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Ambient Water Quality Criteria for

Copper - 1984

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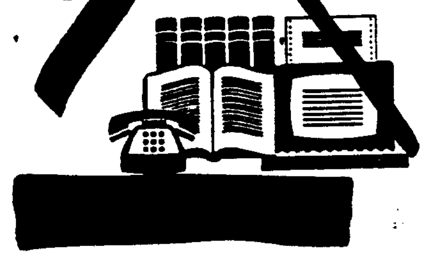

FOREWORD

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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AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR

COPPER

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This report has been reviewed by the Criteria and Standards Division, Office of Water Regulations and Standards, U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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TABLES

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

*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 Scripsiella 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 µg/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	X 6.5†	-	Dave, 1984
Cladoceran, *Daphnia magna*	S, U	-	45	54	21.17	Mount & Norberg, 1984

Table I. (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, *Orconectes limosus*	S, M	Copper chloride	-	600	-	Boutet & Chaisemartin, 1973
Crayfish, *Orconectes rusticus*	FT, M	Copper sulfate	100-125	3,000	1,397	Hubschman, 1967
Crayfish (larva), *Procambarus clarkii*	FT, M	-	17	720	1,990	Rice & Harrison, 1983
Damselfly, Unidentified	S, M	-	50	4,600	4,600	Rehwoldt, et al. 1973
Stonefly, *Acroneuria lycorias*	S, M	Copper sulfate	40	8,300	10,240	Warnick & Bell, 1969
Caddisfly, Unidentified	S, M	-	50	6,200	6,200	Rehwoldt, et al. 1973
Midge (1st instar), *Chironomus tentans*	FT, M	Copper chloride	71-84	298	-	Nebeker, et al. 1984a
Midge (2nd instar), *Chironomus tentans*	FT, M	Copper chloride	71-84	773****	-	Nebeker, et al. 1984a
Midge (3rd instar), *Chironomus tentans*	FT, M	Copper chloride	71-84	1,446****	-	Nebeker, et al. 1984a
Midge (4th instar), *Chironomus tentans*	FT, M	Copper chloride	71-84	1,690****	197.2	Nebeker, et al. 1984a
Midge, *Chironomus* sp.	S, M	Copper sulfate	50	30	30.00	Rehwoldt, et al. 1973
Bryozoan, *Pectinatella magnifica*	S, U	-	190-220	510	135.0	Pardue & Wood, 1980
Bryozoan, *Lophopodella carteri*	S, U	-	190-220	140	37.05	Pardue & Wood, 1980
Bryozoan, *Plumatella emarginata*	S, U	-	190-220	140	37.05	Pardue & Wood, 1980
American eel, *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)**[a]	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, *Salmo gairdneri*	FT, M	Copper chloride	194	274	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	128	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	221	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	165	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	197	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	514	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	243	-	Chakoumakos, et al. 1979
Rainbow trout (alevin), *Salmo gairdneri*	FT, M	Copper chloride	23	28	-	Chapman, 1975, 1978
Rainbow trout (swim-up), *Salmo gairdneri*	FT, M	Copper chloride	23	17	-	Chapman, 1975, 1978
Rainbow trout (parr), *Salmo gairdneri*	FT, M	Copper chloride	23	18	-	Chapman, 1975, 1978
Rainbow trout (smolt), *Salmo gairdneri*	FT, M	Copper chloride	23	29	-	Chapman, 1975, 1978
Rainbow trout (adult), *Salmo gairdneri*	FT, M	Copper chloride	42	57	-	Chapman, 1975; Chapman & Stevens, 1978
Rainbow trout (fry), *Salmo gairdneri*	FT, M	Copper nitrate	-	253	-	Hale, 1977
Rainbow trout, *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; Chynoweth, et al. 1976
Guppy, *Poecilia reticulata*	FT, M	-	67.2	138	-	Black, 1974; 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

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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)

* 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

† 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. 1984b
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, *Esox lucius*	ELS	Copper sulfate	45.4	34.9-104.4	60.36	McKim, et al. 1978
Bluntnose minnow, *Pimephales notatus*	LC	Copper sulfate	194	4.3-18	8.798	Horning & Neiheisel, 1979
Fathead minnow, *Pimephales promelas*	LC	Copper sulfate	198	14.5-33	21.87	Mount, 1968
Fathead minnow, *Pimephales promelas*	LC	Copper sulfate	30	10.6-18.4	13.97	Mount & Stephan, 1969
Fathead minnow, *Pimephales promelas*	LC	Copper sulfate	200	24-32	27.71	Pickering, et al. 1977
Fathead minnow, *Pimephales promelas*	ELS	-	45	13.1-26.2	18.53	Lind, et al. Manuscript
White sucker, *Catostomus commersoni*	ELS	Copper sulfate	45.4	12.9-33.8	20.88	McKim, et al. 1978
Bluegill, *Lepomis macrochirus*	LC	Copper sulfate	45	21-40	28.98	Benoit, 1975
SALTWATER SPECIES						
Mysid, *Mysidopsis bahia*	LC	Copper nitrate	-	38-77	54.09	Lussier, et al. Manuscript

* 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 > 75
Snail, *Physa integra*	35-55	39	10.88	3.585 < 25
Cladoceran, *Daphnia magna*	51-52	26	13.63	1.908 < 25
Cladoceran, *Daphnia magna*	104-105	30	29.33	1.023 < 25
Cladoceran, *Daphnia magna*	207-211	69	9.525	7.244 25-50
Amphipod, *Gammarus pseudolimnaeus*	35-55	20	6.066	3.297 < 25
Chinook salmon, *Oncorhynchus tshawytscha*	23-25	33.1	<7.4	>4.473 < 25
Brook trout, *Salvelinus fontinalis*	45	100	12.86	7.776 25-50
Bluntnose minnow, *Pimephales notatus*	194	231.9*	8.798	26.36 50-75
Fathead minnow, *Pimephales promelas*	198-200	470	21.87	21.49 50-75
Fathead minnow, *Pimephales promelas*	30-31	75	13.97	5.369 25-50
Fathead minnow, *Pimephales promelas*	200	474.8**	27.71	17.13 50-75
Fathead minnow, *Pimephales promelas*	45-48	106.9***	18.53	5.769 25-50
Bluegill, *Lepomis macrochirus*	45	1,100	28.98	37.96 > 75
Mysid, *Mysidopsis bahia*	-	181	54.09	3.346

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

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

***Geometric mean of three values from Lind, et al. (Manuscri... 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, *Acroneuria lycorias*	10,240	-
40	6,200	Caddisfly, Unidentified	6,200	-
39	5,860	White perch, *Morone americanus*	5,860	-
38	4,600	Damselfly, Unidentified	4,600	-
37	4,305	American eel, *Anguilla rostrata*	4,305	-
36	1,990	Crayfish, *Procambarus clarkii*	1,990	-
35	1,877	Snail, *Campeloma decisum*	1,877	156.2
34	1,397	Crayfish, *Orconectes rusticus*	1,397	-
33	900.0	Snail, *Amnicola* sp.	900.0	-
32	807.3	Pumpkinseed, *Lepomis gibbosus*	640.9	-
		Bluegill, *Lepomis macrochirus*	1,017	37.96
31	790.6	Banded killifish, *Fundulus diaphanus*	790.6	-
30	684.3	Mozambique tilapia, *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, *Nais* sp.	90.00	-
16	88.54	Coho salmon, *Oncorhynchus kisutch*	70.25	-
		Sockeye salmon, *Oncorhynchus nerka*	233.8	-
		Chinook salmon, *Oncorhynchus tshawytscha*	42.26	>4.473
15	86.67	Blacknose dace, *Rhinichthys atratulus*	86.67	-
14	83.97	Creek chub, *Semotilus atromaculatus*	83.97	-
13	82.11	Cutthroat trout, *Salmo clarkii*	66.26	-
		Rainbow trout, *Salmo gairdneri*	42.50	-
		Atlantic salmon, *Salmo salar*	196.6	-
12	78.55	Central stoneroller, *Campostoma anomalum*	78.55	-
11	76.92	Midge, *Chironomus tentans*	197.2	-
		Midge, *Chironomus* sp.	30.00	-
10	69.81	Brown bullhead, *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, *Phyllodoce maculata*	120	-
8	69.28	American lobster, *Homanus americanus*	69.28	-
7	65.60	Black abalone, *Haliotis cracherodii*	50	-
		Red abalone, *Haliotis rufescens*	86.08	-
6	49	Dungeness crab, *Cancer magister*	49	-
5	39.97	Copepod, *Acartia clausi*	52	-
		Copepod, *Acartia tonsa*	30.72	-
4	39	Soft-shell clam, *Mya arenaria*	39	-
3	14.92	Pacific oyster, *Crassostrea gigas*	7.807	-
		Eastern oyster, *Crassostrea virginica*	28.52	-
2	13.93	Summer flounder, *Paralichthys dentatus*	13.93	-
1	5.8	Blue mussel, *Mytilus edulis*	5.8	-

Table 3. (Continued)

* 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.

<u>Fresh water</u>

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(Criterion Maximum Intercept) = ln(9.230) - [slope x ln(50)]

= 2.222 - (0.9422 x 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 = $e^{(0.8545[\ln(\text{hardness})]-1.465)}$

<u>Salt water</u>

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	17,700-22,600	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

[a]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; 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, Mixed species	15 days	Reduced colonization rates	100	Buikema, et al. 1983
Rotifer, *Keratella* sp.	24 hrs	EC50	101	Borgmann & Ralph, 1984
Rotifer, *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, *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, *Goniobasis livescens*	48 hrs	LC50	860	Cairns, et al. 1976
Snail, *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, *Lymnaea emarginata*	48 hrs	LC50	300	Cairns, et al. 1976
Asiatic clam (adult), *Corbicula manilensis*	96 hrs	LC50	>2,600	Harrison, et al. 1981, 1984
Asiatic clam (adult), *Corbicula manilensis*	70 days	ILC	<10	Harrison, et al. 1981, 1984
Asiatic clam (larva), *Corbicula manilensis*	24 hrs	53.1% mortality	25	Harrison, et al. 1981, 1984
Cladoceran, *Daphnia ambigua*	72 hrs	LC50 (fed)	67.7	Winner & Farrell, 1976
Cladoceran, *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 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) (10 C) (15 C) (25 C)	90 70 40 7	Cairns, et al. 1978
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 88.8 85 81.5 81.4 85.3	Winner & Farrell, 1976
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, *Daphnia magna*	24 hrs	50	80	Bringmann & Kuhn, 1977b
Cladoceran (3-5 days), *Daphnia magna*	72 hrs	LC50 (10 C) (15 C) (25 C) (30 C)	61 70 21 9.3	Braginskiy & Shcherban, 1978
Cladoceran (adult), *Daphnia magna*	72 hrs	LC50 (30 C)	0.25	Braginskiy & Shcherban, 1978
Cladoceran, *Daphnia magna*	24 hrs	EC50 (immobilization)	70	Bellavere & Gorbi, 1981
Cladoceran, *Daphnia magna*	48 hrs	EC50 (250 µM Tris) EC50 (1,000 µM Tris)	254 1,239	Borgmann & Ralph, 1983
Cladoceran, *Daphnia magna*	Life cycle	Reduced longevity	60	Winner, 1981
Cladoceran, *Daphnia magna*	48 hrs 21 days Life cycle	LC50 (fed) LC50 (fed) Stopped reproduction	18.5 1.4 3.2	Dave, 1984
Cladoceran, *Daphnia parvula*	72 hrs	LC50 (fed)	57 72	Winner & Farrell, 1976
Cladoceran, *Daphnia parvula*	Life cycle	Reduced productivity	49	Winner & Farrell, 1976
Cladoceran, *Daphnia pulex*	72 hrs	LC50 (fed)	54 86	Winner & Farrell, 1976
Cladoceran, *Daphnia pulex*	Life cycle	Reduced productivity	49	Winner & Farrell, 1976
Cladoceran, *Daphnia pule*	48 hrs	LC50 (5 C) (10 C) (15 C) (25 C)	70 60 20 5.6	Cairns, et al. 1978
Cladoceran, *Daphnia pulex*	100 min	LC50 (15 day) delayed mortality	200	Abel, 1980

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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, *Cloeon dipterum*	72 hrs	LC50 (10 C) (15 C) (25 C) (30 C)	193 95.2 33 4.8	Braginskiy & Shcherban, 1978
Mayfly, *Ephemerella grandis*	14 days	LC50	180-200	Nehring, 1976
Mayfly, *Ephemerella subvaria*	48 hrs	LC50	320	Warnick & Bell, 1969
Stonefly, *Pteronarcys californica*	14 days	LC50	10,100-13,900	Nehring, 1976
Caddisfly, *Hydropsyche betteni*	14 days	LC50	32,000	Warnick & Bell, 1969
Midge, *Chironomus tentans*	20 days	EC50	77.5	Nebeker, et al. 1984a
Midge, *Tanytarsus dissimilis*	10 days	LC50	16.3	Anderson, et al. 1980
Midge, Unidentified	32 wks	Emergence	30	Hedtke, 1984
Coho salmon, *Oncorhynchus kisutch*	96 hrs	Reduced survival when transferred to seawater	30	Lorz & McPherson, 1976
Coho salmon, *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	280 370 190 480 440 460 480 560 780 510 520 480	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 5 days	LC50 LC50	190 178	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 LC10	20 15	Chapman, 1978
Chinook salmon (swim-up), *Oncorhynchus tshawytscha*	200 hrs	LC50 LC10	19 14	Chapman, 1978
Chinook salmon (parr), *Oncorhynchus tshawytscha*	200 hrs	LC50 LC10	30 17	Chapman, 1978

Table 6. (Continued)

Species	Duration	Effect	Result (µg/L)	Reference
Chinook salmon (smolt), *Oncorhynchus tshawytscha*	200 hrs	LC50 LC10	26 18	Chapman, 1978
Rainbow trout, *Salmo gairdneri*	96 hrs	LC50	516** 309** 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 LC10	26 19	Chapman, 1978
Rainbow trout (swim-up), *Salmo gairdneri*	200 hrs	LC50 LC10	17 9	Chapman, 1978
Rainbow trout (parr), *Salmo gairdneri*	200 hrs	LC50 LC10	15 8	Chapman, 1978
Rainbow trout (smolt), *Salmo gairdneri*	200 hrs	LC50 LC10	21 7	Chapman, 1978
Rainbow trout (smolt), *Salmo gairdneri*	96 hrs >10 days	LC50 Threshold LC50	102** 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) (15 C) (30 C)	950 430 150	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; 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	140 130	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 54 48 78 18 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) (15 C) (30 C)	2,700 2,900 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), *Cyprinus carpio*	72 hrs	Prevented hatching	700	Hildebrand & Cushman, 1978
Common carp, *Cyprinus carpio*	48 hrs	LC50	170	Harrison & Rice, 1981
Common carp (embryo), *Cyprinus carpio*	-	EC50 (hatch)	4,775	Kapur & Yadav, 1982
Golden shiner, *Notemigonus crysoleucas*	24 hrs	LC50 (5 C) (15 C) (30 C)	330 230 270	Cairns, et al. 1978;
Striped shiner, *Notropis chrysocephalus*	96 hrs	LC50 (high BOD)	8,400 16,000 3,400 4,000 5,000	Geckler, et al. 1976
Striped shiner, *Notropis chrysocephales*	96 hrs	Decrease blood osmolarity	2,500	Lewis & Lewis, 1971
Bluntnose minnow, *Pimephales notatus*	48 hrs	LC50 (21 tests) (high BOD)	750-21,000	Geckler, et al. 1976
Bluntnose minnow, *Pimephales notatus*	96 hrs	LC50 (6 tests) (high BOD)	1,100-20,000	Geckler, et al. 1976
Fathead minnow, *Pimephales promelas*	96 hrs	LC50 (21 tests) high BOD)	1,610-21,000	Brungs, et al. 1976
Fathead minnow, *Pimephales promelas*	Life cycle	Chronic limits (high BOD)	66-120	Brungs, et al. 1976
Fathead minnow, *Pimephales promelas*	96 hrs	LC50 (36 tests) (high BOD)	<650-23,000	Geckler, et al. 1976
Fathead minnow, *Pimephales promelas*	96 hrs	LC50 (7 tests) (high BOD)	740-13,000	Geckler, et al. 1976
Fathead minnow, *Pimephales promelas*	96 hrs	LC50	231	Curtis, et al. 1979; Curtis & Ward, 1981

Table 6. (Continued)

Species	Duration	Effect	Result (µg/L)	Reference
Fathead minnow, *Pimephales promelas*	96 hrs	LC50 (TOC 12 mg/L)	436	Lind, et al. Manuscript
		(TOC 13 mg/L)	516	
		(TOC 36 mg/L)	1,586	
		(TOC 28 mg/L)	1,129	
		(TOC 15 mg/L)	550	
		(TOC 34 mg/L)	1,001	
		(TOC 30 mg/L)	2,050	
		(TOC 30 mg/L)	2,336	
Fathead minnow, *Pimephales promelas*	96 hrs	LC50 (fish from pond contaminated with heavy metals)	360 410	Birge, et al. 1983
Creek chub, *Semotilus atromaculatus*	96 hrs	LC50 (high BOD)	11,500 1,100	Geckler, et al. 1976
Pearl dace, *Semotilus margarita*	7 hrs	Overturning and death	1,010-279,000	Tsai, 1979
Brown bullhead, *Ictalurus nebulosus*	96 hrs	LC50 (high BOD)	11,000	Geckler, et al. 1976
Channel catfish, *Ictalurus punctatus*	94 hrs	Decreased blood osmolarity	2,500	Lewis & Lewis, 1971
Channel catfish, *Ictalurus punctatus*	24 hrs	LC50 (5 C) (15 C) (30 C)	3,700 2,600 3,100	Cairns, et al. 1978;
Channel catfish, *Ictalurus punctatus*	-	Increased albinism	0.5	Westerman & Birge, 1978
Channel catfish, *Ictalurus punctatus*	10 days	EC50 (death and deformity)	6,620	Birge & Black, 1979
Channel catfish, *Ictalurus punctatus*	14 days	LC50	1,200**	Richey and Roseboom, 1978
Flagfish, *Jordanella floridae*	96 hrs 10 days	LC50 LC50	1,270** 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) (15 C) (30 C)	2,590 2,500 3,820	Cairns, et al. 1978;
Bluegill, *Lepomis macrochirus*	96 hrs	LC50 (high BOD)	16,000 17,000	Geckler, et al. 1976
Bluegill, *Lepomis macrochirus*	14 days	LC50	2,500** 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 5,900 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 7,900 5,400 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, <u>Laminaria hyperboria</u>	28 days	Growth decrease	50	Hopkins & Kain, 1971
Hydroid, <u>Campanularia flexuosa</u>	11 days	Growth rate inhibition	10-13	Stebbing, 1976
Hydroid, <u>Campanularia flexuosa</u>	-	Enzyme inhibition	1.43	Moore & Stebbing, 1976
Hydromedusa, <u>Phialidium</u> sp.	24 hrs	LC50	36	Reeve, et al. 1976
Ctenophore, <u>Pleurobrachia pileus</u>	24 hrs	LC50	33	Reeve, et al. 1976 1976
Ctenophore, <u>Mnemiopsis mccrdayi</u>	24 hrs	LC50	17-29	Reeve, et al. 1976
Rotifer, <u>Brachionus plicatilis</u>	24 hrs	LC50	100	Reeve, et al. 1976
Polychaete worm, <u>Phyllodoce maculata</u>	9 days	LC50	80	McLusky & Phillips, 1975
Polychaete worm, <u>Neanthes arenaceodentata</u>	28 days	LC50	44	Pesch & Morgan, 1978
Polychaete worm, <u>Neanthes arenaceodentata</u>	28 days	LC50	100	Pesch & Morgan, 1978
Polychaete worm, <u>Neanthes arenaceodentata</u>	7 days	LC50	137	Pesch & Hoffman, 1982
Polychaete worm, <u>Neanthes arenaceodentata</u>	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; 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, *Homarus americanus*	13 days	LC50	56	McLeese, 1974
Sea urchin, *Arbacia punctulata*	-	58% decrease in sperm motility	300	Young & Nelson, 1974
Arrow worm, *Sagitta hispida*	24 hrs	LC50	43-460	Reeve, et al. 1976
Atlantic menhaden, *Brevoortia tyrannus*	14 days	LC50	610	Engel, et al. 1976
Pacific herring (embryo), *Clupea harengus pallasi*	6 days	Incipient LC50	33	Rice & Harrison, 1978
Pacific herring (larva), *Clupea harengus pallasi*	48 hrs	Incipient LC50	900	Rice & Harrison, 1978
Atlantic cod (embryo), *Gadus morhua*	14 days	LC50	10	Swedmark & Granmo, 1981
Mummichog, *Fundulus heteroclitus*	21 days	Histopathological lesions	<500	Gardner & La Roche, 1973
Mummichog, *Fundulus heteroclitus*	96 hrs	Enzyme inhibition	600	Jackim, 1973
Atlantic silverside, *Menidia menidia*	96 hrs	Histopathological lesions	<500	Gardner & LaRoche, 1973
Pinfish, *Lagodon rhomboides*	14 days	LC50	150	Engel, et al. 1976
Spot, *Leiostomus xanthurus*	14 days	LC50	160	Engel, et al. 1976
Atlantic croaker, *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

* In river water.

**Dissolved copper; no other measurement reported.

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