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Ambient Water Quality Criteria for

Copper - 1984

AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR

COPPER

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FOREWORD

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

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

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

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Introduction*

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Acute Toxicity to Aquatic Animals

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

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

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

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

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

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

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

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

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

Chronic Toxicity to Aquatic Animals

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

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

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

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

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

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

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

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

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

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

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

Toxicity to Aquatic Plants

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

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

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

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

Bioaccumulation

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

Other Data

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

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

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

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

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

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

Unused Data

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

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

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

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

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

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

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

Summary

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

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

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

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

National Criteria

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

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

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

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

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

Table 1. Acute Toxicity of Copper to Aquatic Animals

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

Table 1. (Continued)

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

Table 1. (Continued)

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

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)***	Reference
Crayfish, *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)**	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

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 I. (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. 1984
Chinook salmon, *Oncorhynchus tshawytscha*	ELS	Copper chloride	23	<7.4***	<7.4	Chapman, 1975, 1982
Rainbow trout, *Salmo gairdneri*	ELS	Copper sulfate	45.4	11.4-31.7	19.01	McKim, et al. 1978
Brown trout, *Salmo trutta*	ELS	Copper sulfate	45.4	22.0-43.2	30.83	McKim, et al. 1978
Brook trout, *Salvelinus fontinalis*	LC	Copper sulfate	45	9.5-17.4	12.86	McKim & Benoit, 1971
Brook trout, *Salvelinus fontinalis*	ELS	Copper sulfate	45.4	22.3-43.5	31.15	McKim, et al. 1978
Brook trout, *Salvelinus fontinalis*	ELS	Copper sulfate	37.5	3-5	3.873	Sauter, et al. 1976
Lake trout, *Salvelinus namaycush*	ELS	Copper sulfate	45.4	22.0-42.3	30.51	McKim, et al. 1978

Table 2. (Continued)

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

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

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

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

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

Rank*	Genus Mean Acute Value (μg/L)**	Species	Species Mean Acute Value (μg/L)**	Species Mean Acute-Chronic Ratio
		FRESHWATER SPECIES		
41	10,240	Stonefly, *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, *Homarus 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)

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

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

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

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

<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

*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	LC50	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	Braginsky & Shcherban, 1978
Cladoceran (adult), *Daphnia magna*	72 hrs	LC50 (30 C)	0.25	Braginsky & 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 & R-lph, 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

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, <u>Cloeon dipterum</u>	72 hrs	LC50 (10 C) (15 C) (25 C) (30 C)	193 95.2 53 4.8	Braginskiy & Shcherban, 1978
Mayfly, <u>Ephemerella grandis</u>	14 days	LC50	180-200	Nehring, 1976
Mayfly, <u>Ephemerella subvaria</u>	48 hrs	LC50	320	Warnick & Bell, 1969
Stonefly, <u>Pteronarcys californica</u>	14 days	LC50	10,100-13,900	Nehring, 1976
Caddisfly, <u>Hydropsyche betteni</u>	14 days	LC50	32,000	Warnick & Bell, 1969
Midge, <u>Chironomus tentans</u>	20 days	EC50	77.5	Nebeker, et al. 1984a
Midge, <u>Tanytarsus dissimilis</u>	10 days	LC50	16.3	Anderson, et al. 1980
Midge, Unidentified	32 wks	Emergence	30	Hedtke, 1984
Coho salmon, <u>Oncorhynchus kisutch</u>	96 hrs	Reduced survival when transferred to seawater	30	Lorz & McPherson, 1976
Coho salmon, <u>Oncorhynchus kisutch</u>	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) (TOC 13 mg/L) (TOC 36 mg/L) (TOC 28 mg/L) (TOC 15 mg/L) (TOC 34 mg/L) (TOC 30 mg/L) (TOC 30 mg/L)	436 516 1,586 1,129 550 1,001 2,050 2,336	Lind, et al. Manuscript
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, *Laminaria hyperboria*	28 days	Growth decrease	50	Hopkins & Kain, 1971
Hydroid, *Campanularia flexuosa*	11 days	Growth rate inhibition	10-13	Stebbing, 1976
Hydroid, *Campanularia flexuosa*	-	Enzyme inhibition	1.43	Moore & Stebbing, 1976
Hydromedusa, *Phialidium* sp.	24 hrs	LC50	36	Reeve, et al. 1976
Ctenophore, *Pleurobrachia pileus*	24 hrs	LC50	33	Reeve, et al. 1976 1976
Ctenophore, *Mnemiopsis mccrdayi*	24 hrs	LC50	17-29	Reeve, et al. 1976
Rotifer, *Brachionus plicatilis*	24 hrs	LC50	100	Reeve, et al. 1976
Polychaete worm, *Phyllodoce maculata*	9 days	LC50	80	McLusky & Phillips, 1975
Polychaete worm, *Neanthes arenaceodentata*	28 days	LC50	44	Pesch & Morgan, 1978
Polychaete worm, *Neanthes arenaceodentata*	28 days	LC50	100	Pesch & Morgan, 1978
Polychaete worm, *Neanthes arenaceodentata*	7 days	LC50	137	Pesch & Hoffman, 1982
Polychaete worm, *Neanthes arenaceodentata*	10 days	LC50	98	Pesch & Hoffman, 1982

Table 6. (Continued)

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

Table 6. (Continued)

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

REFERENCES

Abbe, G.R. 1982. Growth, mortality, and copper-nickel accumulation by oysters (Crassostrea virginica) at the Morgantown steam electric station on the Potomac River, Maryland. Jour. Shellfish Res. 2: 3.

Abel, P.D. 1980. A new method for assessing the lethal impact of short-term, high-level discharges of pollutants on aquatic animals. Prog. Water Technol. 13: 347.

Academy of Natural Sciences. 1960. The sensitivity of aquatic life to certain chemicals commonly found in industrial wastes. Philadelphia, Pennsylvania.

Adema, D.M.M. and A.M. Degroot-Van Zijl. 1972. The influence of copper on the water flea Daphnia magna. TNO Nieuws 27: 474.

Ahsanullah, M., et al. 1981. Toxicity of zinc, cadmium and copper to the shrimp Callianassa australiensis. I. effects of individual metals. Mar. Biol. 64: 299.

Allen, H.E., et al. 1983. An algal assay method for determination of copper complexation capacities of natural waters. Bull. Environ. Contam. Toxicol. 30: 448.

Anderson, B.G. 1944. The toxicity thresholds of various substances found in industrial wastes as determined by Daphnia magna. Sew. Works Jour. 16: 1156.

Anderson, B.G. 1948. The apparent thresholds of toxicity to *Daphnia magna* for chlorides of various metals when added to Lake Erie water. Trans. Am. Fish. Soc. 78: 96.

Anderson, P.D. and P.A. Spear. 1980a. Copper pharmacokinetics in fish gills - I. kinetics in pumpkinseed sunfish, *Lepomis gibbosus*, of different body sizes. Water Res. 14: 1101.

Anderson, P.D. and P.A. Spear. 1980b. Copper pharmacokinetics in fish gills - II. body size relationships for accumulation and tolerance. Water Res. 14: 1107.

Anderson, R.L., et al. 1980. Survival and growth of *Tanytarsus dissimilis* (Chironomidae) exposed to copper, cadmium, zinc, and lead. Arch. Environ. Contam. Toxicol. 9: 329.

Andrew, R.W. 1976. Toxicity relationships to copper forms in natural waters. *In*: R.W. Andrew, et al. (eds.), Toxicity to Biota of Metal Forms in Natural Water. International Joint Commission, Windsor, Ontario, Canada. p. 127.

Andrew, R.W., et al. 1977. Effects of inorganic complexing on toxicity of copper to *Daphnia magna*. Water Res. 11: 309.

Andros, J.D. and R.R. Garton. 1980. Acute lethality of copper, cadmium, and zinc to northern squawfish. Trans. Am. Fish. Soc. 109: 235.

Arillo, A., et al. 1984. Biochemical effects of long-term exposure to cadmium and copper on rainbow trout (Salmo gairdneri): validation of water quality criteria. Ecotoxicol. Environ. Safety 8: 106.

Arthur, J.W. and E.N. Leonard. 1970. Effects of copper on Gammarus pseudolimnaeus, Physa integra, and Campeloma decisum in soft water. Jour. Fish. Res. Board Can. 27: 1277.

Bailey, H.C. and D.H.W. Liu. 1980. Lumbricalus variegatus, a benthic oligochaete, as a bioassay organism. In: J.G. Eaton, et al. (eds.), Aquatic Toxicology. ASTM STP 707. American Society for Testing and Materials, Philadelphia, Pennsylvania. p. 205.

Baker, J.T.P. 1969. Histological and electron microscopical observations on copper poisoning in the winter flounder (Pseudopleuronectes americanus). Jour. Fish. Res. Board Can. 26: 2785.

Baker, R.J., et al. 1983. Susceptibility of chinook salmon, Oncorhynchus tshawytscha (Walbaum), and rainbow trout, Salmo gairdneri Richardson, to infection with Vibrio anguillarum following sublethal copper exposure. Jour. Fish Diseases 6: 267.

Bartlett, L., et al. 1974. Effects of copper, zinc and cadmium on Selanastrum capricornutum. Water Res. 8: 179.

Baudouin, M.F. and P. Scoppa. 1974. Acute toxicity of various metals to freshwater zooplankton. Bull. Environ. Contam. Toxicol. 12: 745.

Bellavere, C. and J. Gorbi. 1981. A comparative analysis of acute toxicity of chromium, copper and cadmium to Daphnia magna, Biomphalaria glabrata, and Brachydanio rerio. Environ. Technol. Letters 2: 119.

Benoit, D.A. 1975. Chronic effects of copper on survival, growth, and reproduction of the bluegill (Lepomis macrochirus). Trans. Am. Fish. Soc. 104: 353.

Betzer, S.B. and P.P. Yevich. 1975. Copper toxicity in Busycon canaliculatun L. Biol. Bull. 148: 16.

Biesinger, K.E. and G.M. Christensen. 1972. Effects of various metals on survival, growth, reproduction, and metabolism of Daphnia magna. Jour. Fish Res. Board Can. 29: 1691.

Bills, T.D., et al. 1981. Polychlorinated biphenyl (Aroclor 1254) residues in rainbow trout: effects on sensitivity to nine fishery chemicals. North Am. Jour. Fish. Manage. 1: 200.

Birdsong, C.L. and J.W. Avavit, Jr. 1971. Toxicity of certain chemicals to juvenile pompano. Prog. Fish-Cult. 33: 76.

Birge, W.J. 1978. Aquatic toxicology of trace elements of coal and fly ash. In: J.H. Thorp and J.W. Gibbons (eds.), Energy and Environmental Stress in Aquatic Systems. CONF-771114. National Technical Information Service, Springfield, Virginia. p. 219.

Birge, W.J. and J.A. Black. 1979. Effects of copper on embryonic and juvenile stages of aquatic animals. In: J.O. Nriagu (ed.), Copper in the Environment. Part II. Wiley, New York. p. 374.

Birge, W.J., et al. 1978. Embryo-larval bioassays on inorganic coal elements and in situ biomonitoring of coal-waste effluents. In: D.E. Samuel, et al. (eds.), Surface Mining and Fish/Wildlife Needs in the Eastern United States. PB 298353. National Technical Information Service, Springfield, Virginia. p. 97.

Birge, W.J., et al. 1980. Aquatic toxicity tests on inorganic elements occurring in oil shale. In: C. Gale (ed.), Oil Shale Symposium: Sampling, Analysis and Quality Assurance. EPA-600/9-80-022. National Technical Information Service, Springfield, Virginia. p. 519.

Birge, W.J., et al. 1981. The reproductive toxicology of aquatic contaminants. In: J. Saxena and F. Fisher (eds.), Hazard Assessment of Chemicals: Current Developments. Vol. 1. Academic Press, New York. p. 59.

Birge, W.J., et al. 1983. Induction of tolerance to heavy metals in natural and laboratory populations of fish. PB84-111756. National Technical Information Service, Springfield, Virginia.

Black, G.A.P., et al. 1976. Annotated list of copper concentrations found harmful to aquatic organisms. Technical Report 603. Environment Canada, Burlington, Ontario.

Black, J.A. 1974. The effect of certain organic pollutants on copper toxicity to fish (Lebistes reticulatus). Ph.D. Thesis. University of Michigan, Ann Arbor.

Black, J.A. and W.J. Birge. 1980. An avoidance response bioassay for aquatic pollutants. PB80-180490. National Technical Information Service, Springfield, Virginia.

Borgmann, U. 1981. Determination of free metal ion concentrations using bioassays. Can. Jour. Fish. Aquat. Sci. 38: 999.

Borgmann, U. and K.M. Ralph. 1983. Complexation and toxicity of copper and the free metal bioassay technique. Water Res. 17: 1697.

Borgmann, U. and K.M. Ralph. 1984. Copper complexation and toxicity to freshwater zooplankton. Arch. Environ. Contam. Toxicol. 13: 403.

Bougis, P. 1965. Effect of copper on growth of the pluteus of the sea urchin (Paracentrotus lividus). C.R. Hebd. Seances Acad. Sci. 260: 2929.

Bouquegneau, J.M. and M. Martoja. 1982. La teneur en cuivre et son degre de complexation chez quatre gasteroposed marins. Donnees sur le cadmium et le zinc. Oceanologica Acta 5: 219.

Boutet, C. and C. Chaisemartin. 1973. Specific toxic properties of metallic salts in Austropotamobius pallipes pallipes and Orconectes limosus. C.R. Soc. Biol. 167: 1973.

Boyle, E.A. 1979. Copper in natural waters. In: J.O. Nriagu (ed.), Copper in the Environment. Part I: Ecological Cycling. Wiley, New York. p. 77.

Braginskiy, L.P. and E.P. Shcherban. 1978. Acute toxicity of heavy metals to aquatic invertebrates at different temperatures. Hydrobiol. Jour. 14(6): 78.

Bringmann, G. 1975. Determination of the biologically harmful effect of water pollutants by means of the retardation of cell proliferation of the blue algae Microcystis. Gesundheits-Ing. 96: 238.

Bringmann, G. 1978. Determination of the biological toxicity of water-bound substances towards protozoa. I. bacteriovorous flagellates (model organism: Entosiphon sulcatum Stein). Z. Wasser Abwasser Forsch. 11: 210.

Bringmann, G. and R. Kuhn. 1959a. The toxic effects of waste water on aquatic bacteria, algae, and small crustaceans. Gesundheits-Ing. 80: 115.

Bringmann, G. and R. Kuhn. 1959b. Water toxicology studies with protozoans as test organisms. Gesundheits-Ing. 80: 239.

Bringmann, G. and R. Kuhn. 1976. Comparative results of the damaging effects of water pollutants against bacteria (*Pseudomonas putida*) and blue algae (*Microcystis aeruginosa*). Gas-Wasserfach, Wasser-Abwasser 117: 410.

Bringmann, G. and R. Kuhn. 1977a. Limiting values for the damaging action of water pollutants to bacteria (*Pseudomonas putida*) and green algae (*Scenedesmus quadricauda*) in the cell multiplication inhibition test. Z. Wasser Abwasser Forsch. 10: 87.

Bringmann, G. and R. Kuhn. 1977b. Results of the damaging effect of water pollutants on *Daphnia magna*. Z. Wasser Abwasser Forsch. 10: 161.

Bringmann, G. and R. Kuhn. 1978a. Limiting values for the noxious effects of water pollutant material to blue algae (*Microcystis aeruginosa*) and green algae (*Scenedesmus quadricauda*) in cell propagation inhibition tests. Vom Wasser 50: 45.

Bringmann, G. and R. Kuhn. 1978b. Testing of substances for their toxicity threshold: model organisms *Microcystis* (*Diplocystis*) *aeruginosa* and *Scenedesmus quadricauda*. Mitt. Int. Ver. Theor. Angew. Limnol. 21: 275.

Bringmann, G. and R. Kuhn. 1979. Comparison of toxic limiting concentrations of water contaminants toward bacteria, algae, and protozoa in the cell-growth inhibition test. Haustech. Bauphys. Umwelttech. 100: 249.

Bringmann, G. and R. Kuhn. 1980a. Determination of the harmful biological effect of water pollutants on protozoa. II. bacteriovorous ciliates. Z. Wasser Abwasser Forsch. 13: 26.

Bringmann, G. and R. Kuhn. 1980b. Comparison of the toxicity thresholds of water pollutants to bacteria, algae, and protozoa in the cell multiplication inhibition test. Water Res. 14: 231.

Bringmann, G. and R. Kuhn. 1981. Comparison of the effects of harmful substances on flagellates as well as ciliates and on halozoic bacteriophagous and saprozoic protozoa. Gas-Wasserfach, Wasser-Abwasser 122: 308.

Bringmann, G. and R. Kuhn. 1982. Results of toxic action of water pollutants on _Daphnia magna_ Straus tested by an improved standardized procedure. Z. Wasser Abwasser Forsch. 15: 1.

Bringmann, G., et al. 1980. Determination of the biological damage from water pollutants to protozoa. III. saprozoic flagellates. Z. Wasser Abwasser Forsch. 13: 170.

Brkovic-Popovic, I. and M. Popovic. 1977a. Effects of heavy metals on survival and respiration rate of tubificid worms: Part I-effects on survival. Environ. Pollut. 13: 65.

Brkovic-Popovic, I. and M. Popovic. 1977b. Effects of heavy metals on survival and respiration rate of tubificid worms: Part II-effects on respiration rate. Environ. Pollut. 13: 93.

Brown, B.T. and B.M. Rattigan. 1979. Toxicity of soluble copper and other metal ions to Elodea canadensis. Environ. Pollut. 18: 303.

Brown, V.M. 1968. The calculations of the acute toxicity of mixtures of poisons to rainbow trout. Water Res. 2: 723.

Brown, V.M. and R.A. Dalton. 1970. The acute toxicity to rainbow trout of mixtures of copper, phenol, zinc and nickel. Jour. Fish Biol. 2: 211.

Brown, V.M., et al. 1974. Aspects of water quality and toxicity of copper to rainbow trout. Water Res. 8: 797.

Brungs, W.A., et al. 1973. Acute and long-term accumulation of copper by the brown bullhead, Ictalurus nebulosus. Jour. Fish. Res. Board Can. 30: 583.

Brungs, W.A., et al. 1976. Acute and chronic toxicity of copper to the fathead minnow in a surface water of variable quality. Water Res. 10: 37.

Buckley, J.A. 1983. Complexation of copper in the effluent of a sewage treatment plant and an estimate of its influence on toxicity to coho salmon. Water Res. 17: 1929.

Buckley, J.T., et al. 1982. Chronic exposure of coho salmon to sublethal concentrations of copper - I. effect on growth, on accumulation and distribution of copper, and on copper tolerance. Comp. Biochem. Physiol. 72C: 15.

Buikema, A.L., Jr., et al. 1974a. Rotifers as monitors of heavy metal pollution in water. Bulletin 71. Virginia Water Resources Research Center, Blacksburg, Virginia.

Buikema, A.L., Jr., et al. 1974b. Evaluation of Philodina acutacornis (Rotifera) as a bioassay organism for heavy metals. Water Resources Bull. 10: 648.

Buikema, A.L., Jr., et al. 1977. Rotifer sensitivity to combinations of inorganic water pollutants. Bulletin 92. Virginia Water Resources Research Center, Blacksburg, Virginia.

Buikema, A.L., Jr., et al. 1983. Correlation between the autotrophic index and protozoan colonization rates as indicators of pollution stress. In: W.E. Bishop, et al. (eds.), Aquatic Toxicology and Hazard Assessment: Sixth Symposium. ASTM STP 802. American Society for Testing and Materials, Philadelphia, Pennsylvania. p. 204.

Cabejszek, I. and M. Stasiak. 1960. Studies on the influences of some metals on water biocenosis employing Daphnia magna. Rozniki Panst. Zakl. 11: 303.

Cairns, J., Jr., and A. Scheier. 1968. A comparison of the toxicity of some common industrial waste components tested individually and combined. Prog. Fish-Cult. 30: 3.

Cairns, J., Jr., et al. 1976. Invertebrate response to thermal shock following exposure to acutely sub-lethal concentrations of chemicals. Arch. Hydriobiol. 77: 164.

Cairns, J., Jr., et al. 1978. Effects of temperature on aquatic organism sensitivity to selected chemicals. Bulletin 106. Virginia Water Resources Research Center, Blacksburg, Virginia.

Cairns, J., Jr., et al. 1980. Effects of a sublethal dose of copper sulfate on the colonization rate of freshwater protozoan communities. Am. Midland Natur. 104: 93.

Cairns, J., Jr., et al. 1981. Effects of fluctuating, sublethal applications of heavy metal solutions upon the gill ventilation response of bluegills (Lepomis macrochirus). EPA-600/3-81-003. National Technical Information Service, Springfield, Virginia.

Calabarese, A., et al. 1973. The toxicity of heavy metals to embryos of the American oyster Crassostrea virginica. Mar. Biol. 18: 162.

Calabrese, A., et al. 1977. Survival and growth of bivalve larvae under heavy-metal stress. Mar. Biol. 41: 179

Calamari, D. and R. Marchetti. 1973. The toxicity of mixtures of metals and surfactants to rainbow trout (Salmo gairdneri Rich.). Water Res. 7: 1453.

Calamari, D. and R. Marchetti. 1975. Predicted and observed acute toxicity of copper and ammonia to rainbow trout (Salmo gairdneri Rich.). Prog. Water Technol. 7: 569.

Callahan, M.A., et al. 1979. Water-related environmental fate of 129 priority pollutants. Vol. I. EPA-440/4-79-029a. National Technical Information Service, Springfield, Virginia.

Cardin, J.A. 1982. Memorandum to John H. Gentile. U.S. EPA, Narragansett, Rhode Island.

Chakoumakos, C., et al. 1979. The toxicity of copper to cutthroat trout (Salmo clarki) under different conditions of alkalinity, pH, and hardness. Environ. Sci. Technol. 13: 213.

Chapman, G.A. 1975. Toxicity of copper, cadmium and zinc to Pacific Northwest salmonids. U.S. EPA, Corvallis, Oregon.

Chapman, G.A. 1978. Toxicities of cadmium, copper, and zinc to four juvenile stages of chinook salmon and steelhead. Trans. Am. Fish. Soc. 107: 841.

Chapman, G.A. 1982. Letter to Charles E. Stephan. U.S. EPA, Corvallis, Oregon. December 6.

Chapman, G.A. and J.K. McCrady. 1977. Copper toxicity: a question of form. In: R.A. Tubb (ed.), Recent Advances in Fish Toxicology. EPA-600/3-77-085. National Technical Information Service, Springfield, Virginia. p. 132.

Chapman, G.A. and D.G. Stevens. 1978. Acute lethal levels of cadmium, copper, and zinc to adult male coho salmon and steelhead. Trans. Am. Fish. Soc. 107: 837.

Chapman, G.A., et al. Manuscript. Effects of water hardness on the toxicity of metals to Daphnia magna. U.S. EPA, Corvallis, Oregon.

Chapman, W.H., et al. 1968. Concentration factors of chemical elements in edible aquatic organisms. UCRL-50564. National Technical Information Service, Springfield, Virginia.

Christensen, E.R., et al. 1979. Effects of manganese, copper and lead on Selenastrum capricornutum and Chlorella stigmatophora. Water Res. 13: 79.

Chynoweth, D.P., et al. 1976. Effect of organic pollutants on copper toxicity to fish. In: R.W. Andrew, et al. (eds.), Toxicity to Biota of Metal Forms in Natural Water. International Joint Commission, Windsor, Ontario, Canada. p. 145.

Clendenning, K.A. and W.J. North. 1959. Effects of wastes on the giant kelp, Macrocystis pyrifera. In: E.A. Pearson, (ed.), Proc. 1st Int. Conf. Waste Disposal in the Marine Environment. Berkeley, California. p. 82.

Coglianese, M. and M. Martin. 1981. Individual and interactive effects of environmental stress on the embryonic development of the Pacific oyster, Crassostrea gigas. Part I. toxicity of copper and silver. Mar. Environ. Res. 5: 13.

Collvin, L. 1984. The effects of copper on maximum respiration rate and growth rate of perch, Perca fluviatilis L. Water Res. 18: 139.

Connor, P.M. 1972. Acute toxicity of heavy metals to some marine larvae. Mar. Pollut. Bull. 3: 190.

Cope, O.B. 1966. Contamination of the freshwater ecosystems by pesticides. Jour. Appl. Ecol. 3 (Suppl.): 33.

Cosson, R.P. and J.L.M. Martin. 1981. The effects of copper on the embryonic development, larvae, alevins, and juveniles of Dicentrorchus labrox (L). Rapp. P.V. Reun. Cons. Int. Explor. Mer. 178: 71.

Cote, R. 1983. Toxic aspects of copper on the biomass and productivity of phytoplankton in the Saguenay River, Quebec. Hydrobiologia 98: 85.

Crecelius, E.A., et al. 1982. Copper bioavailability to marine bivalves and shrimp: relationship to cupric ion activity. Mar. Environ. Res. 6: 13.

Curtis, M.W. and C.H. Ward. 1981. Aquatic toxicity of forty industrial chemicals: testing in support of hazardous substance spill prevention regulation. Jour. Hydrol. 51: 359.

Curtis, M.W., et al. 1979. Acute toxicity of 12 industrial chemicals to freshwater and saltwater organisms. Water Res. 13: 137.

Daoust, P. 1981. Acute pathological effects of mercury, cadmium and copper in rainbow trout. Ph.D. Thesis. Saskatoon, Saskatchewan.

Dave, G. 1984. Effects of copper on growth, reproduction, survival and haemoglobin in Daphnia magna. Comp. Biochem. Physiol. 78C: 439.

Davis, J.C. and I.G. Shand. 1978. Acute and sublethal copper sensitivity, growth and saltwater survival in young Babine Lake sockeye salmon. Technical Report No. 847. Environment Canada, West Vancouver, British Columbia.

Debelak, R.W. 1975. Acute toxicity of mixtures of copper, chromium, and cadmium to Daphnia magna. Thesis. Miami University, Oxford, Ohio.

de March, B.G.E. 1979. Survival of Hyallela azteca (Saussure) raised under different laboratory conditions in a pH bioassay, with reference to copper toxicity. Technical Report No. 892. Environment Canada, Winnipeg, Manitoba.

Demayo, A., et al. 1982. Effects of copper on humans, laboratory and farm animals, terrestrial plants, and aquatic life. CRC Crit. Rev. Environ. Control 12: 183.

Deshmukh, S.S. and V.B. Marathe. 1980. Size related toxicity of copper and mercury to Lebistes reticulata (Peter), Labeo rohita (Ham.) and Cyprinus carpio (Linn.). Indian Jour. Exp. Biol. 18: 421.

Dixon, D.G. and J.W. Hilton. 1981. Influence of available dietary carbohydrate content on tolerance of waterborne copper by rainbow trout, _Salmo gairdneri_ Richardson. Jour. Fish Biol. 19: 509.

Dixon, D.G. and J.B. Sprague. 1981a. Acclimation to copper by rainbow trout (_Salmo gairdneri_) - a modifying factor in toxicity. Can. Jour. Fish. Aquat. Sci. 38: 880.

Dixon, D.G. and J.B. Sprague. 1981b. Copper bioaccumulation and hepatoprotein synthesis during acclimation to copper by juvenile rainbow trout. Aquat. Toxicol. 1: 69.

Dixon, W.J. and M.B. Brown, eds. 1979. BMDP Biomedical Computer Programs, P-series. University of California, Berkeley, California. p. 521.

Dodge, E.E. and T.L. Theis. 1979. Effect of chemical speciation on the uptake of copper by _Chironomus tentans_. Environ. Sci. Technol. 13: 1287.

Donaldson, E.M. and H.M. Dye. 1975. Corticosteriod concentrations in sockeye salmon (_Oncorhynchus nerka_) exposed to low concentrations of copper. Jour. Fish. Res. Board Can. 32: 533.

Drummond, R.A., et al. 1973. Some short-term indicators of sublethal effects of copper on brook trout, _Salvelinus fontinalis_. Jour. Fish. Res. Board Can. 30: 698.

Eisler, R. 1977. Acute toxicities of selected heavy metals to the softshell clam, Mya arenaria. Bull. Environ. Contam. Toxicol. 17: 137.

Eisler, R. 1981. Trace Metal Concentrations in Marine Organisms. Pergamon Press, New York.

Eisler, R., et al. 1979. Fourth annotated bibliography on biological effects of metals in aquatic environments. EPA-600/3-79-084. National Technical Information Service, Springfield, Virginia.

Elder, J.F. and A.J. Horne. 1978. Copper cycles and $CuSO_4$ algicidal capacity in two California lakes. Environ. Manage. 2: 17.

Engel, D.W., et al. 1976. Effects of copper on marine eggs and larvae. Environ. Health Perspect. 17: 287.

Erickson, S.J. 1972. Toxicity of copper to Thalassiosira pseudonona in unenriched inshore seawater. Jour. Phycol. 84: 318.

Erickson, S.J., et al. 1970. A screening technique for estimating copper toxicity to estuarine phytoplankton. Jour. Water Pollut. Control Fed. 42: R270.

Evans, M.L. 1980. Copper accumulation in the crayfish (Orconectes rusticus). Bull. Environ. Contam. Toxicol. 24: 916.

Ewing, M.S., et al. 1982. Sublethal copper stress and susceptibility of channel catfish to experimental infections with Ichthyophthirius multifiliis. Bull. Environ. Contam. Toxicol. 28: 674.

Ferard, J.F., et al. 1983. Value of dynamic tests in acute ecotoxicity assessment in algae. In: W.C. McKay (ed.), Proceedings of the Ninth Annual Aquatic Toxicity Workshop. Can. Tech. Rept. Fish. Aquat. Sci. No. 1163. University of Alberta, Edmonton, Alberta. p. 38.

Ferreira, K.T.G. 1978. The effect of copper on frog skin: the role of sulphydryl groups. Biochim. Biophys. Acta 510: 298.

Ferreira, K.T.G., et al. 1979. The mechanism of action of Cu^{2+} on the frog skin. Biochim. Biophys. Acta 552: 341.

Filbin, D.J. and R.A. Hough. 1979. The effects of excess copper sulfate on the metabolism of the duckweed Lemna minor. Aquat. Bot. 7: 79.

Finlayson, B.J. and S.H. Ashuckian. 1979. Safe zinc and copper levels from the Spring Creek drainage for steelhead trout in the Upper Sacremento River, California. California Fish Game 65: 80.

Finlayson, B.J. and K.M. Verrue. 1982. Toxicities of copper, zinc, and cadmium mixtures to juvenile chinook salmon. Trans. Am. Fish. Soc. 111: 645.

Fisher, N.S. 1981. On the selection for heavy metal tolerance, diatoms from the Derwent Estuary, Tasmania. Aust. Jour. Mar. Freshwater Res. 32: 555.

Fisher, N.S. and J.G. Fabris. 1982. Complexation of Cu, Zn and Cd by metabolites excreted from marine diatoms. Mar. Chem. 11: 245.

Fisher, N.S. and G.J. Jones. 1981. Heavy metals and marine phytoplankton: correlation of toxicity and sulfhydryl-binding. Jour. Phycol. 17: 108.

Fogels, A. and J.B. Sprague. 1977. Comparative short-term tolerance of zebrafish, flagfish, and rainbow trout to five poisons including potential reference toxicants. Water Res. 11: 811.

Folmar, L.C. 1976. Overt avoidance reaction of rainbow trout fry to nine herbicides. Bull. Environ. Contam. Toxicol. 15: 509.

Foster, P.L. 1982. Metal resistances of chlorophyta from rivers polluted by heavy metals. Freshwater Biol. 12: 41.

Frey, R.A., et al. 1978. Copper-algae equilibria in complexing situations. Proc. Pennsylvania Acad. Sci. 52: 179.

Furmanska, M. 1979. Studies of the effect of copper, zinc and iron on the biotic components of aquatic ecosystems. Pol. Arch. Hydrobiol. 26: 213.

Gachter, R., et al. 1973. Complexing capacity of the nutrient medium and its relation to inhibition of algal photosynthesis by copper. Schweiz. Z. Hydrol. 35: 252.

Gardner, G.R. and G. LaRoche. 1973. Copper induced lesions in estuarine teleosts. Jour. Fish. Res. Board Can. 30: 363.

Gavis, J., et al. 1981. Cupric ion activity and the growth of phytoplankton clones isolated from different marine environments. Jour. Mar. Res. 39: 315.

Geckler, J.R., et al. 1976. Validity of laboratory tests for predicting copper toxicity in streams. EPA-600/3-76-116. National Technical Information Service, Springfield, Virginia.

Gentile, S.M. 1982. Memorandum to John H. Gentile. U.S. EPA, Narragansett, Rhode Island.

Giattina, J.D., et al. 1982. Avoidance of copper and nickel by rainbow trout as monitored by a computer-based data acquisition system. Trans. Am. Fish. Soc. 111: 491.

Gibbs, P.E., et al. 1981. Copper accumulation by the polychaete _Melinna palmata_: an antipredation mechanism? Jour. Mar. Biol. Assoc. U.K. 61: 707.

Giesy, J.P., et al. 1983. Copper speciation in soft, acid, humic waters: effects on copper bioaccumulation by and toxicity to *Simocephalus serrulatus* (Daphnidae). Sci. Total Environ. 28: 23.

Giles, M.A. and J.F. Klaverkamp. 1982. The acute toxicity of vanadium and copper to eyed eggs of rainbow trout (*Salmo gairdneri*). Water Res. 16: 885.

Gillespie, P.A. and R.F. Vaccaro. 1978. A bacterial bioassay for measuring the copper-chelation capacity of seawater. Limnol. Oceanogr. 23: 543.

Goettl, J.P., et al. 1972. Water pollution studies. *In*: Colorado Fisheries Research Review No. 7. Colorado Division of Wildlife, Fort Collins. p. 36.

Gordon, M., et al. 1980. *Mytilus californianai* as a bioindicator of trace metal pollution: variability and statistical considerations. Mar. Pollut. Bull. 11: 195.

Grande, M. 1966. Effect of copper and zinc on salmonid fishes. Adv. Water Pollut. Res. 1: 97.

Graney, R.L., Jr., et al. 1983. Heavy metal indicator potential of the Asiatic clam (*Corbicula fluminea*) in artificial stream systems. Hydrobiologia 102: 81.

Guy, R.D. and A.R. Kean. 1980. Algae as a chemical speciation monitor - I. a comparison of algae growth and computer calculated speciation. Water Res. 14: 891.

Hale, J.G. 1977. Toxicity of metal mining wastes. Bull. Environ. Contam. Toxicol. 17: 66.

Hall, A. 1980. Heavy metal co-tolerance in a copper-tolerant population of the marine fouling alga, Ecrocarpus siliculosus (Dillu.) Lyngbye. New Phytol. 85: 73.

Hansen, D.J. 1983. Memorandum to William A. Brungs. U.S. EPA, Narragansett, Rhode Island.

Hara, T., et al. 1976. Effects of mercury and copper on the olfactory response in rainbow trout, Salmo gairdneri. Jour. Fish. Res. Board Can. 33: 1568.

Harrison, F.L. and D.J. Bishop. 1984. A review of the impact of copper released into freshwater environments. UCRL-53488. National Technical Information Service, Springfield, Virginia.

Harrison, F.L. and J.R. Lam. 1983. Partitioning of copper among copper-binding proteins in the mussel Mytilus edulis exposed to soluble copper. Estuarine Research Federation Meeting, Virginia Beach, Virginia. October.

Harrison, F.L. and D.W. Rice, Jr. 1981. The sensitivity of adult, embryonic, and larval carp Cyprinus carpio to copper. UCRL-52726. National Technical Information Service, Springfield, Virginia.

Harrison, F.L., et al. 1981. Effects of copper on adult and early life stages of the freshwater clam, Corbicula manilensis. UCRL-52741. National Technical Information Service, Springfield, Virginia.

Harrison, F.L., et al. 1983. Sublethal responses of Mytilus edulis to increased dissolved copper. Sci. Total Environ. 28: 141.

Harrison, F.L., et al. 1984. The toxicity of copper to the adult and early life stages of the freshwater clam, Corbicula manilensis. Arch. Environ. Contam. Toxicol. 13: 85.

Hawkins, P.R. and D.J. Griffith. 1982. Uptake and retention of copper by four species of marine phytoplankton. Bot. Mar. 25: 551.

Hazel, C.R. and S.J. Meith. 1970. Bioassay of king salmon eggs and sac fry in copper solutions. California Fish Game. 56: 121.

Heath, A.G. 1984. Changes in tissue adenylates and water content of bluegill, Lepomis macrochirus, exposed to copper. Jour. Fish Biol. 24: 299.

Hedtke, S.F. 1984. Structure and function of copper-stressed aquatic microcosms. Aquat. Toxicol. 5: 227.

Herbert, D.W.M. and J.M. Vandyke. 1964. The toxicity to fish of mixtures of poisons. II. copper-ammonia and zinc-phenol mixtures. Ann. Appl. Biol. 53: 415.

Heslinga, G.A. 1976. Effects of copper on the coral-reef echinoid Echinometra mathaei. Mar. Biol. 35: 155.

Hetrick, F.M., et al. 1979. Increased susceptibility of rainbow trout to infectious hematopoietic necrosis virus after exposure to copper. Appl. Environ. Microbiol. 37: 198.

Hildebrand, S.G. and R.M. Cushman. 1978. Toxicity of gallium and beryllium to developing carp eggs (Cyprinus carpio) utilizing copper as a reference. Toxicol. Letters 2: 91.

Hinton, M.J. and A.G. Eversole. 1978. Toxicity of ten commonly used chemicals to American eels. Proc. Ann. Conf. S.E. Assoc. Fish. Wildl. Ag. 32: 599.

Hinton, M.J. and A.G. Eversole. 1979. Toxicity of ten chemicals commonly used in aquaculture to the black eel stage of the American eel. Proc. World Maricul. Soc. 10: 554.

Ho, M.S. and P.L. Zubkoff. 1982. The effects of mercury, copper, and zinc on calcium uptake by larvae of the clam, Mulinia lateralis. Water Air Soil Pollut. 17: 409.

Holland, G.A., et al. 1960. Toxic effects of organic and inorganic pollutants on young salmon and trout. Research Bulletin No. 5. Washington Department of Fisheries. p. 223.

Hollibaugh, D.L., et al. 1980. A comparison of the acute toxicities of ten heavy metals to the plankton from Sasnick Inlet, B.C., Canada. Estuarine Coastal Mar. Sci. 10: 93.

Hopkins, R. and J.M. Kain. 1971. The effect of marine pollutants on Laminarea hyperboria. Mar. Pollut. Bull. 2: 75.

Horning, W.B. and T.W. Neiheisel. 1979. Chronic effect of copper on the bluntnose minnow, Pimephales notatus (Rafinesque). Arch. Environ. Contam. Toxicol. 8: 545.

Howard, L.S. and B.E. Brown. 1983. Natural variations in tissue concentration of copper, zinc and iron in the polychaete Nereis diversicolor. Mar. Biol. 78: 87.

Howarth, R.S. and J.B. Sprague. 1978. Copper lethality to rainbow trout in waters of various hardness and pH. Water Res. 12: 455.

Hubschman, J.H. 1967. Effects of copper on the crayfish Orconectes rusticus (Girard): I. acute toxicity. Crustaceana 12: 33.

Hughes, J.S. 1973. Acute toxicity of thirty chemicals to striped bass (Morone saxatilis). Presented at the Western Association of State Game and Fish Commissioners, Salt Lake City, Utah. July.

Huilsom, M.M. 1983. Copper-induced differential mortality in the mussel *Mytilus edulis*. Mar. Biol. 76: 291.

Hutchinson, T.C. 1979. Copper contamination of ecosystems caused by smelter activities. *In*: J.O. Nriagu (ed.), Copper in the Environment. Part I: Ecological Cycling. Wiley, New York. p. 451.

Ingersoll, C.G. and R.W. Winner. 1982. Effect on *Daphnia pulex* (De Geer) of daily pulse exposures to copper or cadmium. Environ. Toxicol. Chem. 1: 321.

Inglis, A. and E.L. Davis. 1972. Effects of water hardness on the toxicity of several organic and inorganic herbicides to fish. Technical Paper No. 67. U.S. Fish and Wildlife Service, Washington, D.C.

Jackim, E. 1973. Influence of lead and other metals on d-aminolevulinate dehydrase activity. Jour. Fish. Res. Board Can. 30: 560.

Jennett, J.C., et al. 1982. Factors influencing metal accumulation by algae. EPA-600/2-82-100. National Technical Information Service, Springfield, Virginia.

Johnson, M.W. and J.H. Gentile. 1979. Acute toxicity of cadmium, copper, and mercury to larval American lobster *Homarus americanus*. Bull. Environ. Contam. Toxicol. 22: 258.

Jones, L.H., et al. 1976. Some effects of salinity on the toxicity of copper to the polychaete Nereis diveriscolor. Estuarine Coastal Mar. Sci. 4: 107.

Joshi, A.G. and M.S. Rege. 1980. Acute toxicity of some pesticides and a few inorganic salts to the mosquitofish Gambusia affinis (Baird and Girard). Indian Jour. Exp. Biol. 18: 435.

Judy, R.D., Jr. 1979. The acute toxicity of copper to Gammarus fasciatus Say, a freshwater amphipod. Bull. Environ. Contam. Toxicol. 21: 219.

Kapur, K. and N.A. Yadav. 1982. The effects of certain heavy metal salts on the development of eggs in common carp, Cyprinus carpio var. communis. Acta Hydrochim. Hydrobiol. 10: 517.

Karbe, L. 1972. Marine hydroiden als testorganismen zur prufung der toxizitat von abwasserstoffen. Die wirkung von schwermetallen auf kolonien von Eirene viridula. Mar. Biol. 12: 316.

Khangarot, B.S. 1981. Chelating agent EDTA decreases the toxicity of copper to fish. Current Sci. 50: 246.

Khangarot, B.S., et al. 1981a. Toxicity of interactions of zinc-nickel, copper-nickel and zinc-nickel-copper to a freshwater teleost, Lebistes reticulatus (Peters). Acta Hydrochim. Hydrobiol. 9: 495.

Khangarot, B.S., et al. 1981b. Studies on the acute toxicity of copper on selected freshwater organisms. Sci. Cult. 47: 429.

Khangarot, B.S., et al. 1983. "Man and the Biosphere" - Studies on Sikkim Himalayas. Part 1: acute toxicity of copper and zinc to common carp Cyprinus carpio (Linn.) in soft water. Acta Hydrochim. Hydrobiol. 11: 667.

Knittel, M.D. 1981. Susceptibility of steelhead trout Salmo gairdneri Richardson to redmouth infection Yersina ruckeri following exposure to copper. Jour. Fish Diseases 4: 33.

Labat, R., et al. 1977. The ecotoxicological action of some metals (Cu, Zn, Pb, Cd) on freshwater fish in the river Lot. Ann. Limnol. 13: 191.

LaPoint, T.W., et al. 1984. Relationships among observed metal concentrations, criteria, and benthic community structural responses in 15 streams. Jour. Water Pollut. Control Fed. 56: 1030.

Laube, V.M., et al. 1980. Strategies of response to copper, cadmium, and lead by a blue-green and a green alga. Can. Jour. Microbiol. 26: 1300.

Lee, H.H. and C.H. Ku. 1984. Effects of metals on sea urchin development: a rapid bioassay. Mar. Pollut. Bull. 15: 18.

Leland, H.V. 1983. Ultrastructural changes in the hepatocytes of juvenile rainbow trout and mature brown trout exposed to copper or zinc. Environ. Toxicol. Chem. 2: 353.

Leland, H.V. and J.L. Carter. 1984. Effects of copper on species composition of periphyton in a Sierra Nevada, California stream. Freshwater Biol. 14: 281.

Leland, H.V. and J.L. Carter. Manuscript. Effects of copper on production of periphyton, nitrogen fixation and processing of leaf litter in a Sierra Nevada, California stream.

Les, A. and R.W. Walker. 1984. Toxicity and binding of copper, zinc, and cadmium by the blue-green alga, Chroococcus paris. Water Air Soil Pollut. 23: 129.

Lett, P.F., et al. 1976. Effect of copper on some aspects of the bioenergetics of rainbow trout (Salmo gairdneri). Jour. Fish. Res. Board Can. 33: 1335.

Lewis, M. 1978. Acute toxicity of copper, zinc and manganese in single and mixed salt solutions to juvenile longfin dace, Agosia chrysogaster. Jour. Fish Biol. 13: 695.

Lewis, M.A. 1983. Effect of loading density on the acute toxicities of surfactants, copper, and phenol to Daphnia magna Straus. Arch. Environ. Contam. Toxicol. 12: 51.

Lewis, S.D. and W.M. Lewis. 1971. The effect of zinc and copper on the osmolality of blood serum of the channel catfish, Ictalurus punctatus

Rafinesque, and golden shiner, Notemigonius crysoleucas Mitchell. Trans. Am. Fish. Soc. 100: 639.

Lind, D., et al. Manuscript. Regional copper-nickel study: aquatic toxicology study.

Lloyd, R. 1961. The toxicity of mixtures of zinc and copper sulphates to rainbow trout (Salmo gairdneri R.). Ann. Appl. Biol. 49: 535.

Lorz, H.W. and B.P. McPherson. 1976. Effects of copper or zinc in fresh water on the adaptation to sea water and ATPase activity, and the effects of copper on migratory disposition of coho salmon (Oncorhynchus kisutch). Jour. Fish. Res. Board Can. 33: 2023.

Lumoa, S.M., et al. 1983. Variable tolerance to copper in two species from San Francisco Bay. Mar. Environ. Res. 10: 209.

Lumsden, B.R. and T.M. Florence. 1983. A new algal assay procedure for the determination of the toxicity of copper species in seawater. Environ. Toxicol. Letters 4: 271.

Lussier, S.M., et al. Manuscript. Acute and chronic effects of heavy metals and cyanide on Mysidopsis bahia (Crustacea: Mysidacea). U.S. EPA, Narragansett, Rhode Island.

MacInnes, J.R. and A. Calabrese. 1978. Response of embryos of the American oyster, Crassostrea virginica, to heavy metals at different temperatures. In: D.S. McLusky and A.J. Berry (eds.), Physiology and Behavior of Marine Organisms. Pergamon Press, New York. p. 195.

MacInnes, J.R. and F.P. Thurberg. 1973. Effects of metals on the behavior and oxygen consumption of the mud snail. Mar. Pollut. Bull. 4: 1895.

Mackey, D.J. 1983. The strong complexing capacity of south-eastern Australian coastal waters. Mar. Chem. 14: 73.

Majori, L. and F. Petronio. 1973. Marine pollution by metals and their accumulation by biological indicators (accumulation factor). Rev. Int. Oceanogr. Med. XXXI.

Maloney, T.E. and C.M. Palmer. 1956. Toxicity of six chemical compounds to thirty cultures of algae. Water Sew. Works 103: 509.

Marking, L.L., et al. 1984. Effects of five diets on sensitivity of rainbow trout to eleven chemicals. Prog. Fish-Cult. 46: 1.

Martin, M., et al. 1977. Copper toxicity experiments in relation to abalone deaths observed in a power plant's cooling waters. California Fish Game 63: 95.

Martin, M., et al. 1981. Toxicities of ten metals to Crassostrea gigas and Mytilus edulis embryos and Cancer magister larvae. Mar. Pollut. Bull. 12: 305.

Martin, M., et al. 1984. Relationships between physiological stress and trace toxic substances in the bay mussel, Mytilus edulis, from San Francisco Bay, California. Mar. Environ. Res. 11: 91.

McCarter, J.A. and M. Roch. 1983. Hepatic metallothionein and resistance to copper in juvenile coho salmon. Comp. Biochem. Physiol. 74C: 133.

McCarter, J.A. and M. Roch. 1984. Chronic exposure of coho salmon to sublethal concentrations of copper - III. kinetics of metabolism of metallothionein. Comp. Biochem. Physiol. 77C: 83.

McCarter, J.A., et al. 1982. Chronic exposure of coho salmon to sublethal concentrations of copper - II. distribution of copper between high- and low-molecular-weight proteins in liver cytosol and the possible role of metallothionein in detoxification. Comp. Biochem. Physiol. 72C: 21.

McIntosh, A.W. and N.R. Kevern. 1974. Toxicity of copper to zooplankton. Jour. Environ. Qual. 3: 166.

McKim, J.M. and D.A. Benoit. 1971. Effects of long-term exposures to copper on survival, growth, and reproduction of brook trout (Salvelinus fontinalis). Jour. Fish. Res. Board Can. 28: 655.

McKim, J.M., et al. 1970. Changes in the blood of brook trout (Salvelinus fontinalis) after short-term and long-term exposure to copper. Jour. Fish. Res. Board Can. 27: 1883.

McKim, J.M., et al. 1978. Metal toxicity to embryos and larvae of eight species of freshwater fish. - II. copper. Bull. Environ. Contam. Toxicol. 19: 608.

McKnight, D. 1980. Chemical and biological processes controlling the response of a freshwater ecosystem to copper stress: a field study of the $CuSO_4$ treatment of Mill Pond reservoir, Burlington, Massachusetts. Final Report NSF Grant No. OCE77-09000.

McKnight, D.M. and F.M.M. Morel. 1979. Release of weak and strong copper-complexing agents by algae. Limnol. Oceanogr. 24: 823.

McKnight, D.M., et al. 1983. $CuSO_4$ treatment of nuisance algal blooms in drinking water reservoirs. Environ. Manage. 7: 311.

McLeese, D.W. 1974. Toxicity of copper at two temperatures and three salinities to the American lobster (*Homarus americanus*). Jour. Fish. Res. Board Can. 31: 1949.

McLusky, D.S. and C.N.K. Phillips. 1975. Some effects of copper on the polychaete *Phyllodoce maculata*. Estuarine Coastal Mar. Sci. 3: 103.

Milanovich, F.P., et al. 1976. Uptake of copper by the polychaete *Cirriformia spirabranchia* in the presence of dissolved yellow organic matter of natural origin. Estuarine Coastal Mar. Sci. 4: 585.

Miller, T.G. and W.C. MacKay. 1980. The effects of hardness, alkalinity and pH of test water on the toxicity of copper to rainbow trout (Salmo gairdneri). Water Res. 14: 129.

Minicucci, D.D. 1971. Flow effects in aquatic bioassays (the toxicity of copper at various flow rates to the guppy, Lebistes reticulatus). Ph.D. Thesis. University of Michigan.

Mishra, S. and A.K. Srivastava. 1980. The acute toxicity effects of copper on the blood of a teleost. Ecotoxicol. Environ. Safety 4: 191.

Moore, M.N. and A.R.D. Stebbing. 1976. The quantitative cytochemical effects of three metal ions on the lysosomal hydrolase of a hydroid. Jour. Mar. Biol. Assoc. U.K. 56: 995.

Moraitou-Apostolopoulou, M. 1978. Acute toxicity of copper to a copepod. Mar. Pollut. Bull. 9: 278.

Moraitou-Apostolopoulou, M. and G. Verriopoulos. 1982. Individual and combined toxicity of three heavy metals, Cu, Cd and Cr for the marine copepod Tisbe holothuriae. Hydrobiologia 87: 83.

Morgan, W.S.C. 1979. Fish locomotor behavior patterns as a monitoring tool. Jour. Water Pollut. Control Fed. 51: 580.

Mount, D.I. 1968. Chronic toxicity of copper to fathead minnows (*Pimephales promelas* Rafinesque). Water Res. 2: 215.

Mount, D.I. and T.J. Norberg. 1984. A seven-day life-cycle cladoceran toxicity test. Environ. Toxicol. Chem. 3: 425.

Mount, D.I. and C.E. Stephan. 1969. Chronic toxicity of copper to the fathead minnow (*Pimephales promelas*) in soft water. Jour. Fish. Res. Board Can. 26: 2449.

Muramoto, S. 1980. Effect of complexans (EDTA, NTA and DTPA) on the exposure to high concentrations of cadmium, copper, zinc and lead. Bull. Environ. Contam. Toxicol. 25: 941.

Muramoto, S. 1982. Effects of complexans (DTPA, EDTA) on the toxicity of low concentrations of copper to fish. Jour. Environ. Sci. Health 17A: 313.

Myint, U.M. and P.A. Tyler. 1982. Effects of temperature, nutritive and metal stressors on the reproductive biology of *Mytilus edulis*. Mar. Biol. 67: 209.

Nakajima, A., et al. 1979. Uptake of copper ion by green microalgae. Agric. Biol. Chem. 43: 1455.

Nebeker, A.V. and A.R. Gaufin. 1964. Bioassays to determine pesticide toxicity to the amphipod crustacean, *Gammarus lacustris*. Proc. Utah Acad. Sci. 41: 64.

Nebeker, A.V., et al. 1984a. Relative sensitivity of Chironomus tentans life stages to copper. Environ. Toxicol. Chem. 3: 151.

Nebeker, A.V., et al. 1984b. Effects of copper, nickel and zinc on the life cycle of the caddisfly Clistoronia magnifica (Limnephilidae). Environ. Toxicol. Chem. 3: 645.

Negilski, D.S., et al. 1981. Toxicity of zinc, cadmium and copper to the shrimp Callianassa australiensis. II. effects of paired and triad combinations of metals. Mar. Biol. 64: 305.

Nehring, R.B. 1976. Aquatic insects as biological monitors of heavy metal pollution. Bull. Environ. Contam. Toxicol. 15: 147.

Neter, J. and W. Wasserman. 1974. Applied Linear Statistical Models. Irwin, Inc., Homewood, Illinois.

Neuhoff, H.G. 1983. Synergistic physiological effects of low copper and various oxygen concentrations on Macoma balthica. Mar. Biol. 77: 39.

Nriagu, J.O. (ed.) 1979. Copper in the Environment. Part I: Ecological Cycling; Part II: Health Effects. Wiley, New York.

O'Hara, J. 1971. Alterations in oxygen consumption by bluegills exposed to sublethal treatment with copper. Water Res. 5: 321.

Okazaki, R.K. 1976. Copper toxicity in the Pacific oyster Crassostrea gigas. Bull. Environ. Contam. Toxicol. 16: 658.

Olson, K.R. and R.C. Harrel. 1973. Effect of salinity on acute toxicity of mercury, copper, and chromium for Rangia cuneata (Pelecypoda, Mactridae). Contrib. Mar. Sci. 17: 9.

Ozoh, P.T.E. and C. Jacobson. 1979. Embryotoxicity and hatchability in Cichlasoma nigrofasciatum (Guenther) eggs and larvae briefly exposed to low concentrations of zinc and copper ions. Bull. Environ. Contam. Toxicol. 21: 782.

Pagenkopf, G.K. 1983. Gill surface interaction model for trace-metal toxicity to fishes: role of complexation, pH, and water hardness. Environ. Sci. Technol. 17: 342.

Pant, S.C., et al. 1980. Toxicity of copper sulphate and zinc sulphate to fresh water teleost Puntius conchonius (Ham.) in hard water. Comp. Physiol. Ecol. 5: 146.

Pardue, W.J. and T.S. Wood. 1980. Baseline toxicity data for freshwater bryozoa exposed to copper, cadmium, chromium, and zinc. Jour. Tennessee Acad. Sci. 55: 27.

Parker, J.G. 1984. The effects of selected chemicals and water quality on the marine polychaete Ophryotrocha diadema. Water Res. 18: 865.

Patrick, R., et al. 1968. The relative sensitivity of diatoms, snails, and fish to twenty common constituents of industrial wastes. Prog. Fish-Cult. 30: 137.

Paulson, P.C., et al. 1983. Relationship of alkaline stress and acute copper toxicity in the snail Goniobasis livescens (Menke). Bull. Environ. Contam. Toxicol. 31: 719.

Pearlmutter, N.L. and M.A. Buchheim. 1983. Copper susceptibility of three growth stages of the green alga Haematococcus. PB83-25678. National Technical Information Service, Springfield, Virginia.

Pesch, C.E. and G.L. Hoffman. 1982. Adaptation of the polychaete Neanthes arenaceodentata to copper. Mar. Environ. Res. 6: 307.

Pesch, C.E. and D. Morgan. 1978. Influence of sediment in copper toxicity tests with polychaete Neanthes arenaceodentata. Water Res. 12: 747.

Pesch, G., et al. 1979. Copper toxicity to the bay scallop (Argopecten irradians). Bull. Environ. Contam. Toxicol. 23: 759.

Petersen, R. 1982. Influence of copper and zinc on the growth of a freshwater algae, Scenedesmus quadricauda: the significance of speciation. Environ. Sci. Technol. 16: 443.

Peterson, H.G., et al. 1984. Metal toxicity to algae: a highly pH dependent phenomenon. Can. Jour. Fish. Aquat. Sci. 41: 974.

Phelps, H.L., et al. 1983. Clam burrowing behavior: inhibiton by copper enriched sediment. Mar. Pollut. Bull. 14: 452.

Phillips, D.J.H. 1976. The common mussel *Mytilus edulis* as an indicator of pollution by zinc, cadmium, lead and copper. I. effects of environmental variables on uptake of metals. Mar. Biol. 38: 59.

Phillips, G.R. and R.C. Russo. 1978. Metal bioaccumulation in fishes and aquatic invertebrates: a literature review. EPA-600/3-78-103. National Technical Information Service, Springfield, Virginia.

Pickering, Q.H. and C. Henderson. 1966. The acute toxicity of some heavy metals to different species of warmwater fishes. Air Water Pollut. Int. Jour. 10: 453.

Pickering, Q., et al. 1977. Effect of exposure time and copper concentration on reproduction of the fathead minnow (*Pimephales promelas*). Water Res. 11: 1079.

Pophan, J.D. and J.M. D'Auria. 1981. Statistical models for estimating seawater metal concentrations from metal concentrations in mussels (*Mytilus edulis*). Bull. Environ. Contam. Toxicol. 27: 660.

Qureshi, S.A. and A.B. Saksena. 1980. The acute toxicity of some heavy metals to Tilapia mossambica (Peters). Aqua 1: 19.

Rachlin, J.W., et al. 1982. The growth response of the green alga (Chlorella saccharophila) to selected concentrations of the heavy metals Cd, Cu, Pb, and Zn. In: D.I. Hemphill (ed.), Trace Substances in Environmental Health-XVI. University of Missouri, Columbia, Missouri. p. 145.

Rachlin, J.W., et al. 1983. The growth response of the diatom Navicula incerta to selected concentrations of the metals: cadmium, copper, lead and zinc. Bull. Torrey Bot. Club 110: 217.

Rai, L.C., et al. 1981. Phycology and heavy-metal pollution. Biol. Rev. 56: 99.

Ray, S., et al. 1981. Accumulation of copper, zinc, cadmium and lead from two contaminated sediments by three marine invertebrates - a laboratory study. Bull. Environ. Contam. Toxicol. 26: 315.

Reed, R.H. and L. Moffat. 1983. Copper toxicity and copper tolerance in Enteromospha compressa (L.) Giev. Jour. Exp. Mar. Biol. Ecol. 69: 85.

Reeve, W.R., et al. 1976. A controlled environmental pollution experiment (CEPEX) and its usefulness in the study of larger marine zooplankton under toxic stress. In: P.M. Lockwood (ed.), Effects of Pollutants on Aquatic Organisms. Cambridge University Press, New York. p. 145.

Rehwoldt, R., et al. 1971. Acute toxicity of copper, nickel and zinc ions to some Hudson River fish species. Bull. Environ. Contam. Toxicol. 6: 445.

Rehwoldt, R., et al. 1972. The effect of increased temperature upon the acute toxicity of some heavy metal ions. Bull. Environ. Contam. Toxicol. 8: 91.

Rehwoldt, R., et al. 1973. The acute toxicity of some heavy metal ions toward benthic organisms. Bull. Environ. Contam. Toxicol. 10: 291.

Rice, D.W., Jr., and F.L. Harrison. 1978. Copper sensitivity of Pacific herring, Clupea harengus pallasi, during its early life history. Fish. Bull. 76: 347.

Rice, D.W., Jr., and F.L. Harrison. 1983. The sensitivity of adult, embryonic, and larval crayfish Procambaris clarkii to copper. UCRL-53048. National Technical Information Service, Springfield, Virginia.

Richey, D. and D. Roseboom. 1978. Acute toxicity of copper to some fishes in high alkalinity water. PB 294923. National Technical Information Service, Springfield, Virginia.

Riedel, G.F. 1983. The copper sensitivity of Oregon coastal phytoplankton. Ph.D. Thesis. Oregon State University.

Riley, J.P. and I. Roth. 1971. The distribution of trace elements in some species of phytoplankton grown in culture. Jour. Mar. Biol. Assoc. U.K. 51: 63.

Rodgers, J.H., et al. 1980. Comparison of heavy metal interactions in acute and artificial stream bioassay techniques for the Asiatic clam (Corbicula fluminen). In: J.G. Eaton, et al. (eds.), Aquatic Toxicology. ASTM STP 707. American Society for Testing and Materials, Philadelphia, Pennsylvania. p. 266.

Roesijadi, G. 1980. Influence of copper on the clam Protothaca staminea: effects on gills and occurrence of copper-binding proteins. Biol. Bull. 158: 233.

Rosko, J.J. and J.W. Rachlin. 1975. The effect of copper, zinc, cobalt and manganese on the growth of the marine diatom Nitzschia closterium. Bull. Torrey Bot. Club 102: 100.

Rosko, J.J. and J.W. Rachlin. 1977. The effect of cadmium, copper, mercury, zinc and lead on cell division, growth, and chlorophyll a content of the chlorophyte Chlorella vulgaris. Bull. Torrey Bot. Club 104: 226.

Rueter, J.G. 1983. Alkaline phosphatase inhibition by copper: implications to phosphorus nutrition and use as a biochemical marker of toxicity. Limnol. Oceanogr. 28: 743.

Rueter, J.G., Jr., et al. 1981. Effects of copper toxicity on silicia acid uptake and growth in Thalassiosira pseudonana. Jour. Phycol. 17: 270.

Saifullah, S.M. 1978. Inhibitory effects of copper on marine dinoflagellates. Mar. Biol. 44: 299.

Sakaguchi, T., et al. 1977. Uptake of copper by Chlorella regularis. Nippon Nog. Kag. Kaishi 51: 497.

Sander, J.G. 1982. The effect of water chlorination on the toxicity of copper to phytoplankton. Maryland Power Plant Siting Program.

Sanders, B.M., et al. 1983. Free cupric ion activity in seawater: effects on metallothionein and growth in crab larvae. Science 222: 53.

Sauter, S., et al. 1976. Effects of exposure to heavy metals on selected freshwater fish. Toxicity of copper, cadmium, chromium and lead to eggs and fry of seven fish species. EPA-600/3-76-105. National Technical Information Service, Springfield, Virginia.

Saward, D., et al. 1975. Experimental studies on the effects of copper on a marine food chain. Mar. Biol. 29: 351.

Scarfe, A.D., et al. 1982. Locomotor behavior of four marine teleosts in response to sublethal copper exposure. Aquat. Toxicol. 2: 335.

Schenck, R.C. 1984. Copper deficiency and toxicity in *Gonyaulax tamarensis* (Lebour). Mar. Biol. Letters 5: 13.

Schmidt, R.L. 1978a. Copper in the marine environment. Part I. CRC Crit. Rev. Environ. Control 8: 101.

Schmidt, R.L. 1978b. Copper in the marine environment. Part II. CRC Crit. Rev. Environ. Control 8: 247.

Scott, D.M. and C.W. Major. 1972. The effect of copper(II) on survival, respiration, and heart rate in the common blue mussel, *Mytilus edulis*. Biol. Bull. 143: 679.

Scott, K.J., et al. Manuscript. Toxicological methods using the benthic amphipod *Ampelisca abdita* Mills. U.S. EPA, Narragansett, Rhode Island.

Seim, W.K., et al. 1984. Growth and survival of developing steelhead trout (*Salmo gairdneri*) continuously or intermittently exposed to copper. Can. Jour. Fish. Aquat. Sci. 41: 433.

Shaw, T.L. and V.M. Brown. 1974. The toxicity of some forms of copper to rainbow trout. Water Res. 8: 377.

Shcherban, E.P. 1977. Toxicity of some heavy metals for *Daphnia magna* Strauss, as a function of temperature. Hydrobiol. Jour. 13(4): 75.

Sheffrin, N.M.H., et al. 1984. A behavioural bioassay for impaired sea-water quality using the plantigrades of the common mussel *Mytilus edulis* L.: the response to copper. Aquat. Toxicol. 5: 77.

Shuster, C.N., Jr., and B.H. Pringle. 1968. Effects of trace metals on estuarine molluscs. Proc. 1st Mid-Atlantic Ind. Waste Conf., Nov. 13-15, 1967.

Shuster, C.N., Jr., and B.H. Pringle. 1969. Trace metal accumulation by the American eastern oyster, *Crassostrea virginica*. Proc. Natl. Shellfish. Assoc. 59: 91.

Smith, J.D., et al. 1981. Distribution and significance of copper, lead, zinc, and cadmium in the Corio Bay ecosystem. Aust. Jour. Mar. Freshwater Res. 32: 151.

Smith, M.J. and A.G. Heath. 1979. Acute toxicity of copper, chromate, zinc, and cyanide to freshwater fish: effect of different temperatures. Bull. Environ. Contam. Toxicol. 22: 113.

Solbe, J.F. and V.A. Cooper. 1976. Studies on the toxicity of copper sulfate to stone loach *Noemacheilus barbatulus* (L.) in hard water. Water Res. 10: 523.

Sosnowski, S.L. and J.H. Gentile. 1978. Toxicological comparison of natural and cultured populations of *Acartia tonsa* to cadmium, copper and mercury. Jour. Fish. Res. Board Can. 35: 1366.

Sosnowski, S.L., et al. 1979. The effect of nutrition on the response of field populations of the calanoid copepod Acartia tonsa to copper. Water Res. 13: 449.

Spear, P. 1977. Copper accumulation kinetics and lethal tolerance in relation to fish size. M.S. Thesis. Concordia University, Montreal, Canada.

Spear, P.A. and R.C. Pierce 1979a. Copper in the aquatic environment: chemistry, distribution and technology. NRCC No. 16454. National Research Council of Canada, Ottawa.

Spear, P.A. and R.C. Pierce. 1979b. An approach towards the toxicology of copper to freshwater fish. In: P.T.S. Wong, et al. (eds.), Proceeding of the Fifth Annual Aquatic Toxicology Workshop. Fisheries and Marine Service Technical Report No. 862. Canada Centre for Inland Waters, Burlington, Ontario. p. 130.

Sprague, J.B. 1964. Lethal concentrations of copper and zinc for young Atlantic salmon. Jour. Fish. Res. Board Can. 21: 17.

Sprague, J.B. 1985. Factors that modify toxicity. In: G.M. Rand and S.R. Petrocelli (eds.), Fundamentals of Aquatic Toxicology: Methods and Applications. Hemisphere Publishing Corporation, Washington, D.C. p. 124.

Sprague, J.B. and B.A. Ramsay. 1965. Lethal levels of mixed copper-zinc solutions for juvenile salmon. Jour. Fish. Res. Board Can. 22: 425.

Stanley, R.A. 1974. Toxicity of heavy metals and salts to Eurasian water-milfoil (Myriophyllum spicatum L.). Arch. Environ. Contam. Toxicol. 2: 331.

Stebbing, A.R.D. 1976. The effects of low metal levels on a clonal hydroid. Jour. Mar. Biol. Assoc. U.K. 56: 977.

Steele, C.W. 1983. Effects of exposure to sublethal copper on the locomotor behavior of the sea catfish, Arius felis. Aquat. Toxicol. 4: 83.

Steele, R.L. and G.B. Thursby. 1983. A toxicity test using life stages of Champia parvula (Rhodophyta). In: W.E. Bishop, et al. (eds.), Aquatic Toxicology and Hazard Assessment. ASTM STP 802. American Society for Testing and Materials, Philadelphia, Pennsylvania. p. 73.

Steemann-Nielsen, E. and H. Bruun-Laursen. 1976. Effect of $CuSO_4$ on the photosynthetic rate of phytoplankton in four Danish lakes. Oikos 27: 239.

Steemann-Nielsen, E. and L. Kamp-Nielsen. 1970. Influence of deleterious concentrations of copper on the growth of Chlorella pyrenoidosa. Physiol. Plant. 23: 828.

Steemann-Nielsen, E. and S. Wium-Andersen. 1970. Copper ions as poison in sea and in freshwater. Mar. Biol. 6: 93.

Stephan, C.E., et al. 1985. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. National Technical Information Service, Springfield, Virginia.

Stephenson, R.R. 1983. Effects of water hardness, water temperature, and size of the test organism on the susceptibility of the freshwater shrimp, Gammarus pulex (L.) to toxicants. Bull. Environ. Contam. Toxicol. 31: 459.

Stokes, P. and T.C. Hutchinson. 1976. Copper toxicity to phytoplankton, as affected by organic ligands, other cations and inherent tolerance of algae to copper. In: R.W. Andrew, et al. (eds.), Toxicity to Biota of Metal Forms in Natural Water. International Joint Commission, Windsor, Ontario, Canada. p. 1591.

Strong, C.R. and S.N. Luoma. 1981. Variations in the correlation of body size with concentrations of Cu and Ag in the bivalve Macoma balthica. Can. Jour. Fish. Aquat. Sci. 38: 1059.

Sullivan, R.K., et al. 1983. Effects of copper and cadmium on growth, swimming and predator avoidance in Eurytemora affinis (Copepoda). Mar. Biol. 77: 299.

Sunda, W.G. and P.A. Gillespie. 1979. The response of a marine bacterium to cupric ion and its use to estimate cupric ion activity in seawater. Jour. Mar. Res. 37: 761.

Sunda, W.G. and J.M. Lewis. 1978. Effect of complexation by natural organic ligands on the toxicity of copper to a unicellular alga, Monochrysis lutheri. Limnol. Oceanogr. 23: 870.

Swallow, K.C., et al. 1978. Potentiometric determination of copper complexation by phytoplankton exudates. Limnol. Oceanogr. 23: 538.

Swedmark, M. and A. Granmo. 1981. Effects of mixtures of heavy metals and a surfactant on the development of cod (Gadus morhua L.). Rapp. P.V. Reun. Cons. Int. Explor. Mer. 178, pp. 95-103.

Tarzwell, C.M. and C. Henderson. 1960. Toxicity of less common metals to fishes. Ind. Wastes 5: 12.

Taylor, J.L. 1978. Toxicity of copper and zinc in two Arkansas streams to mosquitofish (Gambusia affinis). Bios 49: 99.

Thompson, K.W., et al. 1980. Acute toxicity of zinc and copper singly and in combination to the bluegill (Lepomis macrochirus). Bull. Environ. Contam. Toxicol. 25: 122.

Thompson, S.E., et al. 1972. Concentration factors of the chemical elements in edible aquatic organisms. UCRL-50564. Rev. 1. National Technical Information Service, Springfield, Virginia.

Trama, F.B. 1954. The toxicity of copper to the common bluegill (Lepomis machrochirus Rafinesque). Notulae Naturae, No. 257.

Tsai, C. 1979. Survival, overturning and lethal exposure times for the pearl dace, Semotilus margaritus (Cope), exposed to copper solution. Biochem. Physiol. Pflanzen. 64: 1.

Tsai, C. and K. Chang. 1981. Effect of sex and size on copper susceptibility of the common guppy, Lebistes reticulatus (Peter). Jour. Fish Biol. 19: 683.

Tsai, C. and K. Chang. 1984. Intraspecific variation in copper susceptibility of the bluegill sunfish. Arch. Environ. Contam. Toxicol. 13: 93.

Tsai, C.F. and J.A. McKee. 1978. The toxicity to goldfish of mixtures of chloramines, LAS and copper. PB 280554. National Technical Information Service, Springfield, Virginia.

Tsai, C. and J.A. McKee. 1980. Acute toxicity to goldfish of mixtures of chloramines, copper, and linear alkylate sulfonate. Trans. Am. Fish. Soc. 109: 132.

Turnbull, H., et al. 1954. Toxicity of various refinery materials to freshwater fish. Ind. Eng. Chem. 46: 324.

U.S. EPA. 1976. Quality criteria for water. EPA-440/9-76-023. National Technical Information Service, Springfield, Virginia.

U.S. EPA. 1980. Ambient water quality criteria for copper. EPA-440/4-80-036. National Technical Information Service, Springfield, Virginia.

U.S. EPA. 1983a. Methods for chemical analysis of water and wastes. EPA-600/4-79-020 (Revised March 1983). National Technical Information Service, Springfield, Virginia.

U.S. EPA. 1983b. Water quality standards regulation. Federal Register 48: 51400. November 8.

U.S. EPA. 1983c. Water quality standards handbook. Office of Water Regulations and Standards, Washington, D.C.

U.S. EPA. 1985. Technical support document for water quality-based toxics control. Office of Water, Washington, D.C.

Van den Berg, C.M.G., et al. 1979. Measurement of complexing materials excreted from algae and their ability to ameliorate copper toxicity. Jour. Fish. Res. Board Can. 36: 901.

Verma, S.R., et al. 1980. Short term toxicity tests with heavy metals for predicting safe application factor. Toxicol. Letters (Special Issue) 1: 113.

Verriopoulos, G. and M. Moraitou-Apostolopoulou. 1982. Differentiation of the sensitivity to copper and cadmium in different life stages of a copepod. Mar. Pollut. Bull. 13: 123.

Viarengo, A., et al. 1981a. Synthesis of Cu-binding proteins in different tissues of mussels exposed to the metal. Mar. Pollut. Bull. 13: 347.

Viarengo, A., et al. 1981b. Accumulation and detoxication of copper by the mussel Mytilus galloprovincialis: a study of the subcellular distribution in the digestive gland cells. Aquat. Toxicol. 1: 147.

Wagemann, R. and J. Barica. 1979. Speciation and rate of loss of copper from lakewater with implications to toxicity. Water Res. 13: 515.

Waiwood, K.G. 1980. Changes in hematocrit of rainbow trout exposed to various combinations of water hardness, pH, and copper. Trans. Am. Fish. Soc. 109: 461.

Waiwood, K.G. and F.W.H. Beamish. 1978. The effect of copper, hardness and pH on the growth of rainbow trout, Salmo gairdneri. Jour. Fish Biol. 13: 591.

Walbridge, C.T. 1977. A flow-through testing procedure with duckweed (Lemna minor L.). EPA-600/3-77-108. National Technical Information Service, Springfield, Virginia.

Wallen, I.E., et al. 1957. Toxicity to Gambusia affinis of certain pure chemicals in turbid waters. Sew. Ind. Wastes 29: 695.

Warnick, S.L. and H.L. Bell. 1969. The acute toxicity of some heavy metals to different species of aquatic insects. Jour. Water Pollut. Control Fed. 41: 280.

Watling, H.R. 1981. Effects of metals on the development of oyster embryos. South African Jour. Sci. 77: 134.

Watling, H.R. 1982. Comparative study of the effects of zinc, cadmium, and copper on the larvae growth of three oyster species. Bull. Environ. Contam. Toxicol. 28: 195.

Watling, H.R. 1983. Accumulation of seven metals by Crassostrea gigas, Crassostrea margaritacea, Perna perna, and Choromytilus meridionalis. Bull. Environ. Contam. Toxicol. 30: 317.

Weber, C.I. and B.H. McFarland. 1981. Effects of copper on the periphyton of a small calcareous stream. In: J.M. Bates and C.I. Weber (eds.), Ecological Assessments of Effluent Impacts on Communities of Indigenous Aquatic Organisms. ASTM STP 730. American Society for Testing and Materials, Philadelphia, Pennsylvania. p. 101.

Weber, W.J., Jr., and W. Stumm. 1963. Mechanism of hydrogen ion buffering in natural waters. Jour. Am. Water Works Assoc. 55: 1553.

Wellborn, T.L., Jr. 1969. The toxicity of nine therapeutic and herbicidal compounds to striped bass. Prog. Fish-Cult. 31: 27.

Westerman, A.G. and W.J. Birge. 1978. Accelerated rate of albinism in channel catfish exposed to metals. Prog. Fish-Cult. 40: 143.

White, S.L. and P.S. Rainbow. 1982. Regulation and accumulation of copper, zinc and cadmium by the shrimp *Palaemon elegans*. Mar. Ecol. Progress Series 8: 95.

Wikfors, G.H. and R. Ukeles. 1982. Growth and adaptation of estuarine unicellular algae in media with excess copper, cadmium or zinc, and effects of metal-contaminated algal food on *Crassostrea virginica* larvae. Mar. Ecol. Progress Series 7: 191.

Wilson, R.C.H. 1972. Prediction of copper toxicity in receiving waters. Jour. Fish Res. Board Can. 29: 1500.

Winner, R.W. 1981. A comparison of body length, brood size and longevity as indices of chronic copper and zinc stresses in *Daphnia magna*. Environ. Pollut. (Series A) 26: 33.

Winner, R.W. 1984a. The toxicity and bioaccumulation of cadmium and copper as affected by humic acid. Aquat. Toxicol. 5: 267.

Winner, R.W. 1984b. Selenium effects on antennal integrity and chronic copper toxicity in *Daphnia pulex* (deGeer). Bull. Environ. Contam. Toxicol. 33: 605.

Winner, R.W. and M.P. Farrell. 1976. Acute and chronic toxicity of copper to four species of Daphnia. Jour. Fish. Res. Board Can. 33: 1685.

Winner, R.W., et al. 1977. Effect of food type on the acute and chronic toxicity of copper to Daphnia magna. Freshwater Biol. 7: 343.

Wong, M.H., et al. 1977. The effects of zinc and copper salts on Cyprinus carpio and Ctenopharyngodon idellus. Acta Anat. 99: 450.

Wong, P.T.S., et al. 1982. Physiological and biochemical responses of several freshwater algae to a mixture of metals. Chemosphere 11: 367.

Wood, A.M. 1983. Available copper ligands and the apparent bioavailability of copper to natural phytoplankton assemblages. Sci. Total Environ. 28: 51.

Wurtz, C.B. and C.H. Bridges. 1961. Preliminary results from macroinvertebrate bioassays. Proc. Pennsylvania Acad. Sci. 35: 51.

Young, J.S., et al. 1979. Effects of copper on the sabellid polychaete, Eudistylia vancouveri: I. concentration limits for copper accumulation. Arch. Environ. Contam. Toxicol. 8: 97.

Young, L.G. and L. Nelson. 1974. The effect of heavy metal ions on the motility of sea urchin spermatozoa. Biol. Bull. 147: 236.

Young, R.G. and D.J. Lisk. 1972. Effect of copper and silver ions on algae. Jour. Water Pollut. Control Fed. 44: 1643.

Zaroogian, G.E. and M. Johnson. 1983. Copper accumulation in the bay scallop, Argopecten irradians. Arch. Environ. Contam. Toxicol. 12: 127.

Zevenhuizen, L.P.T.M., et al. 1979. Inhibitory effects of copper on bacteria related to the free ion concentration. Microb. Ecol. 5: 139.

Zitko, V. and W.G. Carson. 1976. A mechanism of the effects of water hardness on the lethality of heavy metals to fish. Chemosphere 5: 299.