al. 1984 |
| Rainbow trout, *Salmo gairdneri* | 85 days | Reduced growth (intermittent exposure) | 16 | Seim, et al. 1984 |
| Atlantic salmon, *Salmo salar* | 7 days | Incipient lethal level | 48 | Sprague, 1964 |
| Atlantic salmon, *Salmo salar* | 7 days | Incipient lethal level | 32 | Sprague & Ramsay, 1965 |
| Atlantic salmon, *Salmo salar* | 21 days | Median survival time | 40 | Grande, 1966 |
| Atlantic salmon, *Salmo salar* | 27-38 hrs | Median survival time | 50 | Zitko & Carson, 1976 |
| Brown trout, *Salmo trutta* | 21 days | Median survival time | 45 | Grande, 1966 |
| Brook trout, *Salvelinus fontinalis* | 24 hrs | Significant change in cough rate | 9 | Drummond, et al. 1973 |
| Brook trout, *Salvelinus fontinalis* | 21 days | Significant changes in blood chemistry | 23 | McKim, et al. 1970 |
| Brook trout, *Salvelinus fontinalis* | 337 days | Significant changes in blood chemistry | 17.4 | McKim, et al. 1970 |
| Longfin dace, *Agrosia chrysogaster* | 96 hrs | LC50 | 860** | Lewis, 1978 |
| Central stoneroller, *Campostoma anomalum* | 96 hrs | LC50 (high BOD) | 1,400 | Geckler, et al. 1976 |
| Goldfish, *Carassius auratus* | 24 hrs | LC50 (5 C)<br>(15 C)<br>(30 C) | 2,700<br>2,900<br>1,510 | Cairns, et al. 1978; |
| Goldfish (embryo, larva), *Carassius auratus* | 7 days | EC50 (death and deformity) | 5,200 | Birge, 1978; Birge & Black, 1979 |

**Table 6. (Continued)**

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Common carp (embryo),<br>*Cyprinus carpio* | 72 hrs | Prevented hatching | 700 | Hildubrand & Cushman, 1978 |
| Common carp,<br>*Cyprinus carpio* | 48 hrs | LC50 | 170 | Harrison & Rice, 1981 |
| Common carp (embryo),<br>*Cyprinus carpio* | - | EC50 (hatch) | 4,775 | Kapur & Yadav, 1982 |
| Golden shiner,<br>*Notemigonus crysoleucas* | 24 hrs | LC50 (5 C)<br>(15 C)<br>(30 C) | 330<br>230<br>270 | Cairns, et al. 1978; |
| Striped shiner,<br>*Notropis chrysocephalus* | 96 hrs | LC50 (high BOD) | 8,400<br>16,000<br>3,400<br>4,000<br>5,000 | Geckler, et al. 1976 |
| Striped shiner,<br>*Notropis chrysocephales* | 96 hrs | Decrease blood osmolarity | 2,500 | Lewis & Lewis, 1971 |
| Bluntnose minnow,<br>*Pimephales notatus* | 48 hrs | LC50 (21 tests) (high BOD) | 750-21,000 | Geckler, et al. 1976 |
| Bluntnose minnow,<br>*Pimephales notatus* | 96 hrs | LC50 (6 tests) (high BOD) | 1,100-20,000 | Geckler, et al. 1976 |
| Fathead minnow,<br>*Pimephales promelas* | 96 hrs | LC50 (21 tests) high BOD) | 1,610-21,000 | Brungs, et al. 1976 |
| Fathead minnow,<br>*Pimephales promelas* | Life cycle | Chronic limits (high BOD) | 66-120 | Brungs, et al. 1976 |
| Fathead minnow,<br>*Pimephales promelas* | 96 hrs | LC50 (36 tests) (high BOD) | <650-23,000 | Geckler, et al. 1976 |
| Fathead minnow,<br>*Pimephales promelas* | 96 hrs | LC50 (7 tests) (high BOD) | 740-13,000 | Geckler, et al. 1976 |
| Fathead minnow,<br>*Pimephales promelas* | 96 hrs | LC50 | 231 | Curtis, et al. 1979;<br>Curtis & Ward, 1981 |

Table 6. (Continued)

| Species | Duration | Effect | Result (μg/L) | Reference |
|---|---|---|---|---|
| Fathead minnow,<br>*Pimephales promelas* | 96 hrs | LC50 (TOC 12 mg/L)<br>(TOC 13 mg/L)<br>(TOC 36 mg/L)<br>(TOC 28 mg/L)<br>(TOC 15 mg/L)<br>(TOC 34 mg/L)<br>(TOC 30 mg/L)<br>(TOC 30 mg/L) | 436<br>516<br>1,586<br>1,129<br>550<br>1,001<br>2,050<br>2,336 | Lind, et al. Manuscript |
| Fathead minnow,<br>*Pimephales promelas* | 96 hrs | LC50 (fish from pond contaminated with heavy metals) | 360<br>410 | Birge, et al. 1983 |
| Creek chub,<br>*Semotilus atromaculatus* | 96 hrs | LC50<br>(high BOD) | 11,500<br>1,100 | Geckler, et al. 1976 |
| Pearl dace,<br>*Semotilus margarita* | 7 hrs | Overturning and death | 1,010-279,000 | Tsai, 1979 |
| Brown bullhead,<br>*Ictalurus nebulosus* | 96 hrs | LC50<br>(high BOD) | 11,000 | Geckler, et al. 1976 |
| Channel catfish,<br>*Ictalurus punctatus* | 94 hrs | Decreased blood osmolarity | 2,500 | Lewis & Lewis, 1971 |
| Channel catfish,<br>*Ictalurus punctatus* | 24 hrs | LC50 (5 C)<br>(15 C)<br>(30 C) | 3,700<br>2,600<br>3,100 | Cairns, et al. 1978; |
| Channel catfish,<br>*Ictalurus punctatus* | - | Increased albinism | 0.5 | Westerman & Birge, 1978 |
| Channel catfish,<br>*Ictalurus punctatus* | 10 days | EC50 (death and deformity) | 6,620 | Birge & Black, 1979 |
| Channel catfish,<br>*Ictalurus punctatus* | 14 days | LC50 | 1,200** | Richey and Roseboom, 1978 |
| Flagfish,<br>*Jordanella floridae* | 96 hrs<br>10 days | LC50<br>LC50 | 1,270**<br>680** | Fogels & Sprague, 1977 |

**Table 6. (Continued)**

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Mosquitofish, *Gambusia affinis* | 96 hrs | LC50 (high turbidity) | 75,000 | Wallen, et al. 1957 |
| Guppy, *Poecilia reticulata* | 24 hrs | LC50 | 1,250 | Minicucci, 1971 |
| Guppy, *Poecilia reticulata* | 48 hrs | LC50 | 2,500 | Khangarot, et al. 1981a |
| Rock bass, *Ambloplites rupestris* | 96 hrs | LC50 (high TOC) | 1,432 | Lind, et al. Manuscript |
| Bluegill, *Lepomis macrochirus* | 24-36 hrs | Altered oxygen consumption rates | 300 | O'Hara, 1971 |
| Bluegill, *Lepomis macrochirus* | 48 hrs | LC50 | 2,800 | Cope, 1966 |
| Bluegill, *Lepomis macrochirus* | 24 hrs | LC50 (5 C)<br>(15 C)<br>(30 C) | 2,590<br>2,500<br>3,820 | Cairns, et al. 1978; |
| Bluegill, *Lepomis macrochirus* | 96 hrs | LC50 (high BOD) | 16,000<br>17,000 | Geckler, et al. 1976 |
| Bluegill, *Lepomis macrochirus* | 14 days | LC50 | 2,500**<br>3,700** | Richey & Roseboom, 1978 |
| Bluegill, *Lepomis macrochirus* | 96 hrs | LC50 | 740 | Trama, 1954 |
| Bluegill, *Lepomis macrochirus* | 96 hrs | LC50 | 1,800 | Turnbull, et al. 1954 |
| Bluegill, *Lepomis macrochirus* | 80 min | Avoidance threshold | 8,480 | Black & Birge, 1980 |
| Bluegill, *Lepomis macrochirus* | 96 hrs | Biochemical changes | 2,000 | Heath, 1984 |
| Largemouth bass (embryo, larva), *Micropterus salmoides* | 8 days | EC50 (death and deformity) | 6,560 | Birge, et al. 1978; Birge & Black, 1979 |

Table 6. (Continued)

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Largemouth bass, *Micropterus salmoides* | 24 hrs | Affected opercular rhythm | 48 | Morgan, 1979 |
| Rainbow darter, *Etheostoma caeruleum* | 96 hrs | LC50 (high BOD) | 4,300<br>5,900<br>2,800 | Geckler, et al. 1976 |
| Johnny darter, *Etheostoma nigrum* | 96 hrs | LC50 (high BOD) | 6,800 | Geckler, et al. 1976 |
| Orangethroat darter, *Etheostoma spectabile* | 96 hrs | LC50 (high BOD) | 9,800<br>7,900<br>5,400<br>5,800 | Geckler, et al. 1976 |
| Leopard frog (embryo, larva), *Rana pipiens* | 8 days | EC50 (death and deformity) | 50 | Birge & Black, 1979 |
| Narrow-mouthed toad (embryo, larva), *Gastrophryne carolinensis* | 7 days | EC50 (death and deformity) | 40 | Birge, 1978; Birge & Black, 1979 |
| American toad, *Bufo americanus* | 80 min | Avoidance threshold | 100 | Black & Birge, 1980 |
| Fowler's toad (embryo, larva), *Bufo fowleri* | 7 min | EC50 (death and deformity) | 26,960 | Birge & Black, 1979 |
| Southern gray tree frog (embryo, larva), *Hyla chrysoscelis* | 7 min | EC50 (death and deformity) | 40 | Birge & Black, 1979 |
| Marbled salamander (embryo, larva), *Ambystoma opacum* | 8 days | EC50 (death and deformity) | 770 | Birge, et al. 1978; Birge & Black, 1979 |

**Table 6. (Continued)**

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| | | SALTWATER SPECIES | | |
| Natural phytoplankton populations | 5 days | Reduced chlorophyll a | 19 | Hollibaugh, et al. 1980 |
| Natural phytoplankton populations | 4 days | Reduced biomass | 6.4 | Hollibaugh, et al. 1980 |
| Alga, *Laminaria hyperboria* | 28 days | Growth decrease | 50 | Hopkins & Kain, 1971 |
| Hydroid, *Campanularia flexuosa* | 11 days | Growth rate inhibition | 10-13 | Stebbing, 1976 |
| Hydroid, *Campanularia flexuosa* | - | Enzyme inhibition | 1.43 | Moore & Stebbing, 1976 |
| Hydromedusa, *Phialidium* sp. | 24 hrs | LC50 | 36 | Reeve, et al. 1976 |
| Ctenophore, *Pleurobrachia pileus* | 24 hrs | LC50 | 33 | Reeve, et al. 1976 1976 |
| Ctenophore, *Mnemiopsis mccrdayi* | 24 hrs | LC50 | 17-29 | Reeve, et al. 1976 |
| Rotifer, *Brachionus plicatilis* | 24 hrs | LC50 | 100 | Reeve, et al. 1976 |
| Polychaete worm, *Phyllodoce maculata* | 9 days | LC50 | 80 | McLusky & Phillips, 1975 |
| Polychaete worm, *Neanthes arenaceodentata* | 28 days | LC50 | 44 | Pesch & Morgan, 1978 |
| Polychaete worm, *Neanthes arenaceodentata* | 28 days | LC50 | 100 | Pesch & Morgan, 1978 |
| Polychaete worm, *Neanthes arenaceodentata* | 7 days | LC50 | 137 | Pesch & Hoffman, 1982 |
| Polychaete worm, *Neanthes arenaceodentata* | 10 days | LC50 | 98 | Pesch & Hoffman, 1982 |

**Table 6. (Continued)**

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Polychaete worm, *Neanthes arenaceodentata* | 28 days | LC50 | 56 | Pesch & Hoffman, 1982 |
| Polychaete worm, *Cirriformia spirabranchia* | 26 days | LC50 | 40 | Milanovich, et al. 1976 |
| Larval annelids, Mixed species | 24 hrs | LC50 | 89 | Reeve, et al. 1976 |
| Black abalone, *Haliotis cracherodii* | 96 hrs | Histopathological gill abnormalities | >32 | Martin, et al. 1977 |
| Red abalone, *Haliotis rufescens* | 96 hrs | Histopathological gill abnormalities | >32 | Martin, et al. 1977 |
| Channeled whelk, *Busycon canaliculatum* | 77 days | LC50 | 470 | Betzer & Yevich, 1975 |
| Mud snail, *Nassarius obsoletus* | 72 hrs | Decrease in oxygen consumption | 100 | MacInnes & Thurberg, 1973 |
| Blue mussel, *Mytilus edulis* | 7 days | LC50 | 200 | Scott & Major, 1972 |
| Bay scallop, *Argopecten irradians* | 42 days | EC50 (growth) | 5.8 | Pesch, et al. 1979 |
| Bay scallop, *Argopecten irradians* | 119 days | 100% mortality | 5 | Zaroogian & Johnson, 1983 |
| Eastern oyster (larva), *Crassostrea virginica* | 12 days | LC50 | 46 | Calabrese, et al. 1977 |
| Common rangia, *Rangia cuneata* | 96 hrs | LC50 (<1 g/kg salinity) | 210 | Olson & Harrel, 1973 |
| Clam, *Macoma inquinata* | 30 days | LC50 | 15.7 | Crecelius, et al. 1982 |
| Clam, *Macoma inquinata* | 30 days | LC50 | 20.7 | Crecelius, et al. 1982 |
| Quahog clam (larva), *Mercenaria mercenaria* | 8-10 days | LC50 | 30 | Calabrese, et al. 1977 |

**Table 6. (Continued)**

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Quahog clam (larva), *Mercenaria mercenaria* | 77 days | LC50 | 25 | Shuster & Pringle, 1968 |
| Common Pacific littleneck, *Protothaca staminea* | 17 days | LC50 | 39 | Roesijadi, 1980 |
| Soft-shell clam, *Mya arenaria* | 7 days | LC50 | 35 | Eisler, 1977 |
| Copepod, *Undinula vulgaris* | 24 hrs | LC50 | 192 | Reeve, et al. 1976 |
| Copepod, *Euchaeta marina* | 24 hrs | LC50 | 188 | Reeve, et al. 1976 |
| Copepod, *Metridia pacifica* | 24 hrs | LC50 | 176 | Reeve, et al. 1976 |
| Copepod, *Labidocera scotti* | 24 hrs | LC50 | 132 | Reeve, et al. 1976 |
| Copepod, *Acartia clausi* | 48 hrs | LC50 | 34-82 | Moraitou-Apostolopoulou, 1978 |
| Copepod, *Acartia tonsa* | 6 days | LC50 | 9-73 | Sosnowski, et al. 1979 |
| Copepod, *Acartia tonsa* | 24 hrs | LC50 | 104-311 | Reeve, et al. 1976 |
| Copepod, *Tisbe holothuriae* | 48 hrs | LC50 | 80 | Moraitou-Apostolopoulou & Verriopoulos, 1982 |
| Copepod (nauplius), Mixed species | 24 hrs | LC50 | 90 | Reeve, et al. 1976 |
| Amphipod, *Ampelisca abdita* | 7 days | LC50 | 90 | Scott, et al. Manuscript |
| Euphausiid, *Euphausia pacifica* | 24 hrs | LC50 | 14-30 | Reeve, et al. 1976 |
| Grass shrimp, *Palaemonetes pugio* | 96 hrs | LC50 | 12,600 | Curtis, et al. 1979;<br>Curtis & Ward, 1981 |
| Coon stripe shrimp, *Pandalus danae* | 30 days | LC50 | 27.0 | Crecelius, et al. 1982 |

**Table 6. (Continued)**

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| American lobster,<br>*Homarus americanus* | 13 days | LC50 | 56 | McLeese, 1974 |
| Sea urchin,<br>*Arbacia punctulata* | - | 58% decrease in sperm motility | 300 | Young & Nelson, 1974 |
| Arrow worm,<br>*Sagitta hispida* | 24 hrs | LC50 | 43-460 | Reeve, et al. 1976 |
| Atlantic menhaden,<br>*Brevoortia tyrannus* | 14 days | LC50 | 610 | Engel, et al. 1976 |
| Pacific herring (embryo),<br>*Clupea harengus pallasi* | 6 days | Incipient LC50 | 33 | Rice & Harrison, 1978 |
| Pacific herring (larva),<br>*Clupea harengus pallasi* | 48 hrs | Incipient LC50 | 900 | Rice & Harrison, 1978 |
| Atlantic cod (embryo),<br>*Gadus morhua* | 14 days | LC50 | 10 | Swedmark & Granmo, 1981 |
| Mummichog,<br>*Fundulus heteroclitus* | 21 days | Histopathological lesions | <500 | Gardner & La Roche, 1973 |
| Mummichog,<br>*Fundulus heteroclitus* | 96 hrs | Enzyme inhibition | 600 | Jackim, 1973 |
| Atlantic silverside,<br>*Menidia menidia* | 96 hrs | Histopathological lesions | <500 | Gardner & LaRoche, 1973 |
| Pinfish,<br>*Lagodon rhomboides* | 14 days | LC50 | 150 | Engel, et al. 1976 |
| Spot,<br>*Leiostomus xanthurus* | 14 days | LC50 | 160 | Engel, et al. 1976 |
| Atlantic croaker,<br>*Micropogonias undulatus* | 14 days | LC50 | 210 | Engel, et al. 1976 |

Table 6. (Continued)

| Species | Duration | Effect | Result (µg/L) | Reference |
|---|---|---|---|---|
| Winter flounder, *Pseudopleuronectes americanus* | 14 days | Histopathological lesions | 180 | Baker, 1969 |

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* In river water.

**Dissolved copper; no other measurement reported.

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