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Ambient Water Quality Criteria for Zinc - 1987

AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR

ZINC

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NOTICES

This document has been reviewed by the Criteria and Standards Division, Office of Water Regulations and Standards, U.S. Environmental Protection Agency, and approved for publication.

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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 water quality criteria that accurately reflect the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare that might 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 consideration of comments received from other Federal agencies, State agencies, special interest groups, and individual scientists. Criteria contained in this document replace any previously published EPA aquatic life criteria for the same pollutant(s).

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. Criteria presented in this document are such scientific assessments. If water quality criteria associated with specific stream uses are adopted by a State as water quality standards under section 303, they become enforceable maximum acceptable pollutant concentrations in ambient waters within that State. Water quality criteria adopted in State water quality standards could have the same numerical values as criteria developed under section 304. However, in many situations States might 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 State water quality standards that criteria become regulatory.

Guidelines to assist 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*

Zinc is the fourth most widely used metal in the world (Cammarota 1980), and its major uses are for galvanizing steel, for producing alloys, and as an ingredient in rubber and paints. Because zinc(II) substitutes to some extent for magnesium in the silicate minerals of igneous rocks, weathering of bedrock gives rise to zinc in surface water. Zinc always has the oxidation state of +2 in aqueous solution. Zinc(II) is amphoteric, dissolving in acids to form hydrated Zn(II) cations and in strong bases to form zincate anions, usually $Zn(OH)_4^{-2}$. Complexes of zinc with the common ligands of surface waters are soluble in neutral and acidic solutions, so that zinc is readily transported in most natural waters and is one of the most mobile of the heavy metals. Concentrations of zinc in uncontaminated fresh water are typically in the range of 0.5 to 10 μg/L (Trefry and Presley 1979), whereas concentrations in clean sea water range from 0.002 to 0.1 μg/L and increase with depth (Salomons and Forstner 1984; Wallace et al. 1983).

Zinc occurs in many forms in natural waters and aquatic sediments. At pH = 6.0 in fresh water, the dominant forms of dissolved zinc are the free ion (98%) and zinc sulfate (2%), whereas at pH = 9.0, the dominant forms are the mono-hydroxide ion (78%), zinc carbonate (16%), and the free ion (6%) (Turner et al. 1981). In sea water at pH = 8.1, the dominant species of soluble zinc are zinc hydroxide (62%), the free ion (17%), the mono-chloride ion (6.4%), and zinc carbonate (5.8%)

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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, and the response to public comment (U.S. EPA 1985a) is necessary in order to understand the following text, tables, and calculations.

(Zirino and Yamamoto 1972). At pH = 7.0, the percentage of dissolved zinc present in sea water as the free ion increases to 50%. In the presence of dissolved organic materials, particularly humic substances, the major fraction of dissolved zinc is in the form of zinc-organic complexes (Lu and Chen 1977).

Zinc can be present in sediments in several forms, including precipitated $Zn(OH)_2$, precipitates with ferric and manganic oxyhydroxides, insoluble organic complexes, insoluble sulfides, and residual forms (Patrick et al. 1977). As sediments change from a reduced to an oxidized state, more zinc is mobilized and released in a soluble form (Lu and Chen 1977). The bioavailability of different forms of zinc in sediment varies substantially and is poorly understood (Luoma and Bryan 1979). Baccini (1985), Krantzberg and Stokes (1985), and Salomons (1985) reported that benthic organisms influenced the partitioning of zinc between sediment and the water column.

Most of the zinc introduced into the aquatic environment is partitioned into sediment by sorption onto hydrous iron and manganese oxides, clay minerals, and organic materials (Lu and Chen 1977; Luoma and Bryan 1981; Parker et al. 1982; Warren 1981). Precipitation of the sulfide is an important control on the mobility of zinc in reducing environments, and precipitation of the hydroxide, carbonate, and basic sulfate salts can occur when zinc is present in high concentrations. Formation of complexes with organic and inorganic ligands can increase the solubility of zinc and might increase or decrease the tendency for zinc to be sorbed (Salomons and Forstner 1984).

The tendency of zinc to be sorbed is affected not only by the form of the zinc and the nature and concentration of the sorbent but also by pH and salinity. In a study of heavy metal sorption by two oxides and two soils, zinc was completely removed from solution when pH exceeded 7, but little or no zinc was sorbed when pH was below 6. Addition of inorganic complexing ligands enhanced sorption (Huang et al. 1977). Helz et al. (1975) and Solomons (1980) found less sorption of zinc to particulate matter and sediment as salinity increased. This phenomenon was exhibited by many other metals as well and apparently is due to displacement of the sorbed zinc ions by alkali and alkaline earth cations, which are abundant in brackish and saline waters. An increase in pH can increase sorption of zinc even if salinity increases (Millward and Moore 1982; Solomons 1980). Watanabe et al. (1985) reported that sorption of zinc was also dependent on the organic carbon content of river sediments.

Zinc is an essential micronutrient for all living organisms (Leland and Kuwabara 1985). Because zinc is essential, aquatic organisms have evolved efficient mechanisms for accumulation of zinc from water and food. The concentration of zinc in tissues of aquatic organisms is far in excess of that required for various metabolic functions (Wolfe 1970). Much of the excess zinc is bound to macromolecules or is present as insoluble metal inclusions in tissues (Simkiss et al. 1982). Inducible low molecular weight metal-binding proteins, metallothioneins, are thought to function, in part, in the intracellular sequestration and regulation of the essential metals zinc and copper (Kojima and Kogi 1978; Roesijadi 1981).

Above some theoretical maximum beneficial concentration of zinc in water, there exists a range of zinc concentrations that is readily tolerated through each organism's capacity to regulate the uptake, internal distribution, and excretion of zinc (Weiner and Giesy 1979). This range undoubtedly varies among individuals, species, and larger phylogenetic groups. In addition, this tolerated range probably varies with the range of zinc concentrations to which various populations have been historically exposed and acclimated. Thus, biological variability in tolerance of zinc is probably the result of phylogenetic differences and historic exposure patterns, both short-term and geologic in scale.

Paramount to the question of the toxicity of zinc are the physical and chemical forms of zinc, the toxicity of each form, and the degree of interconversion among the various forms. Presumably, all forms of zinc that can be sorbed or bound by biological tissues are potentially toxic. Most likely, zinc will not be sorbed or bound unless it is dissolved, but some dissolution of zinc can reasonably be expected to occur in the alimentary canal following ingestion of particulates containing undissolved zinc. Thus, the toxicity of undissolved zinc to a particular species probably depends on feeding habits. Therefore, plants and most fish are probably relatively unaffected by suspended zinc, but many invertebrates and some fishes might be adversely affected by ingestion of sufficient quantities of particulates containing zinc.

The toxicity of zinc, as well as other heavy metals, is apparently influenced by a number of chemical factors including calcium, magnesium, hardness, pH, and ionic strength. These factors appear to affect the toxicity of zinc either by influencing the availability of zinc or by inhibiting the sorption or binding of available zinc by biological tissues. In fresh water zinc appears to be less toxic at high hardness for a variety of reasons, such as:

1) The ions contributing to hardness, primarily calcium and magnesium, are divalent and compete with zinc, which is also divalent, for sites of uptake and binding in biological tissues.

2) Harder waters have higher ionic strengths due to the greater quantity of charged ions (primarily mono- and divalent cations and anions) in solution, and these ions electrostatically inhibit the ability of other ions, such as zinc, to approach the sorption or binding sites of the organisms. Thus zinc ions have lower activity in harder waters.

3) Generally, harder waters have higher alkalinities and higher pHs, resulting in the formation of insoluble, and possible soluble, zinc carbonate and hydroxide compounds that are not sorbed by many species.

Thus, hardness appears to be the single best water quality characteristic to reflect the variation in zinc toxicity induced by differences in general water chemistry.

Because of the variety of forms of zinc (Callahan et al. 1979; Hem 1972; Salomons and Forstner 1984) and lack of definitive information about their relative toxicities, no available analytical measurement is known to be ideal for expressing aquatic life criteria for zinc. Previous aquatic life criteria for zinc (U.S. EPA 1980) were expressed in terms of total recoverable zinc (U.S. EPA 1983a), but this measurement is probably too rigorous in some situations. Acid-soluble zinc (operationally defined as the zinc 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 zinc to, and bioaccumulation of zinc by, aquatic organisms. No 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 zinc. For example, results reported in terms of dissolved

zinc would not have been used if the concentration of precipitated zinc had been substantial.

2. On samples of ambient water, measurement of acid-soluble zinc will probably measure all forms of zinc that are toxic to aquatic life or can be readily converted to toxic forms under natural conditions. In addition, this measurement probably will not measure several forms, such as zinc 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 zinc, such as the EDTA complex of zinc, 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 zinc in aqueous effluents. Measurement of acid-soluble zinc probably will be applicable to effluents because it will measure precipitates, such as carbonate and hydroxide precipitates of zinc, 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 zinc might be used to determine whether the receiving water can decrease the concentration of acid-soluble zinc because of sorption.
4. The acid-soluble measurement is probably 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 of most samples of ambient water 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 zinc, the analysis can be performed using either atomic absorption spectrophotometric or ICP-atomic emission spectrometric analysis (U.S. EPA 1983a), as with the total recoverable measurement.

Thus, expressing aquatic life criteria for zinc 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 zinc or for measuring zinc in ambient water or aqueous effluents, measurement of both acid-soluble zinc and total recoverable zinc in ambient water or effluent or both might be useful. For example, there might be cause for concern if total recoverable zinc is much above an applicable limit, even though acid-soluble zinc is below the limit.

Unless otherwise noted, all concentrations reported herein from toxicity and bioconcentration tests are expected to be essentially equivalent to acid-soluble zinc concentrations. All concentrations are expressed as zinc, not as the chemical tested. The criteria presented herein supersede previous aquatic life water quality criteria for zinc (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 excursions (U.S. EPA 1985b). The latest comprehensive literature search for information for this document was conducted in July, 1986; some more recent information might have been included.

Acute Toxicity to Aquatic Animals

Available data, which are usable according to the Guidelines, on the acute toxicity of zinc to aquatic animals are presented in Table 1. Acute values for freshwater invertebrates ranged from 32 to 40,930 µg/L (Table 1), and those for fishes ranged from 66 to 40,900 µg/L, except for two values that appeared high for the guppy. The two ranges are very similar and very wide, probably due at least in part to hardness-related factors.

Although many factors might affect the results of tests of the toxicity of zinc to aquatic organisms (Sprague 1985), water quality criteria can quantitatively take into account only factors for which enough data are available to show that the factor similarly affects the results of tests with a variety of species. Hardness is often thought of as having a major effect on the toxicity of zinc in fresh water, although the observed effect is probably due to one or more of a number of usually interrelated ions, such as hydroxide, carbonate, calcium, and magnesium. Hardness (expressed as mg $CaCO_3$/L) is used here as a surrogate for the ions that affect the results of toxicity tests on zinc. 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. The eight slopes are between 0.56 and 1.65 (see end of Table 1) and most are close to the slope of 1.0 that is expected on the basis that zinc, calcium, magnesium, and carbonate all have a charge of two. An F-test showed that, under the assumption of equality of slopes, the probability of obtaining eight slopes as dissimilar as these is P = 0.77. This was interpreted as indicating that it is reasonable to assume that the slopes for these eight species are the same.

Where possible, the pooled slope of 0.8473 was used to adjust the freshwater acute values in Table 1 to hardness = 50 mg/L. Species Mean Acute Values were calculated as geometric means of the adjusted acute values. Five of the seven most resistant species (Table 3) were tested in a series of experiments reported by Rehwoldt et al. (1971,1972,1973) using Hudson River water, and high acute values were obtained in two other tests whose results were placed in Table 6 because the organisms were not identified to genus. It is not known whether the river water reduced the toxicity of zinc or if the species were inherently resistant. Rehwoldt et al. (1971,1972) also reported LC50s of 6,700 and 6,800 µg/L for the striped bass, Morone saxatilis. These were considerably higher than the LC50s reported by Hughes (1970,1973) and Palawski et al. (1985) for the same species, although the values reported by Hughes were not used due to inadequate acclimation of the test organisms.

Genus Mean Acute Values (GMAVs) at hardness = 50 mg/L (Table 3) were then calculated as geometric means of the available freshwater Species Mean Acute Values. The GMAV for Morone was based only on the SMAV for the striped bass because of the probability that the LC50s reported by Rehwoldt et al. (1971,1972) were two high for both species in this genus. Of the 35 genera for which acute values are available, the most sensitive genus, Ceriodaphnia, is about 950 times more sensitive than the most resistant genus, Argia. Acute values are available for more than one species in each of seven genera and the range of Species Mean Acute Values within each genus is less than a factor of 3.7. The freshwater Final Acute Value for zinc at hardness = 50 mg/L was calculated to be 130.1 µg/L using the procedure described in the Guidelines and the Genus Mean Acute Values in Table 3. This value is above the Species Mean Acute Value for a cladoceran and for the striped bass, but the results for the striped bass were not obtained in a flow-through test in which the concentrations of test material were measured. Thus, the freshwater Criterion Maximum Concentration (in µg/L) = $e^{(0.8473[\ln(\text{hardness})]+0.8604)}$.

Acute tests considered useful in the derivation of a saltwater criterion for zinc have been conducted with 26 species of invertebrates and 7 species of fish (Table 1). The range of Species Mean Acute Values for saltwater invertebrates extends from 195 µg/L for embryos of the quahog clam, Mercenaria mercenaria, (Calabrese and Nelson 1974) to 320,400 µg/L for adults of the clam Macoma balthica (Bryant et al. 1985). The range of Species Mean Acute Values for fish is narrower, extending from 191.4 µg/L for larvae of the cabezon, Scorpaenichthys marmoratus, (Dinnel et al. 1983) to 38,000 µg/L for juvenile spot, Leiostomus xanthurus (Hansen 1983). As a general rule, early life stages of saltwater invertebrates and fish are more sensitive to zinc than juveniles and adults.

Both temperature and salinity affect the results of acute tests on zinc. The effect of temperature has been studied with four bivalve molluscs and one amphipod, whereas the effect of salinity has been studied with a worm, clam, amphipod, two isopods, and a fish (Table 1). In general, the LC50 increases as salinity increases (presumably because complexation by chloride increases) and as temperature decreases. However, the LC50 for a species also seems to decrease as salinity and temperature deviate from the optimum for the species.

Of the 28 genera for which saltwater Genus Mean Acute Values are available (Table 3), the most sensitive genus, Scorpaenichthys is about 1,700 times more sensitive than the most resistant, Macoma. Clams are both sensitive and resistant to zinc. 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 5.2. The saltwater Final Acute Value for zinc was calculated to be 190.2 µg/L, which is slightly lower than the acute value for the most sensitive species.

Chronic Toxicity to Aquatic Animals

Although most of the chronic toxicity tests conducted on zinc with freshwater species were in soft water ranging in hardness from 25 to 52 mg/L, Chapman et al. (Manuscript) studied the chronic toxicity of zinc to *Daphnia magna* at hardnesses of 52, 104, and 211 mg/L (Table 2). They found that the chronic toxicity of zinc decreased when hardness increased from 52 to 104 mg/L. When hardness was further increased to 211 mg/L, the toxicity of zinc did not change. No other data are available concerning the relationship between hardness and the chronic toxicity of zinc.

The chronic values for the two species of freshwater invertebrates ranged from 46.73 to >5,243 μg/L, whereas those for six species of fish ranged from 36.41 to 854.7 μg/L.

A life-cycle toxicity test has been conducted with the saltwater mysid, *Mysidopsis bahia* (Lussier et al. 1985). Survival, days to first brood, and young/female reproductive day were all affected at 231 μg/L, but no effects were detected at 120 μg/L.

Acute-chronic ratios are available for six freshwater and one saltwater species. The freshwater Species Mean Acute-Chronic Ratios range from 0.7027 to 41.20, whereas the saltwater ratio is 2.997 (Table 3). Because the Final Acute-Chronic Ratio is meant to apply to sensitive species, which often have lower acute-chronic ratios than resistant species, it was calculated as the geometric mean of the ratios for the freshwater *Daphnia magna*, chinook salmon, and rainbow trout and the saltwater mysid. The resulting value of 2.208 is lower than all the other Species Mean Acute-Chronic Ratios (Table 3). Division of the freshwater and saltwater Final Acute Values by 2.208 results in freshwater and saltwater Final Chronic Values of 58.92 μg/L (at hardness = 50 mg/L) and 86.14 μg/L, respectively. In spite of the data on the effect of hardness on the chronic toxicity of zinc to *Daphnia magna*, the freshwater chronic slope is assumed to be the same as the acute slope, resulting in a freshwater Final Chronic Value = $e^{(0.8473[\ln(\text{hardness})]+0.7614)}$.

Toxicity to Aquatic Plants

Toxicity tests on zinc have been conducted with 20 species of freshwater plants, which were affected by zinc concentrations ranging from 30 to >200,000 µg/L (Table 4). Although tests have been conducted with several vascular plants, both the highest and lowest values were obtained with algae.

Few data are available concerning the effect of hardness on toxicity to plants. One study with the diatom, *Navicula seminulum*, (Academy of Natural Sciences 1960) tested zinc toxicity at two hardnesses. At hardness = 58.46 mg/L, zinc was more toxic, on the average, than in tests at hardness = 174 mg/L. However, there was overlap in EC50s between the hardnesses tested. The toxicity of zinc to algae might be related to the concentration of phosphate or nitrate (Kuwabara 1985; Rao and Subramanian 1982).

The toxicity of zinc to saltwater plants has been tested with 18 species of phytoplankton and 8 species of macroalgae (Tables 4 and 6). The diatom, *Schroederella schroederi*, was the most sensitive phytoplankter, with a 48-hour EC50 of 19.01 µg/L. Other species affected at concentrations less than the Final Chronic Value are *Cricosphaera carterae*, *Isochrysis gabana*, *Thalassiosira rotula*, *Glenodinium halli*, and *Gymnodinium splendens*. Macroalgae were affected at concentrations ≥100 µg/L. Therefore, although data on most saltwater plants indicate that they will be protected by a saltwater criterion derived from data on animals, some phytoplankters might be affected under certain environmental conditions.

Bioaccumulation

Six freshwater species were exposed to zinc and had tissue concentrations measured after sufficient time to achieve steady-state (Table 5). Bioconcentration factors (BCF) ranged from 51 for the Atlantic salmon (Farmer et al. 1979) to 1,130 for a mayfly (Nehring 1976). A mean BCF of 100 was obtained in three tests with a clam (Graney et al. 1983), and the BCF of 106 for a stonefly was much lower than that for the mayfly. Both the flagfish and the guppy had BCFs between 400 and 500. Atchinson et al. (1977), McIntosh and Bishop (1976), and Murphy et al. (1978a,b) measured the concentrations of zinc in several species of fish obtained from a pond contaminated with zinc. Direct accumulation from water did not appear to be a major route of uptake of zinc by two species of fish in a lake (Klaverkamp et al. 1983). Cushing and Rose (1970), Cushing and Watson (1971), and Cushing et al. (1975) studied the uptake of zinc by periphyton and fish in microcosms. Van der Werff (1984) found that humic and fulvic acids reduced the uptake of zinc by an alga.

Bioaccumulation data for zinc are available for six species of saltwater algae and seven species of saltwater animals (Table 5). Steady-state BCFs derived from laboratory exposures of saltwater algae for periods of 0.5 to 140 days ranged from 75.5 for the brown macroalga, *Laminaria digitata* (Haritonidis et al. 1983) to 10,768 for another brown macroalga, *Fucus serratus* (Young 1975). BCFs based on data derived from field collections of macroalgae ranged from 1,027 to 2,029 for a third brown macroalga, *Fucus vesiculosus* (Foster 1976; Foster and Bale 1975).

BCFs derived from laboratory exposures of saltwater animals for periods of 14 to 126 days range from 3.692 in the whole body of the shrimp, *Pandalus montagui* (Ray et al. 1980) to 23,820 in the total soft tissue of the eastern oyster, *Crassostrea virginica* (Shuster and Pringle 1968).

For the mummichog, *Fundulus heteroclitus*, the BCF for both whole body and scales decreased with increasing concentration in water between 210 and 7,880 µg/L (Sauer and Watabe 1984). At all concentrations, the scales had a higher BCF than the whole body. Sequestration of zinc in scales, which is accompanied by a decrease in scale calcification (Sauer and Watabe 1984), might be a mechanism of zinc storage or detoxification in fish. O'Grady (1981) showed that sea trout, *Salmo trutta*, mobilized zinc stored in its scales during the upstream spawning migration.

For both algae and animals, there is a definite trend toward an inverse relationship between concentration in water and BCF. This is best exemplified by the data in Table 5 for the brown macroalga, *Laminaria digitata* (Bryan 1969) and the mummichog, *Fundulus heteroclitus* (Sauer and Watabe 1984). Seip (1979) developed a mathematical model for the accumulation of zinc and other metals by the brown macroalga, *Ascophyllum nodosum*. The concentration of zinc in the alga was found to be an approximately linear function of the mean concentration of zinc in water up to about 100 µg/L. Because the slope of the curve was less than 1, BCFs tended to decrease with increasing concentration in water.

No U.S. FDA action level or other maximum acceptable concentration in tissue is available for zinc, and, therefore, no Final Residue Value can be calculated.

Other Data

A wide variety of other data is presented in Table 6. In a test on zinc phosphate, growth of a freshwater green alga was inhibited during a 14-day exposure to 64 µg/L (Garton 1972). Growth of *Scenedesmus quadricauda* was inhibited during exposure to 1,200 µg/L in river water (Bringmann and Kuhn 1959a,b). The primary productivity of plankton was reduced when exposed to 15 µg/L for 14 days (Marshall et al. 1983).

Several studies have been conducted on the effect of temperature on the acute toxicity of zinc (Braginskiy and Shcherban 1978; Cairns et al. 1975a, 1978; Pickering and Henderson 1966; See et al. 1974; Smith and Heath 1979). Except for the rainbow trout and golden shiners, the species were more sensitive to zinc at higher temperatures. Snails were more sensitive to thermal shock after exposure to zinc (Cairns et al. 1976).

Concentrations of dissolved oxygen down to 3.5 mg/L did not affect the toxicity of zinc to the bluegill, but lower concentrations did (Pickering 1968). Anderson (1973) and Anderson and Weber (1975) found that the acute sensitivity of the guppy to zinc depended on the weight of the fish. Sabodash (1974) studied the effects of zinc and calcium on survival and growth of larval grass carp.

Most insects were more resistant to zinc than the other freshwater species tested. Mayflies, damselflies, stoneflies, and caddisflies had LC50s ranging from 1,330 to 58,100 µg/L (Table 6). One midge (*Chironomous* sp.) had a 96-hr LC50 of 18,200 µg/L (Rehwoldt et al. 1973), whereas another (*Tanytarsus dissimilis*) had a 10-day LC50 of 36.8 µg/L (Anderson et al. 1980). The *T. dissimilis* value is very low compared to other values obtained with insects.

Although most LC50s for rainbow trout ranged from 2,000 to 5,000 µg/L, Garton (1972) obtained an LC50 of 90 µg/L in a test on zinc phosphate.

A 7-day EC50 of 10 µg/L was obtained with embryos and larva of the narrow-mouthed toad (Birge 1978; Birge et al. 1979).

Cairns et al. (1975b) and Khangarot (1982) examined the effect of feeding on the results of acute tests on zinc, whereas McLeay and Munro (1979) and Sparks et al. (1972b) studied the effects of photoperiod and shelters, respectively. Brafield and Mattiessen (1976), Hughes (1975), Hughes and Tort (1985), and Thompson et al. (1983) studied the effect of zinc on respiration of fishes. Allen et al. (1980) and Muramota (1978) found that various chelating agents reduced the acute toxicity of zinc. Several studies examined the use of fishes as biomonitoring organisms for zinc (Cairns and Waller 1971; Cairns et al. 1973a; Sparks et al. 1972; Waller and Cairns 1972).

Many studies have examined zinc as a dietary requirement for freshwater plants (e.g., Vaughn et al. 1982) and fish (e.g., Barash et al. 1982; Bell et al. 1984; Dabrowski et al. 1981; Gatlina and Wilson 1983,1984; Jeng and Sun 1981; Ketola 1979; Knox et al. 1982,1984; Ogino and Yang 1978,1979; Richardson et al. 1985; Rodgers 1982; Satoh et al. 1983a,b,c; Takeda and Shimma 1977).

Armitage (1980), Armitage and Blackburn (1985), Austin and Munteanu (1984), Carlson et al. (1986), Eichenberger (1981), Eichenberger et al. (1981), Foster (1982a), Harding et al. (1981), Hughes (1985), Lang and Lang-Dobler (1979), Maas (1978), Meyer (1978), Rice (1977), Roline and Boehmke (1981), Ruthven and Cairns (1973), Say and Whitton (1983), Say et al. (1977), Sheehan and Knight (1985), Shehata and Whitton (1981), Solbe (1973), Swain and White (1985), Swift (1985), Wehr and Whitton (1983b,c), Wentsel and McIntosh (1977), Williams and Mount (1965), Yan et al. (1985), Yasuno et al. (1985), and Zanella (1982) investigated relationships between the abundance and diversity of freshwater species and the concentration of zinc in water and sediment.

The detoxification of zinc was studied by Kito et al. (1982), Klaverkamp et al. (1985), Ley et al. (1983), Marofante (1962), Pierson (1985a,b), Roch and McCarter (1984a,b), and Takeda and Shimizu (1982).

Low concentrations of zinc stimulate the rate of growth of saltwater microalgae. Concentrations equal to or less than 100 µg/L stimulated growth of Nitzchia longissima during exposures lasting one to five days (Subramanian et al. 1980). Similarly, growth of Skeletonema costatum was both stimulated by zinc concentrations equal to or lower than 200 µg/L during one to five days of exposure (Subramanian et al. 1980) and reduced by 20% during exposure for 10 to 14 days to 100 µg/L zinc (Braek et al. 1976). Wikfors and Ukeles (1982) reported a 6.7% increase in the growth of Phaeodactylum tricornutum during exposure for 12 days to 4,800 µg/L. Therefore the difference between beneficial and detrimental concentrations of zinc to phytoplankton might be small and dependent on the species and exposure.

Stromgren (1979) studied the effect of zinc on growth of five species of saltwater macroalgae. Growth was reduced at 1,400, but not 100, µg/l for Ascophyllum nodosum, Fucus serratus, Fucus spiralis, and Pelvetia canaliculata, and at 7,000, but not 3,500, µg/L for Fucus vesiculosus. Bryan (1969) reported reduced growth of Laminaria digitata during exposure for 24 days to concentrations as low as 100 µg/L. A concentration of 250 µg/L reduced growth of sporophytes of Laminaria hyperboria, whereas 5,000 µg/L induced abnormal maturation of gametophytes of the same species (Hopkins and Kain 1971). Zinc concentrations as low as 8.8 µg/L altered lipid metabolism in Fucus serratus (Smith and Harwood 1984).

Two ciliate protozoans exhibited markedly different sensitivities to zinc. Growth of *Cristigera* sp. was reduced by exposure for four to five hours to concentrations as low as 50.63 µg/L (Gray 1974; Gray and Ventilla 1973), but a concentration of 10,000 µg/L only reduced the growth of *Euplotes vannus* by 10% (Persoone and Uyttersprot 1975).

Bryan and Hummerstone (1973) compared the sensitivity of the polychaete, *Nereis diversicolor*, from sediments heavily contaminated with zinc and other metals to that of the same species from clean sediments at three salinities (Tables 1 and 6). At all three salinities, worms from the contaminated sediments were less than a factor of two more resistant to zinc than those from clean sediments. Worms from the contaminated sediments also had somewhat lower BCFs than worms from clean sediments when exposed to zinc in the laboratory for 34 days. These results suggest that acclimation or genetic adaptation of the worms to contaminated sediments provided only a minor ability to regulate zinc more efficiently than worms from uncontaminated sediments.

The polychaetes, *Ophryotiocha diadema* and *Ctenodrilus serratus*, were exposed to zinc in partial life-cycle tests that began with adults and examined effects on survival and reproduction (Reish and Carr 1978). Population size was reduced 500 µg/L in both static tests but effects of zinc were not detected at 100 µg/L.

A variety of responses were observed in mud snails, *Nassarius obsoletus*, during exposure for 72 hr to progressively higher concentrations of zinc (MacInnes and Thurberg 1973). At 2,000 µg/L, there was a depression of oxygen consumption. Locomotor behavior was inhibited at 10,000 µg/L, and death ensued at 50,000 µg/L. Similarly, shell deposition by adults of the blue mussel, *Mytilus edulis*, was inhibited by 50% following exposure for two to six days to ≥60 μg/L (Manley et al. 1984; Stromgren 1982). The EC50 based on reduced byssal thread production was 1,800 μg/L, whereas the 7-day LC50 was 5,000 μg/L (Martin et al. 1975). The 72-hr EC50 for development of mussel embryos to the veliger stage was between 96 and 314 μg/L (Dinnel et al. 1983).

Different life stages and developmental processes of gametes, embryos, and larvae of Pacific oysters have different sensitivities to zinc. The ability of oyster sperm to fertilize eggs was depressed by 50% after exposure for 60 min to 443.6 μg/L (Dinnel et al. 1983). The 48-hr LC50 for embryos was 241.5 μg/L (Brereton et al. 1973). Larvae developed abnormally and grew more slowly than controls at zinc concentrations between 125 and 500 μg/L (Brereton et al. 1973), whereas EC50s for growth of 6-day-old and 16-day old larvae exposed for four days were 80 and 95 μg/L, respectively (Watling 1982). The 96-hr LC50 for 6-day and 16-day larvae was in excess of 100 μg/L, whereas that for 19-day larvae was between 30 and 35 μg/L (Watling 1982). Significant delay of, and reduction in, successful settlement was observed after 5 days in 125 μg/L (Boyden et al. 1975) and after 20 days in 10 to 20 μg/L (Watling 1983). Juvenile oyster spat had a 23-day LC50 of 75 μg/L (Watling 1983).

Exposure to 176 μg/L for 72 hr caused a 50% reduction in the rate of calcium uptake by larvae of the clam, *Mulinia lateralis*, whereas a concentration of 200 μg/L caused 53% mortality among the clam larvae in the same time period (Ho and Suboff 1982). The 8 to 10-day LC50 was 195.4 μg/L for larvae of the quahog clam, *Mercenaria mercenaria* and growth of survivors was estimated to be reduced by 38.4% (Calabrese et al. 1977).

At concentrations as low as 250 μg/L, zinc caused significant delays in molting and development rate of larvae of the grass shrimp, *Palaemonetes* pugio, particularly under stressful temperature-salinity regimes (McKenney 1979; McKenney and Neff 1979,1981). Concentrations of 25 to 50 µg/L were without effect on the development rate of larvae of the mud crab, Rhithropanopeus harrisii (Benijts-Claus and Benijts 1975). However, in the presence of lead at 25 to 50 µg/L, these concentrations of zinc produced a significant delay in the rate of larval development of mud crabs. Rate of limb regeneration by adults of the fiddler crab, Uca pugilator, was inhibited at zinc concentrations of 1,000 (Weis 1980). This inhibitory effect was amplified at low salinities.

Motility of the sperm of the sea urchins, Arbacia punctulata and Strongylocentrotus purpuratus, was stimulated by brief exposure to zinc concentrations at or below 1,634 and 654.8 µg/L, respectively (Timourian and Watchmaker 1977; Young and Nelson 1974). At concentrations of 3,269 and 6,538 µg/L, respectively, sperm motility was inhibited. Reduction of the ability of echinoderm sperm to fertilize eggs appeared to be more sensitive than sperm motility to the toxic effects of zinc (Dinnel et al. 1983). EC50s after one hour of exposure of sperm ranged from 28 to 382.8 µg/L. In tests with the sand dollar, Dendraster excentricus, and two sea urchins, Strongylocentrotus droebachiensis and S. purpuratus, development to the pluteus stage was less sensitive than fertilization. Waterman (1937) found that 810 µg/L inhibited gastrulation and that 2,314 µg/L was lethal to embryos of Arbacia punctulata.

Somasundarum et al. (1984a,b,c,d;1985) identified several developmental anomalies and histopathological lesions in developing embryos and larvae of Atlantic herring, Clupea harengus, that were exposed to 50 to 12,000 µg/L. Zinc concentrations below 6,000 µg/L did not affect embryo volume. Below 2,000 µg/L, zinc accelerated embryonic development, but

6,000 µg/L inhibited development. At zinc concentrations as low as 50 µg/L, there was a significant increase in the incidence of jaw and branchial abnormalities. Concentrations above 500 µg/L increased the incidence of vertebral abnormalities. Significant decreases in the size of the otic capsules and eyes were observed at zinc concentrations higher than 2,000 and 6,000 µg/L, respectively. Ultrastructural changes in brain cells and somatic musculature were observed in herring larvae that were allowed to develop for 14 days in sea water containing 50 to 12,000 µg/L.

In contrast to the toxic effects noted above, Weis et al. (1981) found that exposure to 10,000 µg/L ameliorated teratogenic effects on Fundulus heteroclitus exposed to methyl mercury. Also, zinc concentrations of 1,000 µg/L or greater enhanced regeneration of the tail fin and ameliorated effects of methyl mercury on fin regeneration in adult mummichogs (Weis and Weis 1980).

Exposure of adult mummichogs to 2,200 µg/L resulted in increased activity of the hepatic enzyme aminolevulinic acid dehydrase (Jackim 1973), whereas exposure to 60,000 µg/L caused 30% mortality and histopathological lesions in the oral epithelium of survivors (Eisler and Gardner 1973). Calcification of the scales of juvenile mummichogs was inhibited at 760 to 7,100 µg/L (Sauer and Watabe 1984).

Crustaceans and fish are able to accumulate zinc from both water and food. For adult green crabs, Carcinus maenas, the BCF for zinc from water was 130 and the bioaccumulation factor (BAF) for zinc from water and food was 210 (Renfro et al. 1975), but the BAF was not significantly higher. However the BAF was statistically higher than the BCF with adult mosquito fish, Gambusia affinis, and juvenile spot, Leiostomus xanthurus (Willis and Sunda 1984). At 120 days, the BAF and BCF for uptake of zinc from water alone and water plus food by mosquito fish were 45 and 8, respectively. The BAF and BCF for spot after a 28-day exposure were 28 and 3, respectively. These results suggest that these fish obtain five to nine times more zinc from food than from water. It must be recognized, however, that the relative magnitude of the contribution from both sources to the concentration of zinc in saltwater animals will depend on the relative concentrations of zinc in the water and food. Eisler (1967) and Eisler and Gardner (1973) have shown that BCFs for adult mummichogs, *Fundulus heteroclitus*, are inversely related to the concentration of zinc in the water.

Unused Data

Some data on the effects of zinc on aquatic organisms were not used because the studies were conducted with species that are not resident in North America (e.g., Abbasi and Soni 1986; Ahsanullah and Arnott 1978; Baudoin and Scoppa 1974; Bengtsson 1974a,b,c,d,e; Carter and Nicholas 1978; Chapman and Dunlop 1981; Dunlop and Chapman 1981; Greenwood and Fielder 1983; Harrison 1969; Howell 1985; Jones and Wacker 1979; Jones et al. 1984; Karbe et al. 1975; Khangarot 1981,1984; Khangarot et al. 1982, 1985; Kumar and Pant 1984; Lomte and Jackhar 1982; Lyon et al. 1983; Martin et al. 1977; Mathur et al. 1981; McFeters et al. 1983; Mecham and Holliman 1975; Millington and Walker 1983; Milner 1982; Murti and Shukla 1984; Natarajan 1982; Nazarenko 1970; Pentreath 1973; Sartory and Lloyd 1976; Sastry and Subhadra 1984; Saxena and Parashari 1983; Seiffer and Schoof 1967; Shaffi 1979; Shehata and Whitton 1981; Shukla et al. 1983; Solbe and Flook 1975; Speranza et al. 1977; Srivastava et al. 1985; Stary and Krantzer 1982; Subhadra and Sastry 1985; Thorp and Lake 1974; Verma et al. 1984; Wagh et al. 1985; White and Rainbow 1982; Willis 1983) or because the test specices was not obtained in North America and was not identified well enough to determine whether it is resident in North America (e.g., Greichus et al. 1978; Jennett et al. 1981; Pommery et al. 1985; Tishinova 1977). Results (e.g., Bagshaw et al. 1986; Brown and Ahsanullah 1971) of tests conducted with brine shrimp, Artemia sp., were not used because these species are from a unique saltwater environment.

Babich and Stotzky (1985), Biddinger and Gloss (1984), Cairns (1957), Campbell and Stokes (1985), Connolly (1985), Doudoroff and Katz (1953), Duxbury (1985), Eisler (1981), Hartman (1980), Kaiser (1980), LeBlanc (1984), Lim (1972), Lloyd (1965), Macek and Sleight (1977), Mancini (1983), McKim (1977), Pagenkopf (1976), Patrick et al. (1968), Phillips and Russo (1978), Polikarpov (1966), Rai et al. (1981b), Riordan (1976), Skidmore (1964), Skidmore and Firth (1983), Slooff et al. (1986), Sprague et al. (1964), Strufe (1964), Taylor et al. (1982), Thomson and MacPhee (1985), Vernon (1954), Vymazal (1985), Weatherley et al. (1980), and Whitton (1970) only contain data that have been published elsewhere.

Results were not used if either the test procedures, test material, or dilution water was not adequately described (e.g., Back 1983; Bates et al. 1981; Baudin 1983a,b; Berg and Brazzell 1975; Biegert and Valkovic 1980; Birge and Just 1973,1975; Bradley and Sprague 1983; Brauwers 1982; Brkovic-Popovic and Popovic 1977a,b; Brown 1968; Carpenter 1927; Coburn and Friedman 1976; Danil'chenko 1977; Darnall et al. 1986; Dilling and Healy 1927; Fleming and Richards 1982; Hutchinson and Sprague 1985; Ishizaka et al. 1966; Joraensostrorasks and McLaughlin 1974; Knittel 1980; Labat et al. 1977; Miller et al. 1985; Muramoto 1980; Pavicic 1980; Petry 1983; Rao and Saxena 1981; Sabodash 1974; See et al. 1974,1975;

Sicko-Goad and Lazinsky 1981; Tokunago and Kishikawa 1982; Vinot and Larpent 1984).

Data were not used if zinc was a component of an effluent (e.g., Bailey and Liu 1980; Cherry et al. 1979; Finlayson and Ashuchian 1979; Frazier 1976; Grushko et al. 1980; Guthrie et al. 1977; Jay and Muncy 1979; Lewis 1986; Lu et al. 1975; Nagy-Toth and Barna 1983; Nehring and Goettl 1974; Neufeld and Wallach 1984; Newman et al. 1985; O'Conner 1976; Oladimeji and Wade 1984; Ozlmek 1985; Phillips and Gregory 1980; Rana and Kumar 1975; Roesijadi et al. 1984; Saunders and Sprague 1967; Sprecht et al. 1984; Wang 1982; Whitton et al. 1981; Wong and Tam 1984a,b; Wood 1975), mixture (e.g., Baker and Boldigo 1984; Besser 1985; Biesinger et al. 1974; Birge et al. 1978; Borgmann 1980; Brown et al. 1969; Cairns and Scheier 1968; Cearley 1971; Chang et al. 1981; Christensen et al. 1985; Cowgill et al. 1986; Danil'chenko and Stroganov 1975; Davies 1985; Davies and Woodling 1980; Doudoroff 1956; Doudoroff et al. 1966; Eaton 1973; Eisler 1977b; Finlayson and Verrue 1980; Giesy et al. 1980; Hedtke and Puglisi 1980; Henry and Atchison 1979a,b; Hutchinson and Czyrska 1972; Hutchinson and Sprague 1983; Lubinski and Sparks 1981; Markarian et al. 1980; Marking and Bills 1985; McLeese and Ray 1984; Muller and Payer 1980; Muska 1977; Patrick and Loutit 1976,1978; Pope 1981; Roch and McCarter 1984c,1986; Roch et al. 1985,1986; Rodgers and Beamish 1983; Sprague 1965; Stromegren 1980; Vymazal 1984; Wong et al. 1982a,b,1984b), or a sediment (e.g., Arruda et al. 1983; Broberg 1984; Bryan et al. 1983; Dean 1974; Krantzberg 1983; Laskowski-Hoke and Prater 1984; Lewis and McIntosh 1984, 1986; Luoma and Jenne 1977; Malueg 1984; McMurtry 1984; Munawar et al. 1985; Oakden et al. 1984; Ray et al. 1981; Seelye et al. 1982; Wentsel et al. 1977; Wong and Kwan 1981; Wong and Tam 1984; Wong et al. 1984a).

Data were not used if the organisms were exposed to zinc by injection or gavage or in food (e.g., Barash et al. 1982; Baudin 1985; Bell et al. 1984; Cancalon 1982; Cowgill et al. 1985; Dallinger and Wieser 1984; Dixon and Compher 1977; Gatlin and Wilson 1983,1984; Hibiya and Oguri 1961; Jeng and Sun 1981; Knox et al. 1984; Lyon et al. 1984; Mansouri-Aliabadi and Sharp 1985; Marafonte 1976; Ogino and Yang 1978,1979; Patrick and Loutit 1978; Richardson et al. 1985; Saiki and Mori 1955; Satoh et al. 1983a,b; Smith-Sonneborn et al. 1983; Suzuki and Ebihara 1984; Suzuki and Kawamura 1984; Suzuki et al. 1983,1984; Takeda and Shimma 1977; Vaughan et al. 1982; Windom et al. 1982; Young 1975).

Adragna and Privitera (1978,1979), Akberali and Earnshaw (1982), Anderson et al. (1978), Babich et al. (1985,1986a,b), Brown (1976), Burton and Peterson (1979), Cenini and Turner (1983), Crespo (1984), Crist et al. (1981), Doyle et al. (1981), Everaarts et al. (1979), Fleming et al. (1982), George (1983), Hiller and Perlmutter (1971), Hiltibran (1971), Kodama et al. (1982a), Nemosok et al. (1984), Rachlin and Perlmutter (1969), Sirover and Loeb (1976), and Watson and Beamish (1981) only exposed enzymes, excised or homogenized tissue, or cell cultures.

Results of some laboratory tests were not used because the tests were conducted in distilled or deionized water without addition of appropriate salts (e.g., Afflect 1952; Carter and Cameron 1973; Eddy and Fraser 1982; Matthiessen and Brafield 1973; McDonald et al. 1980; Porter and Hakanson 1976; Stary and Kratzer 1982; Stary et al. 1983; Taylor 1978; Vijayamadhavan and Iwai 1975; Wang 1959) or were conducted in chlorinated or "tap" water (e.g., Goodman 1951; Grande 1966; Haider and Wunder 1983; Hughes and Adeney 1977; Jones 1935,1938,1939; Matthiessen and Brafield 1977; Rahel

1981; Shcherban 1977; Skidmore 1970; Skidmore and Tovell 1972). Dilution water was at too low a pH in tests by Michnowicz and Weaks (1984), whereas temperature fluctuated too much in the test reported by Mills (1976b).

Allan et al. (1980), Bates et al. (1983), Buikema et al. (1974a,b, 1977), Cairns and Dickson (1970), Fayed and Abd-El-Shafy (1985), Kuwabara (1985), Mills (1976a,b), Petersen (1982), Rainbow et al. (1980), Ruthven and Cairns (1973), Say and Whitton (1977), Sullivan et al. (1973), and Zitko et al. (1973) used dilution water that contained too high a concentration of chelating agent or other organic matter. Mukhopadhyay and Konar (1984) used a phosphate buffer, which might have detoxified zinc, although their LC50s for two invertebrate species were quite low after adjustment for hardness.

Benson and Birge (1985), Berglind and Dave (1984), and Birge et al. (1983) cultured or acclimated organisms in one water and conducted tests in another. Hughes (1970,1973) did not acclimate organisms for a long enough time. Tests conducted with too few test organisms (e.g., Applegate et al. 1957; Gardner 1975; McLeese 1976; Sprague 1964a; Tishinova 1977) were not used. High control mortalities occurred in tests reported by Cairns and Scheier (1964) and Havas and Hutchinson (1982). The water quality varied too much during tests conducted by Cairns et al. (1981), Nehring and Goettl (1974), and Thompson et al. (1980). Toxicity tests conducted without controls were not used (e.g., Graham et al. 1986). The 96-hr values reported by Buikema et al. (1974a,b) were subject to error because of possible reproductive interactions (Buikema et al. 1977). The test organisms were possibly stressed by disease or parasites during tests reported by Boyce and Yamada (1977), Guth et al. (1977), and Sakanari et al. (1984). Hublou et al. (1954) conducted tests on zinc leached from galvanized trays. Anudu (1983), Bradley et al. (1985a,b), Cairns (1972), Cairns et al. (1973a,b), DeFilippis and Pallaghy (1976), Duncan and Klaverkamp (1980), Foster (1982b), LeBlanc (1982), and Wang (1986b) conducted studies of acclimation to zinc or used organisms that had been exposed or were resistant to zinc.

Biochemical and histological studies were not used (e.g., Anderson and Sparks 1978; Canalon 1982; Cenini and Turner 1979; Eddy and Talbot 1985; Kearns and Atchison 1979; Kodama et al. 1982a,b; Nemcsok et al. 1984; Rachlin et al. 1985; Sailer et al. 1980; Schmitt et al. 1984; Taban et al. 1982; Thomas et al. 1985; Vijayamadhauan and Iwai 1975; Watson and Beamish 1980; Watson and McKoewn 1976; Yamamoto et al. 1977).

Results of chronic tests were not used if the concentration of test material was not measured (e.g., Winner and Gauss 1986) or if the test solutions were only renewed once a week (e.g., Crandall and Goodnight 1962,1963). Data on toxicity or accumulation or both from microcosm or model ecosystem studies were not used if the concentration of zinc in water decreased with time (e.g., Bachman 1963; Davis and Negilski 1972).

Results of laboratory bioconcentration tests were not used if the test was not flow-through or renewal (e.g., Dean 1974; Evtushenko et al. 1984; Fayed et al. 1983; Hughes and Flos 1978; Joyner 1961; Joyner and Eisler 1961; Lyngby et al. 1982; Skipnes et al. 1975; Sklar 1980; Slater 1961; Young 1977) or if the concentration of zinc in the test solution was not adequately measured (e.g., Mellinger 1972; Munda 1979,1984; Phillips 1976,1977). Hardy and Raber (1985) did not measure the concentration of zinc in tissues.

Van Hoof and Van San (1981) found high concentrations of zinc in their control fish. Harvey (1974) studied depuration, but not uptake, of zinc by a freshwater clam, and Ferguson and Bubela (1974) studied uptake by homogenized algal suspensions. The concentration of zinc fluctuated too much in the tests reported by Kormondy (1965) and O'Grady and Obdullah (1985).

Reports of the concentrations of zinc in wild aquatic organisms (e.g., Abdullah et al. 1976; Abo-Rady 1979,1983; Adams et al. 1980,1981; Amemiya and Nakayama 1984; Anderson 1977; Anderson et al. 1978; Arnac and Lassus 1985; Badsha and Goldspink 1982; Bailey and Stokes 1985; Barber and Trefry 1981; Bohn and Fallis 1978; Bosserman 1985; Bradley and Morris 1986; Brezina and Arnold 1977; Brooks et al. 1976; Brown 1977; Brown and Chlow 1977; Burrows and Whitton 1983; Burton and Peterson 1979; Bussey et al. 1976; Caines et al. 1985; Chapman 1985; Chassard and Balvay 1978; Coughtrey and Martin 1977; Cover and Wilhm 1982; Cowx 1982; Dallinger and Kautzky 1985; EIFAC 1977; Elder and Mattraw 1984; Elliott et al. 1981; Elwood et al. 1976; Estabrook et al. 1985; Felat and Melzer 1978; Fletcher and King 1978; Fletcher et al. 1975; Franzin and McFarlane 1980; Frazier 1975; Friant and Koerner 1981; Friant and Sherman 1980; Gale et al. 1973a,b; Giesy and Weiner 1977; Greichus et al. 1978; Guillizzoni 1980; Hakanson 1984; Harding and Whitton 1978; Heit and Klusek 1985; Holm 1980; Howard and Brown 1983; Huggett et al. 1973; Jeng and Lo 1974; Johannessan et al. 1983; Jones et al. 1985; Kleinert et al. 1974; Kole et al. 1978; Korda et al. 1977; Lee et al. 1984; Lewis 1980; Lobel and Wright 1983; Lord et al. 1977; Lowe et al. 1985; Lucas and Edgington 1970; Lundholm and Andersson 1985; Maas 1978; McFarlane and Franzin 1978; McHardy and George 1985; Moreau et al. 1983; Morrison et al. 1985; Nabrzyski 1975; Nabrzyski and Gajewski 1978; Namminga and Wilhm 1977; Ney and Martin 1985; Ney et al. 1982; Norris and Lake 1984; O'Grady 1981; Paul and Pillai 1983; Pennington et al. 1982; Percy and Borland 1985; Peverly 1985; Rabe et al. 1977; Ranta et al. 1978; Ray and White 1979; Rehwoldt et al. 1976; Romberg and Refro 1973; Salanki et al. 1982; Saltes and Bailey 1984; Seagle and Ehlmann 1974; Shearer 1984; Shimma et al. 1984;

Shuman et al. 1977; Simpson 1979; Stary et al. 1982; Stokes et al. 1985; Strufe 1964; Teherani et al. 1979; Tessier et al. 1984; Tisa and Strange 1981; Tsui and McCart 1981; Uthe and Bligh 1971; Van Coillie and Rousseau 1974; Van Loon and Beamish 1977; Villarreal-Trevino et al. 1986; Vinikour et al. 1980; Wachs 1982; Walker et al. 1975; Wehr and Whitton 1983a,b; Wehr et al. 1983; Whitton et al. 1981,1982; Wiener and Giesy 1979; Winger and Andreasen 1985; Wissmar et al. 1982; Young and Blevins 1981, Zadory 1984) were not used to calculate bioaccumulation factors because either the number of measurements of the concentration in water was too small or the range of the measured concentrations in water was too large.

Summary

Acute toxicity values are available for 43 species of freshwater animals and data for eight species indicate that acute toxicity decreases as hardness increases. When adjusted to a hardness of 50 mg/L, sensitivities range from 50.70 µg/L for *Ceriodaphnia reticulata* to 88,960 µg/L for a damselfly. Additional data indicate that toxicity increases as temperature increases. Chronic toxicity data are available for nine freshwater species. Chronic values for two invertebrates ranged from 46.73 µg/L for *Daphnia magna* to >5,243 µg/L for the caddisfly, *Clistoronia magnifica*. Chronic values for seven fish species ranged from 36.41 µg/L for the flagfish, *Jordanella floridae*, to 854.7 µg/L for the brook trout, *Salvelinus fontinalis*. Acute-chronic ratios ranged from 0.2614 to 41.20, but the ratios for the sensitive species were all less than 7.3.

The sensitivity range of freshwater plants to zinc is greater than that for animals. Growth of the alga, *Selenastrum capricornutum*, was inhibited by 30 µg/L. On the other hand, with several other species of green algae, 4-day EC50s exceeded 200,000 µg/L. Zinc was found to bioaccumulate in freshwater animal tissues from 51 to 1,130 times the concentration present in the water.

Acceptable acute toxicity values for zinc are available for 33 species of saltwater animals including 26 invertebrates and 7 fish. LC50s range from 191.5 µg/L for cabezon, Scorpaenichthys marmoratus to 320,400 µg/L for adults of another clam, Macoma balthica. Early life stages of saltwater invertebrates and fishes are generally more sensitive to zinc than juveniles and adults. Temperature has variable and inconsistent effects on the sensitivity of saltwater invetebrates to zinc. The sensitivity of saltwater animals to zinc decreases with increasing salinity, but the magnitude of the effect is species-specific.

A life-cycle test with the mysid, Mysidopsia bahia, found unacceptable effects at 120 µg/L, but not at 231 µg/L, and the acute-chronic ratio was 2.997. Seven species of saltwater plants were affected at concentrations ranging from 19 to 10,100 µg/L. Bioaccumulation data for zinc are available for seven species of saltwater algae and five species of saltwater animals. Steady-state zinc bioconcentration factors for the twelve species range from 3.692 to 23,820.

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 zinc does not exceed the numerical value given by

$e^{(0.8473[\ln(\text{hardness})]+0.7614)}$ 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 $e^{(0.8473[\ln(\text{hardness})]+0.8604)}$ 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 zinc are 59, 110, and 190 µg/L, respectively, and the one-hour average concentrations are 65, 120, and 210 µg/L. If the striped bass is as sensitive as some data indicate, it will not be protected by this criterion.

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 four-day average concentration of zinc does not exceed 86 µg/L more than once every three years on the average and if the one-hour average concentration does not exceed 95 µg/L more than once every three years on the average.

"Acid-soluble" is probably the best measurement at present for expressing criteria for metals and the criteria for zinc were developed on this basis. However, at this time, no EPA approved method for such a measurement is available to implement criteria for metals through the regulatory programs of the Agency and the States. The Agency is considering development and approval of a method for a measurement such as "acid-soluble." Until one is approved, however, EPA recommends applying criteria for metals using the total recoverable method. This has two impacts: (1) certain species of some metals cannot be measured because the total recoverable method cannot distinguish between individual oxidation states, and (2) in some cases these criteria might be overly protective when based on the total recoverable method.

Three years is the Agency's best scientific judgment of the average amount of time aquatic ecosystems should be provided between excursions (U.S. EPA 1985b). The resiliencies of ecosystems and their abilities to recover differ greatly, however, and site-specific allowed excursion frequencies may be established if adequate justification is provided.

Use of criteria for developing water quality-based permit limits and for designing waste treatment facilities requires selection of an appropriate wasteload allocation model. Dynamic models are preferred for the application of these criteria (U.S. EPA 1985b). Limited data or other considerations might make their use impractical, in which case one must rely on a steady-state model (U.S. EPA 1986).

Table 1. Acute Toxicity of Zinc to Aquatic Animals

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
			FRESHWATER SPECIES				
Worm, *Lumbriculus variegatus*	S, U	Zinc chloride	30	6,300	9,712	9,712	Bailey and Liu 1980
Tubificid worm, *Limnodrilus hoffmeisteri*	S, U	Zinc sulfate	100	>2,274	>1,264	>1,264	Wurtz and Bridges 1961
Worm, *Nais* sp.	S, M	-	50	18,400†	18,400	18,400	Rehwoldt et al. 1973
Snail (embryo), *Amnicola* sp.	S, M	-	50	20,200†	20,200	-	Rehwoldt et al. 1973
Snail (adult), *Amnicola* sp.	S, M	-	50	14,000†	14,000	16,820	Rehwoldt et al. 1973
Snail (adult), *Helisoma campanulatum*	S, U	Zinc sulfate	20 (12.8°C)	870	1,891	-	Wurtz 1962
Snail (adult), *Helisoma campanulatum*	S, U	Zinc sulfate	20 (22.8°C)	1,270	2,760	-	Wurtz 1962
Snail (adult), *Helisoma campanulatum*	S, U	Zinc sulfate	100 (12.8°C)	3,030	1,684	-	Wurtz 1962
Snail (adult), *Helisoma campanulatum*	S, U	Zinc sulfate	100 (22.8°C)	1,270	705.9	1,578	Wurtz 1962
Snail (adult), *Physa gyrina*	F, M	Zinc chloride	36	1,274	1,683	1,683	Nebeker et al. 1986
Snail, *Physa heterostropha*	S, U	Zinc chloride	45 (20°C)	1,800	1,968	-	Cairns and Scheier 1958b; Academy of Natural Sciences 1960

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Snail, *Physa heterostropha*	S, U	Zinc chloride	45 (30°C)	1,000	1,093	-	Cairns and Scheier 1958b; Academy of Natural Sciences 1960
Snail, *Physa heterostropha*	S, U	Zinc chloride	170 (20°C)	6,200	2,198	-	Cairns and Scheier 1958b; Academy of Natural Sciences 1960
Snail, *Physa heterostropha*	S, U	Zinc chloride	170 (30°C)	7,100	2,517	-	Cairns and Scheier 1958b; Academy of Natural Sciences 1960
Snail (adult), *Physa heterostropha*	S, U	Zinc sulfate	20	1,110	2,413	-	Wurtz and Bridges 1961; Wurtz 1962
Snail (adult), *Physa heterostropha*	S, U	Zinc sulfate	100	3,160	1,756	-	Wurtz and Bridges 1961; Wurtz 1962
Snail (young), *Physa heterostropha*	S, U	Zinc sulfate	20 (10.6°C)	303	658.6	-	Wurtz 1962
Snail (young), *Physa heterostropha*	S, U	Zinc sulfate	20 (12.8°C)	434	943.3	-	Wurtz 1962
Snail (young), *Physa heterostropha*	S, U	Zinc sulfate	20 (32.2°C)	350	760.8	-	Wurtz 1962
Snail (young), *Physa heterostropha*	S, U	Zinc sulfate	100 (10.6°C)	434	241.2	-	Wurtz 1962
Snail (young), *Physa heterostropha*	S, U	Zinc sulfate	100 (12.8°C)	1,390	772.6	-	Wurtz 1962
Snail (young), *Physa heterostropha*	S, U	Zinc sulfate	100 (32.2°C)	1,110	617.0	1,088	Wurtz 1962
Asiatic clam (10-21 mm), *Corbicula fluminea*	S, M	Zinc sulfate	64	6,040†	4,900	4,900	Cherry et al. 1980; Rodgers et al. 1980

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Cladoceran (<24 hr), *Ceriodaphnia dubia*	R, M	Zinc chloride	52	180	174.1	174.1	Carlson et al. 1986
Cladoceran, *Ceriodaphnia reticulata*	S, U	-	45	76	83.10	-	Mount and Norberg 1984
Cladoceran, *Ceriodaphnia reticulata*	S, U	Zinc chloride	45	41	44.82	-	Carlson and Roush 1985
Cladoceran, *Ceriodaphnia reticulata*	S, M	Zinc chloride	45	32	34.99	50.70	Carlson and Roush 1985
Cladoceran, *Daphnia magna*	S, U	Zinc chloride	-	<71.95	-	-	Anderson 1948
Cladoceran, *Daphnia magna*	S, U	Zinc chloride	45.3	100	108.7	-	Biesinger and Christensen 1972
Cladoceran, *Daphnia magna*	S, M	Zinc sulfate	45	280	306.1	-	Cairns et al. 1978
Cladoceran, *Daphnia magna*	S, U	-	45	68	74.35	-	Mount and Norberg 1984
Cladoceran, *Daphnia magna*	S, M	Zinc chloride	54	334	312.9	-	Chapman et al. Manuscript
Cladoceran, *Daphnia magna*	S, M	Zinc chloride	105	525	280.0	-	Chapman et al. Manuscript
Cladoceran, *Daphnia magna*	S, M	Zinc chloride	196	655	205.8	-	Chapman et al. Manuscript
Cladoceran, *Daphnia magna*	F, M	Zinc chloride	130	798.9	355.5	355.5	Attar and Maly 1982
Cladoceran, *Daphnia pulex*	S, M	Zinc sulfate	45	500	546.7	-	Cairns et al. 1978
Cladoceran, *Daphnia pulex*	S, U	-	45	107	117.0	252.9	Mount and Norberg 1984

Table 1. (Continued)

Species	Method[*]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)[**]	Adjusted LC50 or EC50 (µg/L)[***]	Species Mean Acute Value (µg/L)[****]	Reference
Isopod (3-7 mm), *Asellus bicrenata*	F, M	Zinc sulfate	220	20,110[††]	5,731	5,731	Bosnak and Morgan 1981
Isopod, *Asellus communis*	S, U	Zinc sulfate	20	12,734	27,680	-	Wurtz and Bridges 1961
Isopod, *Asellus communis*	S, U	Zinc sulfate	100	8,755	4,866	11,610	Wurtz and Bridges 1961
Isopod (3-7 mm), *Lirceus alabamae*	F, M	Zinc sulfate	152	8,375[††]	3,265	3,265	Bosnak and Morgan 1981
Amphipod, *Crangonyx pseudogracilis*	R, U	Zinc sulfate	50	19,800	19,800	19,800	Martin and Holdich 1986
Amphipod, *Gammarus* sp.	S, M	-	50	8,100[†]	8,100	8,100	Rehwoldt et al. 1973
Damselfly, *Argia* sp.	S, U	Zinc sulfate	20	40,930	88,960	88,960	Wurtz and Bridges 1961
Bryozoan, *Pectinatella magnifica*	S, U	-	190-220	4,310	1,307	1,307	Pardue and Wood 1980
Bryozoan, *Lophopodella carteri*	S, U	-	190-220	5,630	1,707	1,707	Pardue and Wood 1980
Bryozoan, *Plumatella emarginata*	S, U	-	190-220	5,300	1,607	1,607	Pardue and Wood 1980

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
American eel, <u>Anguilla</u> <u>rostrata</u>	S, M	-	55	14,500†	13,380	-	Rehwoldt et al. 1972
American eel, <u>Anguilla</u> <u>rostrata</u>	S, M	Zinc nitrate	53	14,600†	13,900	13,630	Rehwoldt et al. 1973
Coho salmon (yearling), <u>Oncorhynchus</u> <u>kisutch</u>	R, M	Zinc chloride	94	4,600	2,694	-	Lorz and McPherson 1976,1977
Coho salmon, <u>Oncorhynchus</u> <u>kisutch</u>	F, M	Zinc chloride	25	905	1,628	1,628	Chapman and Stevens 1978
Sockeye salmon (parr), <u>Oncorhynchus</u> <u>nerka</u>	F, M	Zinc chloride	22	749	1,502	1,502	Chapman 1975,1978a
Chinook salmon (alevin), <u>Oncorhynchus</u> <u>tshawytscha</u>	F, M	Zinc chloride	23	>661†††	-	-	Chapman 1975,1978b
Chinook salmon (juvenile), <u>Oncorhynchus</u> <u>tshawytscha</u>	F, M	Zinc sulfate	21	84	175.2	-	Finlayson and Verrue 1982
Chinook salmon (swim-up alevin), <u>Oncorhynchus</u> <u>tshawytscha</u>	F, M	Zinc chloride	23	97	187.3	-	Chapman 1975,1978b
Chinook salmon (parr), <u>Oncorhynchus</u> <u>tshawytscha</u>	F, M	Zinc chloride	23	463	894.0	-	Chapman 1975,1978b
Chinook salmon (smolt), <u>Oncorhynchus</u> <u>tshawytscha</u>	F, M	Zinc chloride	23	701	1,354	446.4	Chapman 1975,1978b
Cutthroat trout (fingerling), <u>Salmo</u> <u>clarki</u>	R, M	Zinc sulfate	-	90†	-	-	Rabe and Sappington 1970
Rainbow trout (juvenile), <u>Salmo</u> <u>gairdneri</u>	F, M	Zinc sulfate	330	7,210	1,457	-	Sinley et al. 1974
Rainbow trout (juvenile), <u>Salmo</u> <u>gairdneri</u>	F, M	Zinc sulfate	25	430	773.6	-	Sinley et al. 1974
Rainbow trout (30.5 g), <u>Salmo</u> <u>gairdneri</u>	F, M	Zinc sulfate	30	430	662.9	-	Goettl et al. 1974
Rainbow trout (22.6 g), <u>Salmo</u> <u>gairdneri</u>	F, M	Zinc sulfate	30	810	1,249	-	Goettl et al. 1974

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Rainbow trout (29.7 g), *Salmo gairdneri*	F, M	Zinc sulfate	30	410	632.1	-	Goettl et al. 1974, 1976
Rainbow trout (18.3 g),	F, M	Zinc sulfate	312	4,520	958.0	-	Goettl et al. 1974,
Rainbow trout (2.0 g), *Salmo gairdneri*	F, M	Zinc sulfate	312	1,190	252.2	-	Goettl et al. 1974, 1976
Rainbow trout (34.6 g), *Salmo gairdneri*	F, M	Zinc sulfate	23	560	1,081	-	Goettle et al. 1974 1976
Rainbow trout (4.9 g), *Salmo gairdneri*	F, M	Zinc sulfate	22	240	481.2	-	Goettl et al. 1974, 1976
Rainbow trout (52.1 g), *Salmo gairdneri*	F, M	Zinc sulfate	30	830	1,280	-	Goettl et al. 1974, 1976
Rainbow trout (15.4 g), *Salmo gairdneri*	F, M	Zinc sulfate	314	7,210	1,520	-	Goettl et al. 1974, 1976
Rainbow trout (72 g), *Salmo gairdneri*	F, M	Zinc sulfate	102	1,000	546.6	-	Goettl et al. 1974, 1976
Rainbow trout (juvenile), *Salmo gairdneri*	R, U	Zinc sulfate	5	280	1,970	-	McLeay 1976
Rainbow trout (alevin), *Salmo gairdneri*	F, M	Zinc chloride	23	815	1,574	-	Chapman 1975,1978b
Rainbow trout (swim-up alevin), *Salmo gairdneri*	F, M	Zinc chloride	23	93	179.6	-	Chapman 1975,1978b
Rainbow trout (parr), *Salmo gairdneri*	F, M	Zinc chloride	23	136	262.6	-	Chapman 1975,1978b
Rainbow trout (smolt), *Salmo gairdneri*	F, M	Zinc chloride	23	>651†††	-	-	Chapman 1975,1978b
Rainbow trout (adult male), *Salmo gairdneri*	F, M	Zinc chloride	83	1,755	1,142	-	Chapman and Stevens 1978

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Zinc sulfate	46.8	370	391.3	-	Holcombe and Andrew 1978
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Zinc sulfate	47.0	517	544.8	-	Holcombe and Andrew 1978
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Zinc sulfate	44.4	756	836.0	-	Holcombe and Andrew 1978
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Zinc sulfate	178	2,510	855.9	-	Holcombe and Andrew 1978
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Zinc sulfate	179	2,960	1,005	-	Holcombe and Andrew 1978
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Zinc sulfate	170	1,910	677.2	-	Holcombe and Andrew 1978
Rainbow trout (fingerling), *Salmo gairdneri*	S, M	Zinc sulfate	14	560	1,647	-	Spry and Wood 1984
Rainbow trout (fry), *Salmo gairdneri*	F, M	Zinc chloride	9.2 (pH=7.0)	66	277.0	689.3	Cusimano et al. 1986
Atlantic salmon (parr), *Salmo salar*	F, M	Zinc sulfate	14	740	2,176	2,176	Carson and Carson 1972
Brook trout (juvenile), *Salvelinus fontinalis*	F, M	Zinc sulfate	46.8	1,550	1,639	-	Holcombe and Andrew 1978
Brook trout (juvenile), *Salvelinus fontinalis*	F, M	Zinc sulfate	47.0	2,120	2,234	-	Holcombe and Andrew 1978
Brook trout (juvenile), *Salvelinus fontinalis*	F, M	Zinc sulfate	44.4	2,420	2,676	-	Holcombe and Andrew 1978
Brook trout (juvenile), *Salvelinus fontinalis*	F, M	Zinc sulfate	178	6,140	2,094	-	Holcombe and Andrew 1978
Brook trout (juvenile), *Salvelinus fontinalis*	F, M	Zinc sulfate	179	6,980	2,369	-	Holcombe and Andrew 1978

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Brook trout (juvenile), *Salvelinus fontinalis*	F, M	Zinc sulfate	170	4,980	1,766	2,100	Holcombe and Andrew 1978
Longfin dace (juvenile), *Agosia chrysogaster*	R, M	Zinc sulfate	217	790†	227.8	227.8	Lewis 1978
Goldfish, *Carassius auratus*	S, U	Zinc sulfate	50	7,500	7,500	-	Cairns et al. 1969
Goldfish (1-2 g), *Carassius auratus*	S, U	Zinc sulfate	20	6,440	14,000	10,250	Pickering and Henderson 1966
Common carp (<20 cm), *Cyprinus carpio*	S, M	Zinc nitrate	53	7,800†	7,424	-	Rehwoldt et al. 1971
Common carp, *Cyprinus carpio*	S, M	-	55	7,800†	7,194	-	Rehwoldt et al. 1972
Common carp (2.1 g), *Cyprinus carpio*	R, U	Zinc sulfate	19	3,120	7,083	7,233	Khangarot et al. 1983
Golden shiner, *Notemigonus crysoleucas*	S, U	Zinc sulfate	50	6,000	6,000	6,000	Cairns et al. 1969
Fathead minnow (embryo), *Pimephales promelas*	F, M	Zinc sulfate	174-198	1,820	599.0	-	Pickering and Vigor 1965
Fathead minnow (embryo), *Pimephales promelas*	F, M	Zinc sulfate	174-198	1,850	608.9	-	Pickering and Vigor 1965
Fathead minnow (fry), *Pimephales promelas*	F, M	Zinc sulfate	174-198	870	286.3	-	Pickering and Vigor 1965
Fathead minnow (1-2 g), *Pimephales promelas*	S, U	Zinc sulfate	20 (15°C)	2,550	5,543	-	Pickering and Henderson 1966

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Fathead minnow (1-2 g) *Pimephales promelas*	S, U	-	20 (15°C)	2,330	5,064	-	Pickering and Henderson 1966
Fathead minnow (1-2 g), *Pimephales promelas*	S, U	Zinc sulfate	20 (25°C)	770 (780)	1,674	-	Pickering and Henderson 1966
Fathead minnow (1-2 g), *Pimephales promelas*	S, U	Zinc sulfate	20 (25°C)	960	2,087	-	Pickering and Henderson 1966
Fathead minnow (1-2 g), *Pimephales promelas*	S, U	Zinc sulfate	360 (25°C)	33,400	6,271	-	Pickering and Henderson 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	63	12,500	10,280	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	54	13,800	12,930	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	97	18,500	10,550	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	103	25,000	13,550	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	212	29,000	8,528	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	208	35,500	10,610	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	54	13,700	12,840	-	Mount 1966

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	63	6,200	5,097	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	100	12,500	6,948	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	99	12,500	7,007	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	186	19,000	6,242	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	195	13,600	4,293	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	54	4,700	4,403	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	49	5,100	5,188	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	98	8,100	4,580	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	102	9,900	5,411	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	193	8,200	2,611	-	Mount 1966
Fathead minnow (1-2 g), *Pimephales promelas*	F, M	Zinc sulfate	216	15,500	4,486	-	Mount 1966
Fathead minnow (44.6 mm), *Pimephales promelas*	S, U	Zinc sulfate	166	7,630	2,760	-	Rachlin and Perlmutter 1968

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Fathead minnow (2-3 g), *Pimephales promelas*	F, M	Zinc sulfate	203	8,400	2,563	-	Brungs 1969
Fathead minnow (2-3 g), *Pimephales promelas*	F, M	Zinc sulfate	203	10,000	3,051	-	Brungs 1969
Fathead minnow (2-3 g), *Pimephales promelas*	S, U	Zinc sulfate	203	12,000	3,661	-	Brungs 1969
Fathead minnow (2-3 g), *Pimephales promelas*	S, U	Zinc sulfate	203	13,000	3,966	-	Brungs 1969
Fathead minnow (4 wk), *Pimephales promelas*	F, M	Zinc sulfate	46	600	643.9	-	Benoit and Holcombe 1978
Fathead minnow (1-2 g), *Pimephales promelas*	S, M	Zinc sulfate	45	3,100	3,389	-	Judy and Davies 1979
Fathead minnow (juvenile), *Pimephales promelas*	F, M	Zinc sulfate	220	2,610	743.8	-	Broderius and Smith 1979
Fathead minnow (larva), *Pimephales promelas*	S, M	Zinc chloride	45	396	433.0	-	Carlson and Roush 1985
Fathead minnow (<24 hr), *Pimephales promelas*	S, M	Zinc chloride	52	551	533.0	3,830	Carlson et al. 1986
Northern squawfish (juvenile), *Ptychocheilus oregonensis*	F, M	Zinc chloride	20-30	3,498	6,404	-	Andros and Garton 1980
Northern squawfish (juvenile), *Ptychocheilus oregonensis*	F, M	Zinc chloride	20-30	3,693	6,761	6,580	Andros and Garton 1980
White sucker (17.7 g), *Catostomus commersoni*	F, M	Zinc chloride	18	2,200	5,228	5,228	Duncan and Klaverkamp 1983

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Banded killifish (<20 cm), *Fundulus diaphanus*	S, M	Zinc nitrate	53	19,100†	18,180	-	Rehwoldt et al. 1971
Banded killifish, *Fundulus diaphanus*	S, M	-	55	19,200†	17,710	17,940	Rehwoldt et al. 1972
Flagfish (juvenile), *Jordanella floridae*	F, M	Zinc sulfate	44	1,500	1,672	1,672	Spehar 1976a,b
Guppy (6 mo), *Poecilia reticulata*	S, U	Zinc sulfate	20	1,270	2,760	-	Pickering and Henderson 1966
Guppy, *Poecilia reticulata*	S, U	Zinc sulfate	120	30,000	14,290	-	Cairns et al. 1969
Guppy (fry), *Poecilia reticulata*	S, M	Zinc sulfate	30	1,740	2,682	-	Pierson 1981
Guppy (adult male), *Poecilia reticulata*	S, M	Zinc sulfate	30	5,050	7,785	-	Pierson 1981
Guppy (adult female), *Poecilia reticulata*	S, M	Zinc sulfate	30	6,400	9,866	-	Pierson 1981
Guppy (adult male), *Poecilia reticulata*	S, U	Zinc sulfate	118	300,000††††	-	-	Sehgal and Saxena 1986
Guppy (adult female), *Poecilia reticulata*	S, U	Zinc sulfate	118	278,000††††	-	6,053	Sehgal and Saxena 1986
Southern platyfish (20.8 mm), *Xiphophorus maculatus*	S, U	Zinc sulfate	166	12,000	4,341	4,341	Rachlin and Perlmutter 1968
White perch (<20 cm), *Morone americana*	S, M	Zinc nitrate	53	14,300†	13,610	-	Rehwoldt et al. 1971
White perch, *Morone americana*	S, M	-	55	14,400†	13,280	13,450†††††	Rehwoldt et al. 1972
Striped bass (fingerling), *Morone saxatilis*	S, M	Zinc nitrate	53	6,700†,††††	-	-	Rehwoldt et al. 1971

Table 1. (Continued)

Species	Method[*]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)[**]	Adjusted LC50 or EC50 (µg/L)[***]	Species Mean Acute Value (µg/L)[****]	Reference
Striped bass, *Morone saxatilis*	S, M	-	55	6,800[†,††††]	-	-	Rehwoldt et al. 1972
Striped bass (63 d), *Morone saxatilis*	S, U	Zinc chloride	40	120	145.0	-	Palawski et al. 1985
Striped bass (63 d), *Morone saxatilis*	S, U	Zinc chloride	285	430	98.40	119.4	Palawski et al. 1985
Pumpkinseed (<20 cm), *Lepomis gibbosus*	S, M	Zinc nitrate	53	20,000[†]	19,040	-	Rehwoldt et al. 1971
Pumpkinseed, *Lepomis gibbosus*	S, M	-	55	20,100[†]	18,540	18,790	Rehwoldt et al. 1972
Bluegill (3.5-3.9 g), *Lepomis macrochirus*	S, U	Zinc chloride	45 (18°C)	4,200	4,592	-	Cairns and Scheier 1957, 1968; Academy of Natural Sciences 1960
Bluegill (3.5-3.9 g), *Lepomis macrochirus*	S, U	Zinc chloride	45 (30°C)	3,500	3,827	-	Cairns and Scheier 1957; Academy of Natural Sciences 1960
Bluegill (3.5-3.9 g), *Lepomis macrochirus*	S, U	Zinc chloride	170 (18°C)	12,900	4,574	-	Cairns and Scheier 1957; Academy of Natural Sciences 1960
Bluegill (3.5-3.9 g), *Lepomis macrochirus*	S, U	Zinc chloride	170 (30°C)	12,500	4,432	-	Cairns and Scheier 1957; Academy of Natural Sciences 1960
Bluegill (2.5-3.9 g), *Lepomis macrochirus*	S, U	Zinc chloride	45	8,020	8,769	-	Cairns and Scheier 1958a; Academy of Natural Sciences 1960
Bluegill (0.96 g), *Lepomis macrochirus*	F, M	Zinc chloride	45	3,573	3,907	-	Cairns and Scheier 1959
Bluegill (2.80 g), *Lepomis macrochirus*	F, M	Zinc chloride	45	3,453	3,775	-	Cairns and Scheier 1959

Table 1. (Continued)

Species	Method[*]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)[**]	Adjusted LC50 or EC50 (µg/L)[***]	Species Mean Acute Value (µg/L)[****]	Reference
Bluegill (54.26 g), *Lepomis macrochirus*	F, M	Zinc chloride	45	3,314	3,623	-	Cairns and Scheier 1959
Bluegill (1-2 g), *Lepomis macrochirus*	S, U	Zinc sulfate	20 (15°C)	6,440	14,000	-	Pickering and Henderson 1966
Bluegill (1-2 g), *Lepomis macrochirus*	S, U	Zinc sulfate	20 (25°C)	5,460	11,870	-	Pickering and Henderson 1966
Bluegill (1-2 g), *Lepomis macrochirus*	S, U	Zinc sulfate	20 (25°C)	4,850	10,540	-	Pickering and Henderson 1966
Bluegill (1-2 g), *Lepomis macrochirus*	S, U	Zinc sulfate	20 (25°C)	5,820	12,650	-	Pickering and Henderson 1966
Bluegill (1-2 g), *Lepomis macrochirus*	S, U	Zinc chloride	20 (25°C)	5,370	11,670	-	Pickering and Henderson 1966
Bluegill (1-2 g), *Lepomis macrochirus*	S, U	Zinc sulfate	360 (25°C)	40,900	7,679	-	Pickering and Henderson 1966
Bluegill, *Lepomis macrochirus*	F, M	Zinc sulfate	46	9,900	10,620	-	Cairns et al. 1971
Bluegill, *Lepomis macrochirus*	F, M	Zinc sulfate	46	12,100	12,990	5,937	Cairns et al. 1971
Mozambique tilapia (18 g), *Tilapia mossambica*	S, U	Zinc chloride	115	1,600[††]	790.0	790.0	Qureshi and Saksena 1980

Table 1. (Continued)

Species	Method*	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)***	Reference
			SALTWATER SPECIES			
Polychaete worm (juvenile), *Neanthes arenaceodentata*	S, U	Zinc sulfate	-	900	-	Reish et al. 1976
Polychaete worm (adult), *Neanthes areanceodentata*	S, U	Zinc sulfate	-	1,800	1,273	Reish et al. 1976
Polychaete worm (adult), *Nereis diversicolor*	R, U	Zinc sulfate	0.35	1,500	-	Bryan and Hummerstone 1973
Polychaete worm (adult), *Nereis diversicolor*	R, U	Zinc sulfate	3.5	11,000	-	Bryan and Hummerstone 1973
Polychaete worm (adult), *Nereis diversicolor*	R, U	Zinc sulfate	17.5	55,000	9,682	Bryan and Hummerstone 1973
Polychaete worm (adult), *Nereis virens*	S, U	Zinc chloride	20	8,100	8,100	Eisler and Hennekey 1977
Polychaete worm (adult), *Ophryotrocha diadema*	S, U	Zinc sulfate	-	1,400	1,400	Reish and Carr 1978
Polychaete worm (adult), *Ctenodrilus serratus*	S, U	Zinc sulfate	-	7,100	7,100	Reish and Carr 1978
Polychaete worm (larva), *Capitella capitata*	S, U	Zinc sulfate	-	1,700	-	Reish et al. 1976
Polychaete worm (adult), *Capitella capitata*	S, U	Zinc sulfate	-	3,500	2,439	Reish et al. 1976
Mud snail (adult), *Nassarius obsoletus*	S, U	Zinc chloride	20	50,000	50,000	Eisler and Hennekey 1977
Blue mussel, *Mytilus edulis planulatus*	R, M	Zinc chloride	34 (21°C)	2,500	-	Ahsanullah 1976
Blue mussel, *Mytilus edulis planulatus*	F, M	Zinc chloride	- (18°C)	3,600	-	Ahsanullah 1976
Blue mussel, *Mytilus edulis planulatus*	F, M	Zinc chloride	- (18°C)	4,300	3,934	Ahsanullah 1976

Table 1. (Continued)

Species	Method*	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)***	Reference
Pacific oyster (embryo), *Crassostrea gigas*	S, M	Zinc chloride	-	263.5*****	-	Nelson 1972
Pacific oyster (embryo), *Crassostrea gigas*	S, M	Zinc chloride	30	206.5	233.3	Dinnel et al. 1983
Eastern oyster (embryo), *Crassostrea virginica*	S, U	Zinc chloride	25	310	-	Calabrese et al. 1973
Eastern oyster (embryo), *Crassostrea virginica*	S, U	Zinc chloride	26	205.7	-	MacInnes and Calabrese 1978
Eastern oyster (embryo), *Crassostrea virginica*	S, U	Zinc chloride	26 (25°C)	324.5	-	MacInnes and Calabrese 1978
Eastern oyster (embryo), *Crassostrea virginica*	S, U	Zinc chloride	26 (30°C)	229.6	262.5	MacInnes and Calabrese 1978
Clam (adult), *Macoma balthica*	S, U	Zinc sulfate	15 (5°C)	140,000	-	Bryant et al. 1985
Clam (adult), *Macoma balthica*	S, U	Zinc sulfate	25 (5°C)	700,000	-	Bryant et al. 1985
Clam (adult), *Macoma balthica*	S, U	Zinc sulfate	35 (5°C)	750,000	-	Bryant et al. 1985
Clam (adult), *Macoma balthica*	S, U	Zinc sulfate	15 (10°C)	210,000	-	Bryant et al. 1985
Clam (adult), *Macoma balthica*	S, U	Zinc sulfate	25 (10°C)	900,000	-	Bryant et al. 1985
Clam (adult), *Macoma balthica*	S, U	Zinc sulfate	35 (10°C)	950,000	-	Bryant et al. 1985
Clam (adult), *Macoma balthica*	S, U	Zinc sulfate	15 (15°C)	60,000	-	Bryant et al. 1985

Table 1. (Continued)

Species	Method*	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)***	Reference
Clam (adult), *Macoma balthica*	S, U	Zinc sulfate	25 (15°C)	180,000	-	Bryant et al. 1985
Clam (adult), *Macoma balthica*	S, U	Zinc sulfate	35 (15°C)	250,000	320,400	Bryant et al. 1985
Quahog clam (embryo), *Mercenaria mercenaria*	S, U	Zinc chloride	25	195	195	Calabrese and Nelson 1974
Soft-shell clam (adult), *Mya arenaria*	S, U	Zinc chloride	20	7,700	-	Eisler and Hennekey 1977
Soft-shell clam (adult), *Mya arenaria*	S, U	Zinc chloride	30	5,200	6,328	Eisler 1977a
Squid (larva), *Loligo opalescens*	S, M	Zinc chloride	30	>1,920	>1,920	Dinnel et al. 1983
Copepod (adult), *Eurytemora affinis*	S, U	Zinc chloride	30	4,074	4,074	Lussier and Cardin 1985
Copepod (adult), *Acartia clausi*	S, U	Zinc chloride	30	1,507	1,507	Lussier and Cardin 1985
Copepod (adult), *Acartia tonsa*	S, U	Zinc chloride	30	294.2	294.2	Lussier and Cardin 1985
Copepod (adult), *Nitocra spinipes*	S, U	Zinc chloride	7	1,450	1,450	Bengtsson 1978
Mysid (juvenile), *Mysidopsis bahia*	S, M	Zinc chloride	30	520.8	-	Lussier and Gentile 1985
Mysid (juvenile), *Mysidopsis bahia*	S, M	Zinc chloride	30	547.2	-	Lussier and Gentile 1985
Mysid (juvenile), *Mysidopsis bahia*	F, M	Zinc chloride	30	499	499	Lussier et al. 1985

Table 1. (Continued)

Species	Method*	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)***	Reference
Mysid (juvenile), *Mysidopsis bigelowi*	S, M	Zinc chloride	30	591.3	591.3	Lussier and Gentile 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	5 (5°C)	1,000	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	10 (5°C)	4,600	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	15 (5°C)	6,500	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	25 (5°C)	12,000	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	35 (5°C)	16,000	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	5 (10°C)	$>128,000^{\dagger\dagger\dagger\dagger}$	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	10 (10°C)	1,600	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	15 (10°C)	8,500	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	25 (10°C)	11,000	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	35 (10°C)	15,000	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	5 (15°C)	1,100	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	10 (15°C)	3,200	-	Bryant et al. 1985

Table 1. (Continued)

Species	Method*	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)***	Reference
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	15 (15°C)	3,400	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	25 (15°C)	4,400	-	Bryant et al. 1985
Amphipod (adult), *Corophium volutator*	S, U	Zinc sulfate	35 (15°C)	3,600	4,683	Bryant et al. 1985
Lobster (adult), *Homarus americanus*	F, U	Zinc sulfate	-	48,000†*	-	Haya et al. 1983
Lobster (larva), *Homarus americanus*	S, U	Zinc chloride	30	575	-	Johnson 1985
Lobster (larva), *Homarus americanus*	S, U	Zinc chloride	30	574.5	-	Johnson 1985
Lobster (larva), *Homarus americanus*	S, U	Zinc chloride	30	362.5	-	Johnson 1985
Lobster (larva), *Homarus americanus*	S, U	Zinc chloride	30	175	380.5	Johnson 1985
Hermit crab (adult), *Pagurus longicarpus*	S, U	Zinc chloride	20	400	400	Eisler and Hennekey 1977
Dungeness crab (larva), *Cancer magister*	S, M	Zinc chloride	30	586.1	586.1	Dinnel et al. 1983
Green crab (larva), *Carcinus maenas*	S, U	Zinc sulfate	-	1,000	1,000	Connor 1972
Starfish (adult), *Asterias forbesii*	S, U	Zinc chloride	20	39,000	39,000	Eisler and Hennekey 1977
Mummichog (adult), *Fundulus heteroclitus*	S, U	Zinc chloride	6.1	17,500	-	Dorfman 1977
Mummichog (adult), *Fundulus heteroclitus*	S, U	Zinc chloride	24	31,500	-	Dorfman 1977

Table 1. (Continued)

Species	Method*	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)***	Reference
Mummichog (adult), *Fundulus heterclitus*	S, U	Zinc sulfate	6.0	32,000	-	Dorfman 1977
Mummichog (adult), *Fundulus heteroclitus*	S, U	Zinc sulfate	22.9	27,500	-	Dorfman 1977
Mummichog (adult), *Fundulus heterclitus*	S, U	Zinc chloride	20	60,000	-	Eisler and Hennekey 1977
Mummichog (larva), *Fundulus heteroclitus*	S, U	Zinc chloride	30	83,040	36,630	Cardin 1985
Atlantic silverside (2-wk larva), *Menidia menidia*	S, U	Zinc chloride	31.2	4,960	-	Cardin 1985
Atlantic silverside (newly hatched larva), *Menidia menidia*	S, U	Zinc chloride	30	4,170	-	Cardin 1985
Atlantic silverside (newly hatched larva), *Menidia menidia*	S, U	Zinc chloride	30.2	3,703	-	Cardin 1985
Atlantic silverside (newly hatched larva), *Menidia menidia*	S, U	Zinc chloride	30	3,060	-	Cardin 1985
Atlantic silverside (newly hatched larva), *Menidia menidia*	S, U	Zinc chloride	30	2,728	3,640	Cardin 1985
Tidewater silverside (juvenile), *Menidia peninsulae*	S, U	Zinc sulfate	20	5,600	5,600	Hansen 1983
Striped bass (63 day), *Morone saxatilis*	S, U	Zinc chloride	1	430	430	Palawski et al. 1985
Spot (juvenile), *Leiostomus xanthurus*	S, U	Zinc sulfate	25	38,000	38,000	Hansen 1983

Table 1. (Continued)

Species	Method*	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)***	Reference
Cabezon (larva), *Scorpaenichthys marmoratus*	S, M	Zinc chloride	27	191.4	191.4	Dinnel et al. 1983
Winter flounder (larva), *Pseudopleuronectes americanus*	S, U	Zinc chloride	30	18,207	-	Cardin 1985
Winter flounder (larva), *Pseudopleuronectes americanus*	S, U	Zinc chloride	30	4,922	9,467	Cardin 1985

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* S = static; R = renewal; F = flow-through; M = measured; U = measured.

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

*** Freshwater LC50s and EC50s were adjusted to hardness = 50 mg/L using the pooled slope of 0.8195 (see text). When the hardness is given as a range, the geometric mean of the limits of the range was used as the hardness.

**** Freshwater Species Mean Acute Values were calculated at hardness = 50 mg/L.

***** Calculated by probit analysis of the authors' data.

† In river water or stream water.

†† Average of values calculated using two different methods.

††† Value not used in calculation of slope or Species Mean Acute Value because this was a "greater than" value and a number of other values are available for this species.

†††† Value not used in calculation of slope or Species Mean Acute Value because value appeared to be high in comparison with other values available for this species.

††††† Not used in calculation of Genus Mean Acute Value (see text).

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

Table 1. (Continued)

Results of Covariance Analysis of Freshwater Acute Toxicity versus Hardness

Species	n	Slope	Standard Deviation	95% Confidence Limits	Degrees of Freedom
Physa heterostropha	12	0.9296	0.2590	0.3521, 1.5071	10
Daphnia magna	7	1.2549	0.4026	0.2206, 2.2892	5
Rainbow trout	25	0.8755	0.1152	0.6370, 1.1140	23
Brook trout	6	0.8179	0.1243	0.4731, 1.1627	4
Fathead minnow	36	0.8310	0.2217	0.3802, 1.2818	34
Guppy	5	1.6441	0.4432	0.2323, 3.0559	3
Striped bass	2	0.6500	-*	-* , -*	0
Bluegill	16	0.5603	0.1461	0.2467, 0.8739	14
All of above	109	0.8473**	0.0866	0.6754, 1.0192	100

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* Standard deviation and confidence limits cannot be calculated because degrees of freedom = 0.

** P = 0.77 for equality of slopes.

Table 2. Chronic Toxicity of Zinc to Aquatic Animals

Species	Test*	Chemical	Hardness (mg/L as $CaCO_3$)	Limits (µg/L)**	Chronic Value (µg/L)	Reference
			FRESHWATER SPECIES			
Cladoceran, *Daphnia magna*	LC	Zinc chloride	45	<140.3[†]	<140.3	Biesinger et al. 1986
Cladoceran, *Daphnia magna*	LC	Zinc chloride	52	97-190	135.8	Chapman et al. Manuscript
Cladoceran, *Daphnia magna*	LC	Zinc chloride	104	43-52	47.29	Chapman et al. Manuscript
Cladoceran, *Daphnia magna*	LC	Zinc chloride	211	42-52	46.73	Chapman et al. Manuscript
Caddisfly, *Clistoronia magnifica*	LC	Zinc chloride	31	>5,243[††]	>5,243	Nebeker et al. 1984
Sockeye salmon, *Oncorhynchus nerka*	ELS	Zinc chloride	32-37	>242[††]	>242	Chapman 1978a
Chinook salmon, *Oncorhynchus tshawytscha*	ELS	Zinc chloride	25	270-510	371.1	Chapman 1975
Rainbow trout, *Salmo gairdneri*	ELS	Zinc sulfate	26	140-547	276.7	Sinley et al. 1974
Rainbow trout, *Salmo gairdneri*	ELS	Zinc chloride	25	444-819	603.0	Cairns et al. 1982
Brook trout, *Salvelinus fontinalis*	LC	Zinc sulfate	45.9	534-1,368	854.7	Holcombe et al. 1979
Fathead minnow, *Pimephales promelas*	LC	Zinc sulfate	46	78-145	106.3	Benoit and Holcombe 1978
Flagfish, *Jordanella floridae*	LC	Zinc sulfate	44	26-51	36.41	Spehar 1976a,b
Guppy, *Poecilia reticulata*	LC	Zinc sulfate	30	<173[†]	<173	Pierson 1981

Table 2. (Continued)

Species	Test[a]	Chemical	Hardness (mg/L as $CaCO_3$)	Limits (µg/L)**	Chronic Value (µg/L)	Reference
SALTWATER SPECIES						
Mysid, *Mysidopsis bahia*	LC	Zinc chloride	30[†††]	120-231	166.5	Lussier et al. 1985

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

** Results are based on measured concentrations of zinc.

[†] Unacceptable effects occurred at all concentrations tested.

[††] The highest concentration tested did not cause unacceptable effects.

[†††] Salinity (g/kg), not hardness.

Table 2. (Continued)

Acute-Chronic Ratio

Species	Hardness (mg/L as $CaCO_3$)	Acute Value (µg/L)	Chronic Value (µg/L)	Ratio
Cladoceran, <u>Daphnia magna</u>	52-54	334	135.8	2.459
Cladoceran, <u>Daphnia magna</u>	104-105	525	47.29	11.10
Cladoceran, <u>Daphnia magna</u>	196-211	655	46.73	14.02
Sockeye salmon, <u>Onchohynchus nerka</u>	32-37	1,470	>242	<6.074
Chinook salmon <u>Oncorhynchus tshawytscha</u>	23-25	97-701*	371.1	0.2614- 1.889
Rainbow trout, <u>Salmo gairdneri</u>	25-26	430	276.7	1.554
Brook trout, <u>Salvelinus fontinalis</u>	45.9	1,996**	854.7	2.335
Fathead minnow, <u>Pimephales promelas</u>	46	600	106.3	5.644
Flagfish, <u>Jordanella floridae</u>	44	1,500	36.41	41.20
Mysid, <u>Mysidopsis bahia</u>	30***	499	166.5	2.997

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* Range of values given in Chapman (1975,1978a) for juveniles.

** Geometric mean of three values in Table I from Holcombe and Andrew (1978).

*** Salinity (g/kg).

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		
35	88,960	Damselfly, *Argia* sp.	88,960	-
34	19,800	Amphipod, *Crangonyx pseudogracilis*	19,800	-
33	18,400	Worm, *Nais* sp.	18,400	-
32	17,940	Banded killifish, *Fundulus diaphanus*	17,940	-
31	16,820	Snail, *Amnicola* sp.	16,820	-
30	13,630	American eel, *Anguilla rostrata*	13,630	-
29	10,560	Pumpkinseed, *Lepomis gibbosus*	18,790	-
		Bluegill, *Lepomis macrochirus*	5,937	-
28	10,250	Goldfish, *Carassius auratus*	10,250	-
27	9,712	Worm, *Lumbriculus variegatus*	9,712	-
26	8,157	Isopod, *Asellus bicrenata*	5,731	-
		Isopod, *Asellus communis*	11,610	-

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)**	Species	Species Mean Acute Value (µg/L)***	Species Mean Acute-Chronic Ratio****
25	8,100	Amphipod, *Gammarus* sp.	8,100	-
24	7,233	Common carp, *Cyprinus carpio*	7,233	-
23	6,580	Northern squawfish, *Ptychocheilus oregonensis*	6,580	-
22	6,053	Guppy, *Poecilia reticulata*	6,053	-
21	6,000	Golden shiner, *Notemigonus crysoleucas*	6,000	-
20	5,228	White sucker, *Catostomus commersoni*	5,228	-
19	4,900	Asiatic clam, *Corbicula fluminea*	4,900	-
18	4,341	Southern platyfish, *Xiphophorus maculatus*	4,341	-
17	3,830	Fathead minnow, *Pimephales promelas*	3,830	5.644
16	3,265	Isopod, *Lirceus alabamae*	3,265	-
15	2,100	Brook trout, *Salvelinus fontinalis*	2,100	2.335
14	1,707	Bryozoan, *Lophopodella carteri*	1,707	-

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)**	Species	Species Mean Acute Value (µg/L)***	Species Mean Acute-Chronic Ratio****
13	1,672	Flagfish, *Jordanella floridae*	1,672	41.20
12	1,607	Bryozoan, *Plumatella rostrata*	1,607	-
11	1,578	Snail, *Helisoma campanulatum*	1,578	-
10	1,353	Snail, *Physa gyrina*	1,683	-
		Snail, *Physa heterostropha*	1,088	-
9	1,307	Bryozoan, *Pectinatella magnifica*	1,307	-
8	>1,264	Tubificid worm, *Limnodrilus hoffmeisteri*	>1,264	-
7	1,225	Rainbow trout, *Salmo gairdneri*	689.3	1.554
		Atlantic salmon, *Salmo salar*	2,176	-
6	1,030	Coho salmon, *Oncorhynchus kisutch*	1,628	-
		Sockeye salmon, *Oncorhynchus nerka*	1,502	<6.074
		Chinook salmon, *Oncorhynchus tshawytscha*	446.4	0.7027†
5	790.0	Mozambique tilapia, *Tilapia mossambica*	790.0	-

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)**	Species	Species Mean Acute Value (µg/L)***	Species Mean Acute-Chronic Ratio****
4	299.8	Cladoceran, *Daphnia magna*	355.5	7.260††
		Cladoceran, *Daphnia pulex*	252.9	-
3	227.8	Longfin dace, *Agosia chrysogaster*	227.8	-
2	119.4	Striped bass, *Morone saxatilis*	119.4	-
1	93.95	Cladoceran, *Ceriodaphnia dubia*	174.1	-
		Cladoceran, *Ceriodaphnia reticulata*	50.70	-

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)**	Species	Species Mean Acute Value (µg/L)***	Species Mean Acute-Chronic Ratio****
		SALTWATER SPECIES		
28	320,400	Clam, *Macoma balthica*	320,400	-
27	50,000	Mud snail, *Nassarius obsoletus*	50,000	-
26	39,000	Starfish, *Asterias forbesii*	39,000	-
25	38,000	Spot, *Leiostomus xanthurus*	38,000	-
24	36,630	Mummichog, *Fundulus heteroclitus*	36,630	-
23	9,467	Winter flounder, *Pseudopleuronectes americanus*	9,467	-
22	7,100	Polychaete worm, *Ctenodrilus worm*	7,100	-
21	6,328	Soft-shell clam, *Mya arenaria*	6,328	-
20	4,683	Amphipod, *Corophium volutator*	4,683	-
19	4,515	Atlantic silverside, *Menidia menidia*	3,640	-
		Tidewater silverside, *Menidia peninsulae*	5,600	-

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)**	Species	Species Mean Acute Value (µg/L)***	Species Mean Acute-Chronic Ratio****
18	8,856	Polychaete worm, *Nereis diversicolor*	9,682	-
		Polychaete worm, *Nereis virens*	8,100	-
17	4,074	Copepod, *Eurytemora affinis*	4,074	-
16	3,934	Blue mussel, *Mytilus edulis*	3,934	-
15	2,439	Polychaete worm, *Capitella capitata*	2,439	-
14	>1,920	Squid, *Loligo opalescens*	>1,920	-
13	1,450	Copepod, *Nitocra spinipes*	1,450	-
12	1,400	Polychaete worm, *Ophryotrocha diadema*	1,400	-
11	1,273	Polychaete worm *Neanthes arenaceodentata*	1,273	-
10	1,000	Green crab, *Carcinus maenus*	1,000	-
9	665.9	Copepod, *Acartia clausi*	1,507	-
		Copepod, *Acartia tonsa*	294.2	-
8	586.1	Dungeness crab, *Cancer magister*	586.1	-

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)**	Species	Species Mean Acute Value (µg/L)***	Species Mean Acute-Chronic Ratio****
7	543.2	Mysid, *Mysidopsis bahia*	499	2.997
		Mysid, *Mysidoopsis bigelowi*	591.3	-
6	430	Striped bass, *Morone saxatilis*	430	-
5	400	Hermit crab, *Pagurus longicarpus*	400	-
4	380.5	Lobster, *Homarus americanus*	380.5	-
3	247.5	Pacific oyster, *Crassostrea gigas*	233.3	-
		Eastern oyster, *Crassostrea virginica*	262.5	-
2	195	Quahog clam, *Mercenaria mercenaria*	195	-
1	191.4	Cabezon, *Scorpaenichthys marmoratus*	191.4	-

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* Ranked from most resistant to most sensitive based on Genus Mean Acute Value. Inclusion of "greater than" values does not necessarily imply a true ranking, but does allow use of all genera for which useful data are available so that the Final Acute Value is not unnecesarily lowered.

** Freshwater Genus Mean Acute Values are at hardness = 50 mg/L.

*** From Table 1; freshwater values are at hardness = 50 mg/L.

**** From Table 2.

† Geometric mean of range given in Table 2.

†† Geometric mean of three values in Table 2.

Table 3. (Continued)

Fresh water

Final Acute Value = 130.1 µg/L (at hardness = 50 mg/L)

Criterion Maximum Concentration = (130.1 µg/L) / 2 = 65.05 µg/L (at hardness = 50 mg/L)

Pooled Slope = 0.8473 (see Table 1)

ln(Criterion Maximum Intercept) = ln(65.05) - [slope x ln(50)]

= 4.175 - (0.8473 x 3.9120) = 0.8604

Criterion Maximum Concentration = $e^{(0.8473[\ln(\text{hardness})]+0.8604)}$

Final Acute-Chronic Ratio = 2.208 (see text)

Final Chronic Value = (130.1 µg/L) / 2.208 = 58.92 µg/L (at hardness = 50 mg/L)

Assumed Chronic Slope = 0.8473 (see text)

ln(Final Chronic Intercept) = ln(58.92) - [slope x ln(50)]

= 4.076 - (0.8473 x 3.9120) = 0.7614

Final Chronic Value = $e^{(0.8473[\ln(\text{hardness})]+0.7614)}$

Salt water

Final Acute Value = 190.2 µg/L

Criterion Maximum Concentration = (190.2 µg/L) / 2 = 95.10 µg/L

Final Acute-Chronic Ratio = 2.208 (see text)

Final Chronic Value = (190.2 µg/L) / 2.208 = 86.14 µg/L

Table 4. Toxicity of Zinc to Aquatic Plants

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)[a]	Reference
			FRESHWATER SPECIES			
Blue-green alga, *Chroococcus paris*	Zinc sulfate	-	10	Reduced growth	>400	Les and Walker 1984
Green alga, *Chlamydomonas variabilis*	-	-	6	30% reduction in division rate	503	Bates et al. 1983
Green alga, *Chlamydomonas sp.*	Zinc sulfate	68	10	Reduced growth	15,000	Cairns et al. 1978
Green alga, *Chlorella pyrenoidosa*	Zinc sulfate	-	4	LC50	>200,000	Wong et al. 1979
Green alga, *Chlorella saccharophila*	Zinc chloride	-	4	EC50	7,100	Rachlin et al. 1982
Green alga, *Chlorella salina*	Zinc sulfate	-	4	LC50	>200,000	Wong et al. 1979
Green alga, *Chlorella vulgaris*	Zinc sulfate	-	4	EC50 (growth)	2,400	Rachlin and Farran 1974
Green alga, *Chlorella vulgaris*	Zinc chloride	-	15	EC50 (growth)	11,990-23,980	Rai et al. 1981a
Green alga, *Chlorella vulgaris*	Zinc chloride	-	33	EC50 (cell division)	5,100	Rosko and Rachlin 1977
Green alga, *Scenedesmus quadricauda*	Zinc sulfate	68	5	Reduced growth	20,000	Cairns et al. 1978
Green alga, *Scenedesmus quadricauda*	Zinc sulfate	-	4	LC50	>200,000	Wong et al. 1979
Green alga, *Selenastrum capricornutum*	Zinc chloride	-	7	Incipient growth inhibition	30	Bartlett et al. 1974
Green alga, *Selenastrum capricornutum*	Zinc chloride	-	14	EC95 (growth)	40.4	Greene et al. 1975

Table 4. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)*	Reference
Green alga, *Selenastrum capricornutum*	Zinc chloride	-	14	EC95 (growth)	68	Greene et al. 1975
Green alga, *Selenastrum capricornutum*	-	-	14-21	EC50 (biomass)	50.9	Turbak et al. 1986
Diatom, *Cyclotella meneghiniana*	Zinc sulfate	68	5	Reduced growth	20,000	Cairns et al. 1978
Diatom, *Navicula incerta*	Zinc chloride	-	4	EC50	10,000	Rachlin et al. 1983
Diatom, *Navicula seminulum*	-	58 (22°C)	5	EC50 (growth)	4,290	Academy of Natural Sciences 1960
Diatom, *Navicula seminulum*	-	58 (28°C)	5	EC50 (growth)	1,590	Academy of Natural Sciences 1960
Diatom, *Navicula seminulum*	-	58 (30°C)	5	EC50 (growth)	1,320	Academy of Natural Sciences 1960
Diatom, *Navicula seminulum*	-	174 (22°C)	5	EC50 (growth)	4,050	Academy of Natural Sciences 1960
Diatom, *Navicula seminulum*	-	174 (28°C)	5	EC50 (growth)	2,310	Academy of Natural Sciences 1960
Diatom, *Navicula seminulum*	-	174 (30°C)	5	EC50 (growth)	3,220	Academy of Natural Sciences 1960
Diatom, *Nitzschia linearis*	Zinc chloride	294.6	5	LC50	4,300	Patrick et al. 1968
Duckweed, *Lemna gibba*	Zinc sulfate	-	70	Did not reduce biomass	654	Van der Werff and Pruyt 1982
Duckweed, *Lemna minor*	Zinc sulfate	-	28	EC50 (tissue damage and death)	67,700	Brown and Rattigan 1979
Duckweed, *Lemna minor*	-	-	4	EC50 (growth)	10,000	Wang 1986a

Table 4. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)*	Reference
Duckweed, *Spirodela polyrhiza*	Zinc sulfate	-	70	Did not reduce biomass	654	Van der Werff and Pruyt 1982
Macrophyte, *Callitriche plataycarpa*	Zinc sulfate	-	73	Did not reduce biomass	654	Van der Werff and Pruyt 1982
Eurasian watermilfoil, *Myriophyllum spicatum*	-	-	32	EC50 (root weight)	21,600	Stanley 1974
Macrophyte, *Elodea canadensis*	Zinc sulfate	-	28	EC50 (tissue damage and death)	22,500	Brown and Rattigan 1979
Macrophyte, *Elodea nuttallii*	Zinc sulfate	-	73	Did not reduce biomass	654	Van der Werff and Pruyt 1982
		SALTWATER SPECIES				
Diatom, *Navicula incerta*	Zinc chloride	-	4	EC50 (growth)	10,100	Rachlin et al. 1983
Diatom, *Nitzschia closterium*	Zinc sulfate	-	4	EC50 (growth)	271	Rosko and Rachlin 1975
Diatom, *Nitzschia closterium*	Zinc sulfate	-	4	EC50** (growth)	360	Rosko and Rachlin 1975
Diatom, *Schroederella schroederi*	Zinc sulfate	32***	4	EC50 (growth)	19.01†	Kayser 1977
Dinoflagellate, *Gymnodinium splendens*	Zinc sulfate	32***	4	EC50 (growth)	3,716†	Kayser 1977
Dinoflagellate, *Procentrum micans*	Zinc sulfate	32***	4	EC50 (growth)	319.1†	Kayser 1977

Table 4. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)*	Reference
Coccolithophorid, *Cricosphaera carterae*	Zinc sulfate	-	4	EC50 (growth)	76.69**	Stillwell 1977
Giant kelp (young fronds), *Macrocystis pyrifera*	-	-	4	EC50 (photosynthetic rate)	10,000	Clendenning and North 1959

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* Concentration of zinc, not the chemical.

** With chelating agent.

*** Salinity (g/kg), not hardness.

† Calculated from author's data.

Table 5. Bioaccumulation of Zinc by Aquatic Organisms

Species	Chemical	Concentration in water (µg/L)*	Hardness (mg/L as $CaCO_3$)	Duration (days)	Tissue	BCF or BAF**	Reference
			FRESHWATER SPECIES				
Asiatic clam, (1-3 yr), *Corbicula fluminea*	Zinc sulfate	218	58.3	28	Soft tissue	126.2***	Graney et al. 1983
Asiatic clam, (1-3 yr), *Corbicula fluminea*	Zinc sulfate	433	58.3	28	Soft tissue	71.6***	Graney et al. 1983
Asiatic clam, (1-3 yr), *Corbicula fluminea*	Zinc sulfate	835	58.3	28	Soft tissue	102.2***	Graney et al. 1983
Mayfly, *Ephemerella grandis*	Zinc sulfate	-	30-70	14	Whole body	1,130	Nehring 1976
Stonefly, *Pteronarcys californica*	Zinc sulfate	-	30-70	14	Whole body	106	Nehring 1976
Atlantic salmon, *Salmo salar*	Zinc sulfate	-	12-24	80	Whole body	51	Farmer et al. 1979
Flagfish, *Jordanella floridae*	Zinc sulfate	139	45	100	Whole body	417.3***	Spehar et al. 1978
Guppy, *Poecilia reticulata*	Zinc sulfate	173	30	134	Whole body	477.8 534.9	Pierson 1981
Guppy, *Poecilia reticulata*	Zinc sulfate	328	30	134	Whole body	492.8 965.5	Pierson 1981
Guppy, *Poecilia reticulata*	Zinc sulfate	607	30	134	Whole body	466.3 512.4	Pierson 1981

Table 5. (Continued)

Species	Chemical	Concentration in water (µg/L)*	Salinity (g/kg)	Duration (days)	Tissue	BCF or BAF**	Reference
			SALTWATER SPECIES				
Green alga, *Dunaliella tertiolecta*	Zinc chloride	7.2-98,000	-	0.5****	Whole cells	10,000	Fisher et al. 1984
Diatom, *Thalassiosira pseudonana*	Zinc chloride	7.2-98,000	-	0.5****	Whole cells	12,000	Fisher et al. 1984
Brown macroalga, *Ascophyllum nodosum*	-	11.3	-	*****	Whole plant	1,318***,†	Foster 1976
Brown macroalga, *Fucus serratus*	Zinc chloride	9.5	-	140	Whole plant	10,768†	Young 1975
Brown macroalga, *Fucus vesiculosus*	-	5.21-11.9	-	*****	Whole plant	2,029 (5)	Morris and Bale 1975
Brown macroalga, *Fucus vesiculosus*	-	11.3	-	*****	Whole plant	1,027***,†	Foster 1976
Brown macroalga, *Laminaria digitata*	Zinc sulfate	2.4-500	-	30-31††	Growth region above stipe	75.5-295.0***†	Bryan 1969
Periwinkle (adult), *Littorina obtusata*	Zinc chloride	11	-	50	Soft tissue	670†	Young 1975
Eastern oyster (adult), *Crassostrea virginica*	Zinc chloride	100	-	126	Soft tissue	23,820†	Schuster and Pringle 1968
Eastern oyster (adult), *Crassostrea virginica*	Zinc chloride	200	-	126	Soft tissue	17,640†	Schuster and Pringle 1968
Soft-shell clam (adult), *Mya arenaria*	Zinc chloride	200	-	50	Soft tissue	85†	Pringle et al. 1968
Soft-shell clam (adult), *Mya arenaria*	Zinc chloride	200	-	49	Soft tissue	135†	Schuster and Pringle 1968

Table 5. (Continued)

Species	Chemical	Concentration in water (µg/L)*	Salinity (g/kg)	Duration (days)	Tissue	BCF or BAF**	Reference
Barnacle (adult), *Balanus balanoides*	-	18.6	-	30	Soft tissue	951.6[†]	White and Walker 1981
Shrimp (adult), *Pandalus montagui*	Zinc chloride	65	-	14	Whole body	3.692[***,†,†††]	Ray et al. 1980
Mummichog (juvenile), *Fundulus heteroclitus*	Zinc chloride	210	-	56	Scales	40.95[†,†††]	Sayer and Watabe 1984
Mummichog (juvenile), *Fundulus heteroclitus*	Zinc chloride	210	-	56	Whole body	18.10[†,†††]	Sayer and Watabe 1984
Mummichog (juvenile), *Fundulus heteroclitus*	Zinc chloride	810	-	56	Scales	43.21[†,†††]	Sayer and Watabe 1984
Mummichog (juvenile), *Fundulus heteroclitus*	Zinc chloride	810	-	56	Whole body	15.80[†,†††]	Sayer and Watabe 1984
Mummichog (juvenile), *Fundulus heteroclitus*	Zinc chloride	7,880	-	56	Scales	28.60[†,†††]	Sayer and Watabe 1984
Mummichog (juvenile), *Fundulus heteroclitus*	Zinc chloride	7,880	-	56	Whole body	4.467[†,†††]	Sayer and Watabe 1984

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[*] Measured concentration of zinc.

[**] Bioconcentration factors (BCFs) and bioaccumulation factors (BAFs) are based on measured concentrations of zinc in water and in tissue. Number of exposure concentrations from which the geometric mean factor was calculated is given in parentheses when it is greater than 1.

[***] Factor was converted from dry weight to wet weight basis.

[****] Steady-state reached.

[*****] Field study.

[†] Calculated from authors' data or graph.

[††] Steady-state not reached.

[†††] Concentration of zinc was the same in exposed and control animals.

Table 6. Other Data on Effects of Zinc on Aquatic Organisms

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
			FRESHWATER SPECIES			
Green alga, *Chlorella vulgaris*	Zinc sulfate	-	1 hr	33% reduction in survival	100,000	Agrawal 1984
Green alga, *Selenastrum capricornutum*	Zinc phosphate	-	14 days	Inhibited growth	64	Garton 1972
Green alga, *Selenastrum capricornutum*	Zinc sulfate	-	4 hr	EC50 (oxygen production)	1,000	Hendricks 1978
Green alga, *Chlorella vulgaris*	Zinc sulfate	-	3 wk	BCF=210	-	Coleman et al. 1971
Green alga, *Pediastrum tetras*	Zinc sulfate	-	3 wk	BCF=133	-	Coleman et al. 1971
Green alga, *Scenedesmus quadricauda*	Zinc sulfate	-	96 hr	Incipient inhibition (river water)	1,066-1,400 (1,200)	Bringmann and Kuhn 1959a,b
Periphyton, Mixed species	-	-	3 wk**	BAF=1,100-6,304	-	Johnson et al. 1978
Waterweed, *Elodea (Anacharis) canadensis*	Zinc sulfate	-	1 day	EC50 (oxygen) production)	8,100	Brown and Rattigan 1979
Moss, *Fontinalis antipyretica*	Zinc chloride	-	1-6 days	Reduced photosynthesis	100	Weise et al. 1985
Bacterium, *Escherichia coli*	Zinc sulfate	-	30 min	EC50 (inhibition of TDH activity)	653.7	Cenci et al. 1985
Bacterium, *Escherichia coli*	Zinc sulfate	-	-	Incipient inhibition	1,400-2,300	Bringmann and Kuhn 1959a
Mixed hetertrophic bacteria	Zinc chloride	-	0.5 hr	No significant mortality	1,000	Albright et al. 1972
Mixed heterotrophic bacteria	Zinc chloride	-	3 days	Reduced growth	50	Albright and Wilson 1974

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)[a]	Reference
Bacterium, <u>Nitrobacter</u> sp. and <u>Nitrosomonas</u> sp.	-	-	4 hr	EC50	100,000	Williamson and Nelson 1983
Protozoan, <u>Microregma heterostoma</u>	Zinc sulfate	-	28 hr	Incipient inhibition	330	Bringmann and Kuhn 1959b
Protozoan, <u>Paramecium caudatum</u>	Zinc sulfate	-	1.5 hr	Reduced vitality	3,500	Mills 1976a
Euglena, <u>Euglena viridis</u>	Zinc sulfate	-	3 wk	BCF=144	-	Coleman et al. 1971
Plankton, Mixed species	-	-	2 wk	Reduced primary productivity	15	Marshall et al. 1983
Zooplankton, Mixed species	Zinc chloride	-	3 wk	Reduced crustacean density and diversity	100	Marshall et al. 1981
Rotifer, <u>Philodina acuticornis</u>	Zinc sulfate	45	48 hr	LC50(5°C)	1,550	Cairns et al. 1978
				(10°C)	1,300	
				(15°C)	780	
				(20°C)	600	
				(25°C)	500	
Worm, <u>Aeolosoma headleyi</u>	Zinc sulfate	45	48 hr	LC50(5°C)	18,100	Cairns et al. 1978
				(10°C)	17,600	
				(15°C)	15,600	
				(20°C)	15,000	
				(25°C)	13,500	
Tubificid worm, <u>Tubifex tubifex</u>	Zinc sulfate	34.2	48 hr	LC50	2,980	Brkovic-Popovic and Popovic 1977a
Tubificid worm, <u>Tubifex tubifex</u>	Zinc chloride	224	48 hr	LC50	130,000	Qureshi et al. 1980
Tubificid worm, <u>Tubifex tubifex</u> and <u>Limnodrilus hoffmeisteri</u>	Zinc sulfate	-	24 hr	LC50	46,000	Whitley 1968

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Snail, *Goniobasis livescens*	Zinc sulfate	137-171	48 hr	LC50	13,500	Cairns et al. 1976
Snail, *Nitocris* sp.	Zinc sulfate	45	48 hr	LC50(5°C)	4,800	Cairns et al. 1978
				(10°C)	4,600	
				(15°C)	2,800	
				(20°C)	1,900	
				(25°C)	1,650	
Snail, *Lymnaea emarginata*	Zinc sulfate	137-171	48 hr	LC50	4,150	Cairns et al. 1976
Snail (adult), *Physa gyrina*	Zinc chloride	36	30 days	No effect	570	Nebeker et al. 1986
				LC50	771	
Snail, *Physa integra*	Zinc sulfate	137-171	48 hr	LC50	4,400	Cairns et al. 1976
Cladoceran, *Ceriodaphnia dubia*	Zinc chloride	36	7 days	Chronic value (river water)	167	Carlson et al. 1986
Cladoceran, *Ceriodaphnia dubia*	Zinc chloride	36	48 hr	EC50 (immobilization; river water)	164	Carlson et al. 1986
		36	48 hr		149	
		68	48 hr		222	
		82	48 hr		366	
		90	48 hr		255	
Cladoceran (<6 hr), *Ceriodaphnia reticulata*	Zinc chloride	353	48 hr	EC50 (high solids)	224	Carlson and Roush 1985
		376			114	
		392			96	
		362			264	
		392			195	

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Cladoceran (adult), *Daphnia galeata mendotae*	-	-	2 wk	BCF=9,400 BCF=5,833 BCF=6,333	15 30 60	Marshall et al. 1983
Cladoceran (young), *Daphnia galeata mendotae*	-	-	2 wk	BCF=9,933 BCF=6,933	15 30	Marshall et al. 1983
Cladoceran, *Daphnia magna*	Zinc sulfate	-	16 hr	EC50 (immobilization)	<19,440	Anderson 1944
Cladoceran, *Daphnia magna*	Zinc sulfate	-	48 hr	EC50 (river water)	1,800	Bringmann and Kuhn 1959a,b
Cladoceran, *Daphnia magna*	Zinc chloride	45.3	48 hr	EC50 (immobilization) (fed)	280	Biesinger and Christensen 1972
Cladoceran, *Daphnia magna*	Zinc chloride	45.3	21 days	EC50 (immobilization)	158	Biesinger and Christensen 1972
Cladoceran, *Daphnia magna*	Zinc chloride	45.3	21 days	16% reproductive impairment	70	Biesinger and Christensen 1972
Cladoceran, *Daphnia magna*	Zinc chloride	288	24 hr	EC50 (swimming)	14,000	Bringmann and Kuhn 1977
Cladoceran (3-5 days), *Daphnia magna*	Zinc sulfate	-	72 hr	LC50 (10°C) (15°C) (25°C) (30°C)	5,050 1,096 565 14.0	Braginskiy and Shcherban 1978
Cladoceran (adult), *Daphnia magna*	Zinc sulfate	-	72 hr	LC50 (10°C) (15°C) (25°C) (30°C)	1,316 1,100 1,010 5.0	Braginskiy and Shcherban 1978
Cladoceran, *Daphnia magna*	Zinc sulfate	45	48 hr	LC50 (5°C) (10°C) (15°C) (20°C)	2,300 1,700 1,100 560	Cairns et al. 1978

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)^a	Reference
Cladoceran, *Daphnia magna*	Zinc sulfate	130-160	50-70 days	Reduced longevity	100	Winner 1981
Cladoceran, *Daphnia pulex*	Zinc sulfate	45	48 hr	LC50(5°C) (10°C) (15°C) (25°C)	1,600 1,200 940 280	Cairns et al. 1978
Cladoceran *Bosmina longirostris*	-	-	2 wk	BCF=11,930 BCF= 6,300 BCF= 5,183	15 30 60	Marshall et al. 1983
Cladoceran, *Eubosmina coregoni*	-	-	2 wk	BCF=10,870 BCF= 6,833 BCF= 3,867	15 30 60	Marshall et al. 1983
Copepod (adult), *Tropocykops prasinus*	Zinc chloride	10 10 120	48 hr	EC50 (motility)	52 264 2,934	Lalande and Pinel-Alloul 1986
Crayfish (adult), *Orconectes virilis*	Zinc sulfate	26	14 days	LC50	84,000	Mirenda 1986
Mayfly, *Cloeon dipterum*	Zinc sulfate	-	72 hr	LC50(10°C) (15°C) (25°C) (30°C)	35,710 6,920 2,846 1,330	Braginskiy and Shcherban 1978
Mayfly (naiad), *Ephemerella grandis*	Zinc sulfate	30-70	14 days	LC50	>9,200	Nehring 1976
Mayfly, *Ephemerella subvaria*	Zinc sulfate	54	10 days	LC50	16,000	Warnick and Bell 1969
Damselfly, Unidentified	-	50	96 hr	LC50	26,200	Rehwoldt et al. 1973
Stonefly (naiad), *Pteronarcys californica*	Zinc sulfate	30-70	14 days	LC50	>13,900	Nehring 1976
Stonefly, *Acroneuria lycorias*	Zinc sulfate	50	14 days	LC50	32,000	Warnick and Bell 1969
Caddisfly, *Hydropsyche betteni*	Zinc sulfate	52	11 days	LC50	32,000	Warnick and Bell 1969

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)[a]	Reference
Caddisfly, Unidentified	-	50	96 hr	LC50	58,100	Rehwoldt et al. 1973
Mosquito (pupa), *Aedes aegypti*	Zinc sulfate	4	72 hr	20% mortality 30% mortality	500 5,000	Abbasi et al. 1985
Midge, *Chironomous* sp.	-	50	96 hr	LC50	18,200	Rehwoldt et al. 1973
Midge (embryo to 3rd instar), *Tanytarsus dissimilis*	Zinc chloride	46.8	10 days	LC50	36.8	Anderson et al. 1980
Coho salmon (fry), *Oncorhynchus kisutch*	Zinc sulfate	3-10	24 hr	Decrease white blood cells	500	McLeay 1975
Coho salmon (2.9 g), *Oncorhynchus kisutch*	Zinc chloride	30.5	1.75 hr	No effect on olfaction	654	Rehnberg and Schreck 1986
Sockeye salmon (alevin) (acclimated to zinc), *Oncorhynchus nerka*	Zinc chloride	-	96 hr	LC50	1,663	Chapman 1978a
Sockeye salmon (alevin) (acclimated to zinc), *Oncorhynchus nerka*	Zinc chloride	-	115 hr	LC50	>630	Chapman 1978a
Sockeye salmon (alevin), *Oncorhynchus nerka*	Zinc chloride	-	115 hr	LC50	447	Chapman 1978a
Sockeye salmon, *Oncorhynchus nerka*	Zinc chloride	20-84	3 mo	None (adult to smolt)	112	Chapman 1978a
Rainbow trout, *Salmo gairdneri*	Zinc sulfate	320	285 min 180 min 162 min	LT50	10,000 11,000 11,500	Lloyd 1960
Rainbow trout (7.62 cm), *Salmo gairdneri*	Zinc sulfate	15-20	7 days	LC50 (fed)	560	Lloyd 1961a,b
Rainbow trout (7.62 cm), *Salmo gairdneri*	Zinc sulfate	320	3 days	LC50 (fed)	3,500	Lloyd 1961a,b
Rainbow trout (fingerling), *Salmo gairdneri*	Zinc sulfate	320	48 hr	LC50	3,860	Herbert and Shurben 1964

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Rainbow trout, *Salmo gairdneri*	Zinc sulfate	44	48 hr	LC50 (high sodium chloride)	910	Herbert and Shurben 1964
Rainbow trout, *Salmo gairdneri*	Zinc sulfate	320	48 hr	LC50 (low D.O.)	2,400	Herbert and Shurben 1964
Rainbow trout (3-4 mo), *Salmo gairdneri*	Zinc sulfate	320	48 hr	LC50	2,460	Herbert and VanDyke 1964
Rainbow trout (yearling), *Salmo gairdneri*	Zinc sulfate	320	48 hr	LC50	5,000	Herbert and Wakeford 1964
Rainbow trout (46.7-125.5 g), *Salmo gairdneri*	Zinc sulfate	290	5 days	LC50	4,600	Ball 1967
Rainbow trout (13.7 g), *Salmo gairdneri*	Zinc sulfate	290	100 days	Damaged gills	800	Brown et al. 1968
Rainbow trout, *Salmo gairdneri*	Zinc sulfate	13-15	10 min	Avoidance	5.6	Sprague 1968
Rainbow trout (1 yr), *Salmo gairdneri*	Zinc sulfate	240	48 hr	LC50	4,000	Brown and Dalton 1970
Rainbow trout (100.9 g), *Salmo gairdneri*	Zinc sulfate	51	-	Tissue hypoxia	40,000	Burton et al. 1972b
Rainbow trout (fry), *Salmo gairdneri*	Zinc phosphate	20	96 hr	LC50	90	Garton 1972
Rainbow trout (embryo), *Salmo gairdneri*	Zinc sulfate	25	5 days	LC50	135	Sinley et al. 1974
Rainbow trout (fingerling to adult), *Salmo gairdneri*	Zinc sulfate	333	22 mo	LC10	1,055	Sinley et al. 1974
Rainbow trout (15-17.5 cm), *Salmo gairdneri*	Zinc sulfate	504	48 hr	LC50	4,760	Solbe 1974
Rainbow trout, *Salmo gairdneri*	Zinc sulfate	51-68	48 hr	Decreased blood pO_2 and pH	1,430	Sellers et al. 1975
Rainbow trout (200 mm), *Salmo gairdneri*	Zinc sulfate	98	10 days	LC50	800	Goettl et al. 1976

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as CaCO$_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Rainbow trout, *Salmo gairdneri*	Zinc sulfate	-	5.1-10.5 hr	Increased lactic acid	15,340	Hodson 1976
Rainbow trout (yearling), *Salmo gairdneri*	Zinc sulfate	374	85 days	Inhibited growth	1,120	Watson and McKeown 1976
Rainbow trout (2 mo), *Salmo gairdneri*	Zinc acetate	-	96 hr	LC50	550	Hale 1977
Rainbow trout, *Salmo gairdneri*	Zinc sulfate	36	24 hr	LC50(5°C) (15°C) (30°C)	2,800 1,560 2,100	Cairns et al. 1978
Rainbow trout (embryo, larva), *Salmo gairdneri*	Zinc chloride	104 (92-110)	28 days	EC50 (death and deformity)	1,060 (1,120)	Birge 1978; Birge et al. 1978,1980,1981
Rainbow trout, *Salmo gairdneri*	Zinc chloride	112	40 min	94% avoidance	47	Black and Birge 1980a,b
Rainbow trout (80-120 g), *Salmo gairdneri*	Zinc sulfate	-	30 days	Increased gill enzymes	290	Watson and Beamish 1980
Rainbow trout (50 g), *Salmo gairdneri*	Zinc sulfate	18.7	72 hr	LC50	2,000	Lovegrove and Eddy 1982
Rainbow trout, *Salmo gairdneri*	Zinc chloride	-	96 hr	Circulatory vasoconstriction	1,250	Tuurala and Soivio 1982
Rainbow trout (juvenile), *Salmo gairdneri*	Zinc sulfate	6.0-6.5	9 days	Hyperglycemia	352	Wagner and McKeown 1982
Rainbow trout (juvenile), *Salmo gairdneri*	-	-	42 days	Damaged hepatocytes	431.5	Leland 1983
Rainbow trout (fingerling), *Salmo gairdneri*	Zinc sulfate	14 (pH=6.0)	96 hr	LC50	670	Spry and Wood 1984

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Rainbow trout (gamete), *Salmo gairdneri*	Zinc sulfate	-	40 min	Reduction in spermatozoa survival; no effect on fertilization	20,000	Billard and Roubaud 1985
Rainbow trout (2.7-3.3 g), *Salmo gairdneri*	-	385 (pH=6.99)	9.4 hr	LT50	19,100	Bradley and Sprague 1985
		30.5 (pH=6.98)	10.4 hr		5,780	
		390 (pH=5.49)	11.5 hr		18,900	
		32.5 (pH=5.49)	16.0 hr		5,570	
		389 (pH=7.00)	6.3 hr		26,900	
		385 (pH=6.99)	9.4 hr		19,100	
		388 (pH=7.02)	12.9 hr		13,800	
Rainbow trout (embryo), *Salmo gairdneri*	Zinc nitrate	30	10 hr	LT50	14,000	Rombough 1985
			9 hr		13,000	
			20 hr		12,000	
			18 hr		11,000	
			18 hr		10,000	
			18 hr		9,000	
			20 hr		8,000	
			36 hr		6,000	
			>168 hr		2,000	
Rainbow trout (embryo with capsule removed), *Salmo gairdneri*	Zinc nitrate	30	14 hr	LT50	14,000	Rombough 1985
			18 hr		13,000	
			36 hr		12,000	
			30 hr		11,000	
			37 hr		10,000	
			58 hr		9,000	
			70 hr		8,000	
			>168 hr		6,000	
			>168 hr		2,000	

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Rainbow trout (5 days post fertilization), *Salmo gairdneri*	Zinc sulfate	87.7	48 hr	LC50	24,000	Shazili and Pascoe 1986
Rainbow trout (10 days post fertilization), *Salmo gairdneri*	Zinc sulfate	87.7	48 hr	LC50	<1,000	Shazili and Pascoe 1986
Rainbow trout (15 days post fertilization), *Salmo gairdneri*	Zinc sulfate	87.7	48 hr	LC50	9,100	Shazili and Pascoe 1986
Rainbow trout (22 days post fertilization), *Salmo gairdneri*	Zinc sulfate	87.7	48 hr	LC50	7,000	Shazili and Pascoe 1986
Rainbow trout (29 days post fertilization), *Salmo gairdneri*	Zinc sulfate	87.7	48 hr	LC50	4,300	Shazili and Pascoe 1986
Rainbow trout (36 days post fertilization), *Salmo gairdneri*	Zinc sulfate	87.7	48 hr	LC50	9,200	Shazili and Pascoe 1986
Rainbow trout (2 days post hatch), *Salmo gairdneri*	Zinc sulfate	87.7	48 hr	LC50	3,200	Shazili and Pascoe 1986
Rainbow trout (7 days post hatch), *Salmo gairdneri*	Zinc sulfate	87.7	48 hr	LC50	3,400	Shazili and Pascoe 1986
Atlantic salmon (parr), *Salmo salar*	Zinc sulfate	18	4 hr	EC50 (avoidance)	49.88	Sprague 1964b
Atlantic salmon (7.38 g), *Salmo salar*	-	14	23-25 hr	LT50	954.4	Zitko and Carson 1976
Atlantic salmon, *Salmo salar*	-	14	-	Incipient lethal level	150-1,000	Zitko and Carson 1977

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)^a	Reference
Atlantic salmon (juvenile), *Salmo salar*	Zinc sulfate	12.1-24.4	21 days	LC50	1,450	Farmer et al. 1979
					1,600	
					510	
					1,460	
					340	
					350	
Atlantic salmon (yearling), *Salmo salar*	Zinc sulfate	14	>168 hr	LT50	300	Sprague and Ramsay 1965
			58 hr		410	
			15.6 hr		650	
			9.4 hr		1,060	
			2.6 hr		4,190	
Goldfish (3-5 g), *Carassius auratus*	Zinc sulfate	-	1-4 hr	LT50	100,000	Ellis 1937
Goldfish (immature), *Carassius auratus*	Zinc sulfate	29	7 days	Histological damage	2,000	Bromage and Fuchs 1976
Goldfish (embryo, larva), *Carassius auratus*	Zinc chloride	195	7 days	EC50 (death and deformity)	2,540	Birge 1978
Goldfish, *Carassius auratus*	Zinc sulfate	36	24 hr	LC50(5°C)	103,000	Cairns et al. 1978
				(15°C)	40,000	
				(30°C)	24,000	
Common carp (embryo), *Cyprinus carpio*	Zinc sulfate	360	-	EC50 (hatch)	14,420	Kapur and Yadav 1982
Common carp (350-400 g), *Cyprinus carpio*	Zinc chloride	-	2 hr	GOT, GPT and LDH unaffected	4,797	Nemcsok and Boross 1982
Common carp (2.1 g), *Cyprinus carpio*	Zinc sulfate	19	48 hr	LC50	7,280	Khangarot et al. 1984
Golden shiner, *Notemigonus crysoleucas*	Zinc sulfate	36	24 hr	LC50(5°C)	11,400	Cairns et al. 1978
				(15°C)	7,760	
				(30°C)	8,330	

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Fathead minnow (1-2 g), *Pimephales promelas*	Zinc acetate	20	96 hr	LC50	880	Pickering and Henderson 1966
Fathead minnow, *Pimephales promelas*	Zinc sulfate	203	10 mo	EC83 (fecundity)	180	Brungs 1969
Fathead minnow, (adult), *Pimephales promelas*	Zinc chloride	103 254-271	96 hr	LC50 (Fish from pond contaminated with heavy metals)	6,140 5,960	Birge et al. 1983
Fathead minnow, (larva), *Pimephales promelas*	Zinc chloride	392	96 hr	LC50 (high solids)	<2,660 <2,930	Carlson and Roush 1985
Fathead minnow (larva), *Pimephales promelas*	-	48	7 days	Reduced growth	125	Norberg and Mount 1985
Fathead minnow (<24 hr), *Pimephales promelas*	Zinc chloride	36 55 68 82 90	96 hr	LC50 (river water)	393 440 556 655 807	Carlson et al. 1986
Channel catfish, (fingerling), *Ictalurus punctatus*	Zinc sulfate	206-236	40 hr	Decreased blood osmolarity	12,000	Lewis and Lewis 1971
Channel catfish, (embryo, larva), *Ictalurus punctatus*	Zinc chloride	90	5 days	Increased albanism	-	Westerman and Birge 1978
Channel catfish, (fingerling), *Ictalurus punctatus*	Zinc sulfate	313	14 days	LC50 (high alkalinity)	8,200	Reed et al. 1980
Guppy (5 mo), *Poecilia reticulata*	Zinc sulfate	-	4 mo	Reduced reproduction	880	Uviovo and Beatty 1979
Guppy, *Poecilia reticulata*	Zinc sulfate	260	96 hr	LC50 (high solids)	54,950	Khangarot 1981

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Guppy (184 mg), *Poecilia reticulata*	Zinc sulfate	260	48 hr	LC50	75,000	Khangarot et al. 1981
Guppy (fry), *Poecilia reticulata*	Zinc sulfate	30	167.5 hr	LC50	1,450	Pierson 1981
Striped bass (embryo), *Morone saxatilis*	-	137	20-25 hr	LC50	1,850	O'Rear 1971
Striped bass (fry), *Morone saxatilis*	-	137	48 hr	LC50	1,180	O'Rear 1971
Bluegill (2.5-3.9 g), *Lepomis macrochirus*	Zinc chloride	44.3	96 hr	LC50 (periodic low D.O.)	4,900	Cairns and Scheier 1958a; Academy of Natural Sciences 1960
Bluegill, *Lepomis macrochirus*	Zinc sulfate	370	20 days	LC50(DO=1.91) (DO=2.12) (DO=3.46) (DO=3.29) (DO=5.50) (DO=5.53)	7,200 7,500 10,700 10,500 12,000 10,700	Pickering 1968
Bluegill (fry), *Lepomis macrochirus*	Zinc sulfate	51	3 days	Lethal	235	Cairns and Sparks 1971; Sparks et al. 1972b.
Bluegill (18.7 g), *Lepomis macrochirus*	Zinc sulfate	68	12 hr 4.7 hr	LT50(20°C) (30°C)	32,000 32,000	Burton et al. 1972a
Bluegill (39.97 g), *Lepomis macrochirus*	Zinc sulfate	-	1-24 hr	Increased cough response	3,000	Sparks et al. 1972a
Bluegill, *Lepomis macrochirus*	Zinc sulfate	36	24 hr	LC50(5°C) (15°C) (30°C)	23,000 19,100 8,850	Cairns et al. 1978
Bluegill (juvenile), *Lepomis macrochirus*	Zinc chloride	112	40 min	13% avoidance	43,700	Black and Birge 1980
Bluegill (fry), *Lepomis macrochirus*	Zinc sulfate	313	14 days	LC50 (high alkalinity)	11,000	Reed et al. 1980

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Largemouth bass (embryo, larva), *Micropterus salmoides*	Zinc chloride	93-105	8 days	EC50 (death and deformity)	5,160	Birge et al. 1978
Largemouth bass (juvenile), *Micropterus salmoides*	Zinc sulfate	112	40 min	57% avoidance	7,030	Black and Birge 1980
Largemouth bass (embryo, larva), *Micropterus salmoides*	Zinc chloride	-	9 days	EC50 (death and deformity)	5,180	Black and Birge 1980
Largemouth bass (fingerling), *Micropterus salmoides*	Zinc sulfate	313	14 days	LC50 (high alkalinity)	8,000	Reed et al. 1980
Narrow-mouthed toad (embryo, larva), *Gastrophryne carolinensis*	Zinc chloride	195	7 days	EC50 (death and deformity)	10	Birge 1978; Birge et al. 1979
Marbled salamander (embryo, larva), *Ambystoma opacum*	Zinc chloride	93-105	8 days	EC50 (death and deformity)	2,380	Birge et al. 1978

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
			SALTWATER SPECIES			
Green alga, <u>Carteria</u> sp.	^{65}Zinc	35	7 days	BCF = 2.184***	-	Styron et al. 1976
Green alga, <u>Chlamydomonas</u> sp.	^{65}Zinc	34	7 days	BCF = 16.12***	-	Styron et al. 1976
Green alga, <u>Dunaliella euchlora</u>	Zinc chloride	-	12 days	EC50 (growth)	>33,600	Wikfors and Ukeles 1982
Green alga, <u>Dunaliella euchlora</u>	Zinc sulfate	-	12 days	EC50 (growth)	37,220†	Wikfors and Ukeles 1982
Green alga, <u>Dunaliella salina</u>	^{65}Zinc	44	7 days	BCF = 43.88***	-	Styron et al. 1976
Green alga, <u>Dunaliella tertiolecta</u>	Zinc sulfate	-	15 min	No effect on potassium retention	6,538	Overnell 1975
Green alga, <u>Dunaliella trertiolecta</u>	Zinc sulfate	-	15 min	EC50 (oxygen production)	65,380	Overnell 1976
Green alga, <u>Dunaliella tertiolecta</u>	Zinc chloride	-	72 hr	EC50 (growth)	13,000	Fisher et al. 1984
Green alga, <u>Nanochloris atomus</u>	^{65}Zinc	42	7 days	BCF = 16.12***	-	Styron et al. 1976
Golden-brown alga, <u>Isochrysis galbana</u>	-	12	48 hr (16°C)	Reduced chlorophyll <u>a</u> about 65%	2,000	Wilson and Freeberg 1980
		16			430	
		20			810	
		28			1,200	
Golden-brown alga, <u>Isochrysis galbana</u>	-	7	48 hr (20°C)	Reduced chlorophyll <u>a</u> about 65%	4,400	Wilson and Freeberg 1980
		12			1,300	
		16			74	
		20			520	
		28			100	
		37			2,300	
Golden-brown alga, <u>Isochrysis galbana</u>	-	12	48 hr (28°C)	Reduced chlorophyll <u>a</u> about 65%	1,000	Wilson and Freeberg 1980
		16			3,000	
		20			800	
		28			3,000	

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Golden-brown alga, *Isochrysis galbana*	Zinc chloride	-	12 days	EC50 (growth)	>33,600	Wikfors and Ukeles 1982
Golden-brown alga, *Isochrysis galbana*	Zinc sulfate	-	12 days	EC50 (growth)	33,100†	Wikfors and Ukeles 1982
Golden-brown alga, *Monochrysis lutheri*	Zinc sulfate	-	15 min	EC50 (reducted oxygen production)	1,308-1,961	Overnell 1976
Golden-brown alga, *Monochrysis lutheri*	Zinc chloride	-	12 days	EC50 (growth)	>33,600	Wikfors and Ukeles 1982
Golden-brown alga, *Monochrysis lutheri*	Zinc sulfate	-	12 days	EC50 (growth)	31,010†	Wikfors and Ukeles 1982
Diatom, *Achnanthes brevipes*	^{65}Zinc	40	7 days	BCF = 0.04***	-	Styron et al. 1976
Diatom, *Nitzschia longissima*	Zinc sulfate	30	1-5 days	Stimulated growth	≤100	Subramanian et al. 1980
Diatom, *Phaeodactylum tricornutum*	Zinc chloride	-	11-15 days	23% reduction in growth	25,000	Jensen et al. 1974
Diatom, *Phaeodactylum tricornutum*	Zinc chloride	-	13 days	BCF = 1,800***,†	250	Jensen et al. 1974
Diatom, *Phaeodactylum tricornutum*	Zinc chloride	-	14 days	BCF = 873***,†	10,000	Jensen et al. 1974
Diatom, *Phaeodactylum tricornutum*	Zinc sulfate	-	15 min	No effect on oxygen evolution	>65,380	Overnell 1976
Diatom, *Phaeodactylum tricornutum*	^{65}Zinc	37	7 days	BCF = 16.12***	-	Styron et al. 1976
Diatom, *Phaeodactylum tricornutum*	Zinc sulfate	25	10-14 days	19% reduction in growth	3,000	Braek et al. 1980
Diatom, *Phaeodactylum tricornutum*	Zinc chloride	-	12 days	EC50 (growth)	>33,600	Wikfors and Ukeles 1982

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Diatom, *Phaeodactylum tricornutum*	Zinc sulfate	-	12 days	74.2% reduction in growth	48,000	Wikfors and Ukeles 1982
Diatom, *Skeletonema costatum*	Zinc chloride	-	13 days	BCF = 4,000***,†	-	Jensen et al. 1974
Diatom, *Skeletonema costatum*	Zinc chloride	-	12 days	BCF = 160***,†	-	Jensen et al. 1974
Diatom, *Skeletonema costatum*	Zinc chloride	-	11-15 days	23% reduction in growth	50	Jensen et al. 1974
Diatom, *Skeletonema costatum*	Zinc sulfate	-	10-14 days	EC50 (growth)	192.9†	Braek et al. 1976
Diatom, *Skeletonema costatum*	Zinc sulfate	-	10-14 days	EC50 (growth)	175.6†	Braek et al. 1976
Diatom, *Skeletonema costatum*	Zinc sulfate	-	15 min	No effect on oxygen evolution	>65,380	Overnell 1976
Diatom, *Skeletonema costatum*	Zinc sulfate	25	10-14 days	20% reduction in growth	100	Braek et al. 1980
Diatom, *Skeletonema costatum*	Zinc sulfate	30	1-3 days	Stimulated growth	≤200	Subramanian et al. 1980
Diatom, *Skeletonema costatum*	Zinc chloride	-	3 days	Altered cytoplasmic morphology	265	Smith 1983
Diatom, *Skeletonema costatum*	Zinc chloride	-	3 days	BCF = 765	-	Smith 1983
Diatom, *Thalassiosira pseudonana*	Zinc chloride	-	11-15 days	41% reduction in growth	500	Jensen et al. 1974
Diatom, *Thalassiosira pseudonana*	Zinc chloride	-	13 days	BCF = 148***,†	-	Jensen et al. 1974
Diatom, *Thalassiosira pseudonana*	Zinc chloride	-	15 days	BCF = 350***,†	-	Jensen et al. 1974

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Diatom, *Thalassiosira pseudonana*	Zinc sulfate	-	10-14 days	EC50 (growth)	470.8†	Braek et al. 1976
Diatom, *Thalassiosira pseudonana*	-	14	2 days	Reduced chlorophyll *a* about 65%		Wilson and Freeberg 1980
			(12°C)		<100	
			(16°C)		170	
			(20°C)		<100	
			(24°C)		<100	
			(28°C)		200	
Diatom, *Thalassiosira pseudonana*	Zinc chloride	-	72 hr	EC50 (growth)	823.1	Fisher et al. 1984
Diatom, *Thalassiosira rotula*	Zinc sulfate	32	5 days	EC50 (growth)	25.80†	Kayser 1977
Phytoplankton (diatom)	-	-	**	BAF = 113	-	Martin and Knauer 1972
Dinoflagellate, *Amphidinium carteri*	Zinc sulfate	-	10-14 days	EC50 (growth)	559.2†	Braek et al. 1976
Dinoflagellate, *Amphidinium carteri*	Zinc sulfate	-	10-14 days	No significant effect on growth; inhibited growth in presence of 50 µg copper/L	200	Braek et al. 1976
Dinoflagellate, *Glenodinium halli*	-	28	2 days	Reduced chlorophyll *a* about 65%	20	Wilson and Freeberg 1980
Dinoflagellate, *Gymnodinium splendens*	-	14	2 days	Reduced chlorophyll *a* about 65%		Wilson and Freeberg 1980
			(16°C)		700	
			(30°C)		1,400	
Dinoflagellate, *Gymnodinium splendens*	-	28	2 days	Reduced chlorophyll *a* about 65%		Wilson and Freeberg 1980
			(16°C)		392	
			(20°C)		240	
			(24°C)		110	
			(28°C)		120	
			(30°C)		300	

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Dinoflagellate, *Scrippsiella faeroense*	Zinc sulfate	32	50 days	33% reduction in cell numbers	10,000	Kayser 1977
Brown macroalga, *Ascophyllum nodosum*	-	-	**	BAF = 1,603***,††	-	Melhuus et al. 1978
Brown macroalga, *Ascophyllum nodosum*	Zinc chloride	33	10 days	Decreased growth; no effect at 100 µg/L	250	Stromgren 1979
Brown macroalga, *Fucus serratus*	Zinc chloride	33	10 days	Decreased growth; no effect at 100 µg/L	1,400	Stromgren 1979
Brown macroalga, *Fucus serratus*	Zinc chloride	-	1 hr	Altered lipid metabolism	≥8.8	Smith and Harwood 1984
Brown macroalga, *Fucus spiralis*	Zinc chloride	33	10 days	Decreased growth; no effect at 100 µg/L	1,400	Stromgren 1979
Brown macroalga, *Fucus vesiculosis*	-	-	**	BAF = 1,612***,††	-	Melhuus et al. 1978
Brown macroalga, *Fucus vesiculosis*	Zinc chloride	33	10 days	Decreased growth; no effect at 2,900 µg/L	7,000	Stromgren 1979
Brown macroalga, *Laminaria digitata*	Zinc sulfate	-	24 days	Reduced growth	≥100	Bryan 1969
Brown macroalga, *Laminaria hyperboria*	Zinc sulfate	-	8-10 days	Reduced growth of sporophytes	250	Hopkins and Kain 1971
Brown macroalga, *Laminaria hyperboria*	Zinc sulfate	-	7 days	Abnormal maturation of gametophytes	5,000	Hopkins and Kain 1971
Brown macroalga, *Pelvetia canaliculata*	Zinc chloride	33	10 days	Decreased growth; no effect at 100 µg/L	1,400	Stromgren 1979
Green macroalga, *Ulva lactuca*	Zinc chloride	-	6 days	BCF = 255***,†	65.38	Haritonidis et al. 1983
Green macroalga, *Ulva lactuca*	Zinc chloride	-	6 days	BCF = 5,150***,†	6,538	Haritonidis et al. 1983

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Red macroalga, *Gracilaria verrucosa*	Zinc chloride	-	6 days	BCF = 107.5***,†	65.38	Haritonidis et al. 1983
Red macroalga, *Gracilaria verrucosa*	Zinc chloride	-	6 days	BCF = 16.25***,†	653.8	Haritonidis et al. 1983
Red macroalga, *Gracilaria verrucosa*	Zinc chloride	-	6 days	BCF = 3.225***,†	6,538	Haritonidis et al. 1983
Ciliate protozoan, *Cristigera* sp.	Zinc sulfate	34	4-5 hr	Reduced growth	50.63	Gray and Ventilla 1973; Gray 1974
Ciliate protozoan, *Euplotes vannus*	Zinc chloride	35	48 hr	10% reduction in growth	10,000	Persoone and Uyttersprot 1975
Ciliate protozoan, *Euplotes vannus*	Zinc chloride	35	48 hr	100% reduction in in growth	100,000	Persoone and Uyttersprot 1975
Polychaete worm (juvenile), *Neanthes arenaceodentata*	Zinc sulfate	-	28 days	LC50	900	Reish et al. 1976
Polychaete worm (adult), *Neanthes arenaceodentata*	Zinc sulfate	-	28 days	LC50	1,400	Reish et al. 1976
Polychaete worm (adult),††† *Nereis diversicolor*	Zinc sulfate	0,35 3.5 17.5	96 hr	LC50	2,300 14,600 94,000	Bryan and Hummerstone 1973
Polychaete worm (adult),††† *Nereis diversicolor*	Zinc sulfate	17.5	34 days	BCF = 26,57† 9,214 19.71 15.47 3.314 2.867 1.274 1.204	10,000 10,000 25,000 25,000 100,000 100,000 250,000 250,000	Bryan and Hummerstone 1973
Polychaete worm (adult), *Ophryotrocha diadema*	Zinc chloride	31	48 hr	LC50	330-1,000	Parker 1984

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Polychaete worm, *Ophryotrocha diadema*	Zinc sulfate	-	21 days	Chronic value;**** (acute-chronic ratio = 6.261)	223.6	Reish and Carr 1978
Polychaete worm, *Ctenodrilus serratus*	Zinc sulfate	-	21 days	Chronic value;**** (acute-chronic ratio = 31.75)	223.6	Reish and Carr 1978
Polychaete worm (larva), *Capitella capitata*	Zinc sulfate	-	>16 days	Abnormal development	50-100	Reish et al. 1974
Polychaete worm (adult), *Capitella capitata*	Zinc sulfate	-	28 days	LC50	1,250	Reish et al. 1976
Mud snail (adult), *Nassarius obsoletus*	Zinc chloride	25	72 hr	Depressed oxygen consumption	≥2,000	MacInnes and Thurberg 1973
Mud snail (adult), *Nassarius obsoletus*	Zinc chloride	25	72 hr	Inhibited locomotor behavior	10,000	MacInnes and Thurberg 1973
Mud snail (adult), *Nassarius obsoletus*	Zinc chloride	25	72 hr	Mortality	50,000	MacInnes and Thurberg 1973
Blue mussel (adult), *Mytilus edulis*	Zinc sulfate	-	7 days	LC50	>5,000	Martin et al. 1975
Blue mussel (adult), *Mytilus edulis*	Zinc sulfate	-	7 days	EC50 (byssal thread production)	1,800	Martin et al. 1975
Blue mussel (adult), *Mytilus edulis*	Zinc chloride	22	Approx.	LT50		Cotter et al., 1982
			10 days	(10°C)	3,000	
			6 days	(16°C)	3,000	
			4 days	(22°C)	3,000	
Blue mussel (adult), *Mytilus edulis*	Zinc chloride	35	14 days	Reduced resistance to thermal shock	800-1,000	Cotter et al. 1982

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Blue mussel (adult), *Mytilus edulis*	Zinc chloride	33.1	2-6 days	EC50 (shell growth)	60	Stromgren 1982
Blue mussel (embryo), *Mytilus edulis*	Zinc chloride	30	72 hr	EC50 (development to veliger)	>96<314	Dinnel et al. 1983
Blue mussel (adult), *Mytilus edulis*	-	-	3 days	Reduced shell deposition	≥200	Manley et al. 1984
Pacific oyster (larva), *Crassostrea gigas*	Zinc sulfate	29	6 days	Abnormal development and decreased growth	≥125	Brereton et al. 1973
Pacific oyster (embryo), *Crassostrea gigas*	Zinc sulfate	29	2 days	LC50	241.5†	Brereton et al. 1973
Pacific oyster (larva), *Crassostrea gigas*	Zinc sulfate	29	5 days	Delayed and reduced larval settlement	125	Boyden et al. 1975
Pacific oyster (6-day larva), *Crassostrea gigas*	Zinc chloride	34	4 days	EC50 (growth)	80	Watling 1982
Pacific oyster (6-day larva), *Crassostrea gigas*	Zinc chloride	34	4 days	LC50	>100	Watling 1982
Pacific oyster (16-day larva), *Crassostrea gigas*	Zinc chloride	34	4 days	EC50 (growth)	95	Watling 1982
Pacific oyster (16-day larva), *Crassostrea gigas*	Zinc chloride	34	4 days	LC50	>100	Watling 1982
Pacficic oyster (sperm), *Crassostrea gigas*	Zinc chloride	27	60 min	EC50 (fertilization) success)	443.6	Dinnel et al. 1983
Pacific oyster (19-day larva), *Crassostrea gigas*	-	34	20 days	Reduced larval settlement	10-20	Watling 1983

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Pacific oyster (19-day larva), *Crassostrea gigas*	-	34	6 days	EC50 (larval settling)	30-35	Watling 1983
Pacific oyster (juvenile), *Crassostrea gigas*	-	34	23 days	LC50	75	Watling 1983
Clam (larva), *Mulinia lateralis*	Zinc chloride	34	72 hr	53% mortality	200	Ho and Zubkoff 1982
Clam (larva), *Mulinia lateralis*	Zinc chloride	34	72 hr	EC50 (uptake of calcium)	176	Ho and Zubkoff 1982
Quahog clam (larva), *Mercenaria mercenaria*	Zinc chloride	24	8-10 days	LC50	195.4	Calabrese et al. 1977
Copepod (adult), *Paracalanus parvus*	Zinc chloride	35	24 hr	LC50	1,380	Arnott and Ahsanullah 1979
Copepod (adult), *Pseudodiaptomus coronatus*	Zinc chloride	30	72 hr	LC50	3,150	Lussier and Cardin 1985
Copepod (adult), *Acartia clausi*	Zinc chloride	30	72 hr	LC50	707.1	Lussier and Cardin 1985
Copepod (adult), *Acartia simplex*	Zinc chloride	35	24 hr	LC50	1,860	Arnott and Ahsanullah 1979
Copepod (adult), *Scutellidium* sp.	Zinc chloride	35	24 hr	LC50	1,090	Arnott and Ahsanullah 1979
Zooplankton (copepod and euphausid)	-	-	**	BAF = 1,670	-	Martin and Knauer 1972
Barnacle (adult), *Balanus balanoides*	Zinc nitrate	-	2 days	LC90	32,000	Clarke 1947
Barnacle (adult), *Balanus balanoides*	Zinc nitrate	-	5 days	LC90	8,000	Clarke 1947

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Isopod (adult), *Idotea baltica*	Zinc sulfate	13.6	48 hr	LT50	10,000	Jones 1975
		20.4	80 hr			
		27.2	70 hr			
Isopod (adult), *Idotea baltica*	Zinc sulfate	34.0	120 hr	40% mortality	10,000	Jones 1975
Isopod (adult), *Idotea baltica*	Zinc sulfate	27.2-34.0	120 hr	No effect on osmoregulatory ability	10,000	Jones 1975
Isopod (adult), *Idotea baltica*	Zinc sulfate	13.6	<24 hr	LT50	20,000	Jones 1975
		20.4	30 hr			
		27.2	70 hr			
		34.0	54 hr			
Iospod (adult), *Idotea baltica*	Zinc sulfate	34.0	120 hr	Affected osmoregulatory ability	20,000	Jones 1975
Isopod (adult), *Jaera albifrons*	Zinc sulfate	13.6	120 hr	80% mortality	10,000	Jones 1975
		20.4		30% mortality		
		27.2		6% mortality		
		34.0		16% mortality		
Iospod (adult), *Jaera albifrons*	Zinc sulfate	13.6	120 hr	84% mortality	20,000	Jones 1975
		20.4		44% mortality		
		27.2		40% mortality		
		34.0		22% mortality		
Isopod (adult), *Jaera albifrons*	Zinc sulfate	3.4	120 hr	Affected osmoregulatory ability	20,000	Jones 1975
Isopod (adult), *Jaera albifrons*	Zinc sulfate	17-34	120 hr	No effect on osmoregulatory ability	20,000	Jones 1975
Grass shrimp (larva), *Palaemonetes pugio*	Zinc chloride	3-31	35 days	Mortality related to salinity and temperature; altered development rates	≥250	McKenney 1979; McKenney and Neff 1979,1981

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Pink shrimp (adult), *Pandalus montagui*	Zinc sulfate	-	48 hr	LC50	4,050†	Portman 1968
American lobster (adult), *Homarus americanus*	Zinc sulfate	-	96 hr	No significant effects on adenylate energy charge; significant decreases in activity of Na/K-ATPase and residual ATPase in gills	62,000	Haya et al. 1983
American lobster (adult), *Homarus americanus*	Zinc sulfate	-	96 hr	BCF = 20.56 (gill)†	25,000-62,000	Haya et al. 1983
Green crab (adult), *Carcinus maenas*	Zinc sulfate	-	48 hr	LC50	14,500	Connor 1972
Green crab (adult), *Carcinus maenas*	Zinc sulfate	-	48 hr	LC50	Approx. 8,100†	Portman 1968
Green crab (adult), *Carcinus maenas*	^{65}Zinc chloride	38	3 mo	BCF = 130	-	Renfro et al. 1975
Green crab (adult), *Carcinus maenas*	^{65}Zinc chloride	38	3 mo	BAF = 210	-	Renfro et al. 1975
Mud crab (larva), *Rhithropanopeus harrisii*	Zinc chloride	20	13-18 days	No significan delay in development rate	25-50	Benijts-Claus and Benijts 1975
Mud crab (larva), *Rhithropanopeus harrisii*	Zinc chloride	20	13-18 days	Significant delay in development in combination with 25-50 µg lead/L	25-50	Benijts-Claus and Benijts 1975
Fiddler crab (adult), *Uca pugilator*	Zinc chloride	15 and 30	21 days	Inhibited limb regeneration; effect greater at lower salinities	≥1,000	Weis 1980
Starfish (adult), *Asterias forbesii*	Zinc sulfate	-	24 hr	Loss of equilibrium	2,212	Galtsoff and Loosanoff 1937

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Sand dollar (sperm), <u>Dendraster excentricus</u>	Zinc chloride	27	60 min	EC50 (fertilization success)	28	Dinnel et al. 1983
Sand dollar (embryo), <u>Dendraster excentricus</u>	Zinc chloride	30	72 hr	EC50 (development to pluteus stage)	580-820	Dinnel et al. 1983
Sea urchin (embryo), <u>Arbacia punctulata</u>	Zinc chloride	-	21-42 hr	Inhibited gastrulation	1,199	Waterman 1937
Sea urchin (embryo), <u>Arbacia punctulata</u>	Zinc chloride	-	21-42 hr	Mortality and inhibition of gastrulation	3,998	Waterman 1937
Sea urchin (embryo), <u>Arbacia punctulata</u>	Zinc sulfate	-	21-42 hr	Inhibited gastrulation	810	Waterman 1937
Sea urchin (embryo), <u>Arbacia punctulata</u>	Zinc sulfate	-	21-42 hr	Mortality and inhibition of gastrulation	2,314	Waterman 1937
Sea urchin (embryo), <u>Arbacia punctulata</u>	Zinc acetate	-	21-42 hr	Inhibited gastrulation	3,564	Waterman 1937
Sea urchin (gamete), <u>Arbacia punctulata</u>	Zinc chloride	-	4-12 min	Stimulated sperm motility	1,634	Young and Nelson 1974
Sea urchin (gamete), <u>Arbacia punctulata</u>	Zinc chloride	-	4-12 min	Reduced sperm motility	3,269	Young and Nelson 1974
Green sea urchin (sperm), <u>Strongylocentrotus droebachiensis</u>	Zinc chloride	27	60 min	EC50 (fertilization success)	147.6 382.8	Dinnel et al. 1983
Green sea urchin (embryo), <u>Strongylocentrotus droebachiensis</u>	Zinc chloride	30	5 days	EC50 (development to pluteus stage	>26.6<50.6	Dinnel et al. 1983
Red sea urchin (sperm), <u>Strongylocentrotus franciscanus</u>	Zinc chloride	27	60 min	EC50 (fertilization success)	313.3	Dinnel et al. 1983

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Purple sea urchin (gamete), *Strongylocentrotus purpuratus*	-	-	100-400 min	Enhanced sperm motility	653.8	Timourian and Watchmaker 1977
Purple sea urchin (gamete), *Strongylocentrotus purpuratus*	-	-	0-100 min	No effect on sperm motility	6,538	Timourian and Watchmaker 1977
Purple sea urchin (gamete), *Strongylocentrotus purpuratus*	-	-	100-400 min	Inhibited sperm motility	6,538	Timourian and Watchmaker 1977
Purple sea urchin (sperm), *Strongylocentrotus purpuratus*	Zinc chloride	27	60 min	EC50 (fertilization success)	206.1 261.8	Dinnel et al. 1983
Purple sea urchin (embryo), *Strongylocentrotus purpuratus*	Zinc chloride	30	5 days	EC50 (development to pluteus stage)	23.1	Dinnel et al. 1983
Atlantic herring (embryo), *Clupea harengus*	Zinc sulfate	21	17 days	Reduced embryo volume	≥2,000	Somasundaram et al. 1984a
Atlantic herring (embryo), *Clupea harengus*	Zinc sulfate	21	17 days	Faster yolk utilization	≥100	Sonasundaram et al. 1984a
Atlantic herring (embryo), *Clupea harengus*	Zinc sulfate	21	17 days	Slower development rate	6,000	Somasundarum et al. 1984a
Atlantic herring (embryo and larva), *Clupea harengus*	Zinc sulfate	21	27 days	Jaw and branchial abnormalities	≥50	Somasundaram et al. 1984a
Atlantic herring (larva), *Clupea harengus*	Zinc sulfate	21	27 days	Vertebral abnormalities	≥500	Somasundaram et al. 1984a
Atlantic herring (larva), *Clupea harengus*	Zinc sulfate	21	27 days	Decrease in size of otic capsul	≥2,000	Somasundaram et al. 1984a
Atlantic herring (larva), *Clupea harengus*	Zinc sulfate	21	27 days	Decrease in eye/body length ratio	≥6,000	Somasundaram et al. 1984a

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)^{a}	Reference
Atlantic herring (larva), *Clupea harengus*	Zinc sulfate	21	14 days	Ultrastructural changes in brain cells and somatic muscle tissues	$\geq$500	Somasundaram et al. 1984c,d
Coho salmon (sperm), *Oncorhynchus kisutch*	Zinc chloride	27	60 min	EC50 (fertilization success)	1,208	Dinnel et al. 1983
Rainbow trout (yearling), *Salmo gairdneri*	Zinc sulfate	5.8	48 hr	LC50	27,000†	Herbert and Wakeford 1964
		11.5			64,000†	
		16.3			64,000†	
		24.1			34,000†	
Atlantic salmon (smolt), *Salmo salar*	Zinc sulfate	5.8	48 hr	LC50	16,000†	Herbert and Wakeford 1964
		11.5			35,000†	
		16.3			32,000†	
		24.1			27,000†	
Mummichog (adult), *Fundulus heteroclitus*	Zinc chloride	24	192 hr	100% survival	43,000	Eisler 1967
Mummichog (adult), *Fundulus heteroclitus*	Zinc chloride	24	48 hr	100% mortality	157,000	Eisler 1967
Mummichog (adult), *Fundulus heteroclitus*	Zinc chloride	24	48 hr	BCF = 7,643***,† (fish that died during exposure)	157,000	Eisler 1967
Mummichog (adult), *Fundulus heteroclitus*	Zinc chloride	20	96 hr	BCF = 35.61***,†	36,000	Eisler and Gardner 1973
Mummichog (adult), *Fundulus heteroclitus*	Zinc chloride	20	96 hr	BCF = 18.83***,†	60,000	Eisler and Gardner 1973
Mummichog (adult), *Fundulus heteroclitus*	Zinc chloride	20	96 hr	30% mortality; histopathological lesions in oral epithelium	60,000	Eisler and Gardner 1973

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Mummichog (adult), *Fundulus heteroclitus*	Zinc chloride	-	14 days	Increased activity of liver enzyme	2,200	Jackim 1973
Mummichog (adult), *Fundulus heteroclitus*	Zinc chloride	10-30	14 days	Enhanced regeneration of tail fin and ameliorated effects of methyl mercury	≥1,000	Weis and Weis 1980
Mummichog (embryo), *Fundulus heteroclitus*	Zinc chloride	30	96 hr	Ameliorated teratogenic effects of methyl mercury	10,000	Weis et al. 1981
Mummichog (juvenile), *Fundulus heteroclitus*	Zinc chloride	25	70 days	Inhibited scale calcification	760- 7,100	Sauer and Watabe 1984
Mummichog (juvenile), *Fundulus heteroclitus*	Zinc chloride	30	56 days	BCF = 33.91-240.0 (scales)	210- 7,880	Sauer and Watabe 1984
Mosquitofish (adult), *Gambusia affinis*	††††	30	120 days	BCF = 8† (uptake from water alone)	650	Willis and Sunda 1984
Mosquitofish (adult), *Gambusia affinis*	††††	30	120 days	BAF = 45† (uptake from food and water)	650	Willis and Sunda 1984
Spot (juvenile), *Leiostomus xanthurus*	††††	30	28 days	BCF = 3† (uptake from water alone)	650	Willis and Sunda 1984
Spot (juvenile), *Leiostomus xanthurus*	††††	30	28 days	BAF = 28† (uptake from food and water)	650	Willis and Sunda 1984

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* Concentration of zinc, not the chemical.

** Field study.

*** Converted from dry weight to wet weight basis.

**** Static test; concentrations not measured.

† Derived from authors' data or graph.

†† Geometric mean of data from four stations, but concentrations in water varied widely.

††† Animals obtained from sediment heavily contaminated with zinc.

†††† Nitrilotriacetic acid (NTA) was used to buffer the concentration of zinc ions.

REFERENCES

Abbasi, S.A. and R. Soni. 1986. An examination of environmentally safe levels of zinc (II), cadmium (II), and lead (II) with reference to impact on channelfish *Nuria denricus*. Environ. Pollut. (Series A) 40:37-51.

Abbasi, S.A., P.C. Nipaney and R. Soni. 1985. Environmental consequences of the inhibition in the hatching of pupae of *Aedes aegypti* by mercury, zinc and chromium - The abnormal toxicity of zinc. Int. J. Environ. Stud. 24:107-114.

Abdullah, M.I., J.W. Banks, D.L. Miles and K.T. O'Grady. 1976. Environmental dependence of manganese and zinc in the scales of Atlantic salmon, *Salmo salar* (L) and brown trout, *Salmo trutta* (L). Freshwater Biol. 6:161-166.

Abo-Rady, M.D.K. 1979. The levels of heavy metals (Cd, Cu, Hg, Ni, Pb, Zn) in brook trout from the River Leine in the area of Gottingen (West Germany). Z. Lebensm. Unters. Forsch. 168:259-263.

Abo-Rady, M.D.K. 1983. Enrichment of heavy metals in brook trout in comparison to aquatic macrophytes and sediments. Z. Lebensm. Unters. Forsch. 117:339-334.

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

Adams, T.G., G.J. Atchison and R.J. Vetter. 1980. The impact of an industrially contaminated lake on heavy metal levels in its effluent stream. Hydrobiologia 69:187-193.

Adams, T.G., G.J. Atchison and R.J. Vetter. 1981. The use of the three-ridge clam (*Amblema perplicata*) to monitor trace metal contamination. Hydrobiologia 83:67-72.

Adragna, P.J. and C.A. Privitera. 1978. Zinc effects on fathead minnow cell cultures. Comp. Biochem. Physiol. 60C:159-163.

Adragna, P.J. and C.A. Privitera. 1979. Zinc effects on LDH, MDH and alkaline phosphatase from cultures of fathead minnow cells. Comp. Biochem. Physiol. 64B:219-224.

Affleck, R.J. 1952. Zinc poisoning in a trout hatchery. Aust. J. Mar. Freshwater Res. 3:142-169.

Agrawal, S.C. 1984. The effects of zinc sulphate on the ultraviolet light sensitivity of *Chlorella vulgaris* Beijernick. Curr. Sci. 53:989-990.

Ahsanullah, M. 1976. Acute toxicity of cadmium and zinc to seven invertebrate species from Western Port, Victoria. Aust. J. Mar. Freshwater Res. 27:187-196.

Ahsanullah, M. and G.H. Arnott. 1978. Acute toxicity of copper, cadmium, and zinc to larvae of the crab *Paragrapsus quadridentatus* (H. Milne Edwards), and implications for water quality criteria. Aust. J. Mar. Freshwater Res. 29:1-8.

Akberali, H.B. and M.J. Earnshaw. 1982. Studies of the effects of zinc on the respiration of mitochondria from different tissues in the bivalve mollusc *Mytilus edulis* (L.). Comp. Biochem. Physiol. 72C:149-152.

Albright, L.J. and E.M. Wilson. 1974. Sub-lethal effects of several metallic salts-organic compounds upon the heterotrophic microflora of a natural water. Water Res. 8:101-105.

Albright, L.J., J.W. Wentworth and E.M. Wilson. 1972. Technique for measuring metallic salt effects upon the indigenous heterotrophic microflora of a natural water. Water Res. 6:1589-1596.

Allen, H.E., R.H. Hall and T.D. Brisbin. 1980. Metal speciation. Effects on aquatic toxicity. Environ. Sci. Technol. 14:441-443.

Amemiya, Y. and O. Nakayama. 1984. The chemical composition and metal adsorption capacity of the sheath materials isolated from *Microcystis*, cyanobacteria. Jpn. J. Limnol. 45:187-193.

Anadu, D.I. 1983. Fish acclimation and the development of tolerance to zinc as a modifying factor in toxicity. Ph.D. thesis. Oregon State University, Corvallis, OR. Available from: University Microfilms, Ann Arbor, MI. Order No. DA83-20401.

Anderson, B.G. 1944. The toxicity thresholds of various substances found in industrial wastes as determined by the use of *Daphnia magna*. Sewage Works J. 16:1156-1165.

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. 78:96-113.

Anderson, K.B., R.E. Sparks and A.A. Paparo. 1978. Rapid assessment of water quality, using the fingernail clam, *Musculium transversum*. Research Report No. 133. Water Resources Center, University of Illinois, Urbana, IL.

Anderson, P.D. 1973. An approach to the study of multiple toxicity through the derivation and use of quantal response curves. Ph.D. thesis. Oregon State University, Corvallis, OR. Available from: University Microfilms, Ann Arbor, MI. Order No. 74-4187.

Anderson, P.D. and L.J. Weber. 1975. Toxic response as a quantitative function of body size. Toxicol. Appl. Pharmacol. 33:471-483.

Anderson, R.L., C.T. Walbridge and J.T. Fiandt. 1980. Survival and growth of Tanytarsus dissimilis (Chironomidae) exposed to copper, cadmium, zinc, and lead. Arch. Environ. Contam. Toxicol. 9:329-335.

Anderson, R.V. 1977. Concentration of Cd, Cu, Pb and Zn in six species of freshwater clams. Bull. Environ. Contam. Toxicol. 4:492-496.

Anderson, R.V., W.S. Vinikour and J.E. Brower. 1978. The distribution of Cd, Cu, Pb and Zn in the biota of two freshwater sites with different trace metal inputs. Holarct. Ecol. 1:377-384.

Andros, J.D. and R.R. Garton. 1980. Acute lethality of copper, cadmium, and zinc to northern squawfish. Trans. Am. Fish. Soc. 109:235-238.

Applegate, V.C., J.H. Howell, A.E. Hall, Jr. and M.A. Smith. 1957. Toxicity of 4,346 chemicals to larval lampreys and fishes. Special Scientific Report-Fisheries No. 207. U.S. Fish and Wildlife Service, Washington, DC.

Armitage, P.D. 1980. The effects of mine drainage and organic enrichment on benthos in the River Nent System, Northern Pennines. Hydrobiologia 74:119-128.

Armitage, P.D. and J.H. Blackburn. 1985. Chironomidae in a Pennine stream system receiving mine drainage and organic enrichment. Hydrobiologia 121:165-172.

Arnac, M. and C. Lassus. 1985. Heavy metal accumulation (Cd, Cu, Pb and Zn) by smelt (Osmerus mordax) from the north shore of the St. Lawrence estuary. Water Res. 19:725-734.

Arnott, G.H. and M. Ahsanullah. 1979. Acute toxicity of copper, cadmium and zinc to three species of marine copepod. Aust. J. Mar. Freshwater Res. 30:63-71.

Arruda, J.A., G.R. Marzolf and R.T. Faulk. 1983. The role of suspended sediments in the nutrition of zooplankton in turbid reservoirs. Ecology 64:1225-1235.

Atchison, G.J., B.R. Murphy, W.E. Bishop, A.W. McIntosh and R.A. Mayes. 1977. Trace metal contamination of bluegill (Lepomis macrochirus) from two Indiana lakes. Trans. Am. Fish. Soc. 106:637-640.

Attar, E.N. and E.J. May. 1982. Acute toxicity of cadmium, zinc, and cadmium-zinc mixtures to Daphnia magna. Arch. Environ. Contam. Toxicol. 11:291-296.

Austin, A. and N. Munteanu. 1984. Evaluation of changes in a large oligotrophic wilderness park lake exposed to mine tailing effluent for 14 years: The phytoplankton. Environ. Pollut. (Series A) 33:39-62.

Babich, H. and G. Stotzky. 1985. Heavy metal toxicity to microbe-medited ecologic processes: A review and potential application to regulatory policies. Environ. Res. 36:111-137.

Babich, H., J.A. Puerner and E. Borenfreund. 1985. Comparative in vitro cytotoxicities of cationic metal pollutants to mammalian and fish cells. J. Cell Biol. 101:87A.

Babich, H., J.A. Puerner and E. Borenfreund. 1986a. In vitro cytotoxicity of metals to bluegill (BF-2) cells. Arch. Environ. Contam. Toxicol. 15:31-37.

Babich, H., C. Shopsis and E. Borenfreund. 1986b. In vitro cytotoxicity testing of aquatic pollutants (cadmium, copper, zinc, nickel) using established fish cell lines. Ecotoxicol. Environ. Safety 11:91-99.

Baccini, P. 1985. Metal transport and metal/biota interactions in lakes. Environ. Technol. Lett. 6:327-334.

Bachmann, R.W. 1963. Zinc-65 in studies of the freshwater zinc cycle. In: Radioecology. Shultz, V. and A.W. Klement, Jr. (Eds.). Reinhold Publishing Corporation, New York, NY. pp. 485-496.

Back, H. 1983. Interactions, uptake and distribution of barium, cadmium, lead and zinc in tubificid worms (Annelida, Oligochaeta). In: Heavy metals in the environment. Vol. 1. CEP Consultants, Ltd., Edinburgh, U. K. pp. 370-373.

Badsha, K.S. and C.R. Goldspink. 1982. Preliminary observations on the heavy metal content of four species of freshwater fish in New England. J. Fish Biol. 21:251-267.

Bagshaw, J.C., P. Rafiee, C.O. Matthews and T.H. MacRae. 1986. Cadmium and zinc reversibly arrest development of Artemia larvae. Bull. Environ. Contam. Toxicol. 37:289-296.

Bailey, H.C. and D.H.W. Liu. 1980. Lumbriculus variegatus, a benthic oligochaete, as a bioassay organism. In: Aquatic toxicology. Eaton, J.C., P.R. Parrish and A.C. Hendricks (Eds.). ASTM STP 707. American Society for Testing and Materials, Philadelphia, PA. pp. 205-215.

Bailey, R.C. and P.M. Stokes. 1985. Evaluation of filamentous algae as biomonitors of metal accumulation in software lakes: A multivariate approach. In: Aquatic toxicology and hazard assessment: Seventh symposium. Cardwell, R.D., R. Purdy and R.C. Bahner (Eds.). ASTM STP 854. American Society for Testing and Materials, Philadelphia, PA. pp. 5-26.

Baker, J.R. and B.P. Baldigo. 1984. Toxicity persistence in Prickly Pear Creek, Montana. EPA-600/4-84-087 or PB85-137149. National Technical Information Service, Springfield, VA.

Ball, I.R. 1967. The relative susceptibilities of some species of fresh-water fish to poisons-II. Zinc. Water Res. 1:777-783.

Barash, H., H.A. Poston and G.L. Rumsey. 1982. Differentiation of soluble proteins in cataracts caused by deficiencies of methionine, riboflavin or zinc in diets fed to Atlantic salmon, Salmo salar, rainbow trout, Salmo gairdneri, and lake trout, Salvelinus namaycush. Cornell Vet. 72:361-371.

Barber, S. and J.H. Trefry. 1981. Balanus eburneus: A sensitive indicator of copper and zinc pollution in the coastal zone. Bull. Environ. Contam. Toxicol. 27:654-659.

Bartlett, L., F.W. Rabe and W.H. Funk. 1974. Effects of copper, zinc and cadmium on Selanastrum capricornutum. Water Res. 8:179-185.

Bates, S., A. Tessier and M. Letourneau. 1981. Zinc bioaccumulation by Chlamydomonas variabilis as a function of zinc speciation. In: Proceedings of the seventh annual aquatic toxicity workshop. Bermingham, N., C. Blaise, P. Couture, B. Hummel, G. Joubert and M. Speyer (Eds.). Canadian Technical Report of Fisheries and Aquatic Sciences No. 990. Department of Fisheries and Oceans, Ottawa, Ontario, Canada. pp. 119-120.

Bates, S.S., M. Letourneau, A. Tessier and P.G.C. Campbell. 1983. Variation in zinc adsorption and transport during growth of Chlamydomonas variabilis (Chlorophyceae) in batch culture with daily addition of zinc. Can. J. Fish. Aquat. Sci. 40:895-904.

Baudin, J.P. 1983a. Bioaccumulation and elimination of ^{65}Zn by *Gammarus aequicauda*. Mar. Environ. Res. 7:227-233; Aquat. Sci. Fish. Abstr. 1983. 13(4):168. Abstr. No. 5524-1Q13.

Baudin, J.P. 1983b. Experimental study of the bioaccumulation and excretion of ^{65}Zn by a freshwater fish, *Cyprinus carpio* L. Acta Oecol. Oecol. Appl. 4:139-149.

Baudin, J.P. 1985. Experiments on the accumulation of zinc-65 in various trophic levels with *Cyprinus carpio* L. Int. Ver. Theor. Angew. Limnol. Verh. 22:2476-2480.

Baudouin, M.F. and P. Scoppa. 1974. Acute toxicity of various metals to freshwater zooplankton. Bull. Environ. Contam. Toxicol. 12:745-751.

Bell, G.R., D.A. Higgs and G.S. Traxler. 1984. The effect of dietary ascorbate, zinc, and manganese on the development of experimentally induced bacterial kidney disease in sockeye salmon (*Oncorhynchus nerka*). Aquaculture 36:293-311.

Bengtsson, B.E. 1974a. The effects of zinc on the mortality and reproduction of the minnow, *Phoxinus phoxinus* L. Arch. Environ. Contam. Toxicol. 2:342-355.

Bengtsson, B.E. 1974b. Effect of zinc on the movement pattern of the minnow, *Phoxinus phoxinus* L. Water Res. 8:829-833.

Bengtsson, B.E. 1974c. Vertebral damage to minnows *Phoxinus phoxinus* exposed to zinc. Oikos 25:134-139.

Bengtsson, B.E. 1974d. Effect of zinc on growth of the minnow *Phoxinus phoxinus*. Oikos 25:370-373.

Bengtsson, B.E. 1974e. The effect of zinc on the ability of the minnow, *Phoxinus phoxinus* L., to compensate for torque in a rotating water-current. Bull. Environ. Contam. Toxicol. 12:654-658.

Bengtsson, B.E. 1978. Use of a harpacticoid copepod in toxicity tests. Mar. Pollut. Bull. 9:238-241.

Benijts-Claus, C. and F. Benijts. 1975. The effect of low lead and zinc concentrations on the larval development of the mud-crab Rhithropanopeus harrisii Gould. In: Sublethal effects of toxic chemicals on aquatic animals. Koeman, J.H. and J.J.T.W.A. Strik (Eds.). Elsevier, Amsterdam, Netherlands. pp. 43-52.

Benoit, D.A. and G.W. Holcombe. 1978. Toxic effects of zinc on fathead minnows Pimephales promelas in soft water. J. Fish Biol. 13:701-708.

Benson, W.H. and W.J. Birge. 1985. Heavy metal tolerance and metallothionein induction in fathead minnows: Results from field and laboratory investigations. Environ. Toxicol. Chem. 4:209-217.

Berg, A. and A. Brazzelli. 1975. Zinc-65 transfer in a freshwater fish with particular reference to the two methods of absorption and to the metabolism of the stable element. Radioprotection 10:61-84.

Berglind, R. and G. Dave. 1984. Acute toxicity of chromate, DDT, PCP, TPBS, and zinc to Daphnia magna cultured in hard and soft water. Bull. Environ. Contam. Toxicol. 33:63-68.

Besser, J.M. 1985. Bioavailability and toxicity of heavy metals in mine tailings leachate to aquatic invertebrates. M.S. thesis. University of Missouri, Columbia, MO.

Biddinger, G.R. and S.P. Gloss. 1984. The importance of trophic transfer in the bioaccumulation of chemical contaminants in aquatic ecosystems. Residue Rev. 91:104-145.

Biegert, E.K. and V. Valkovic. 1980. Acute toxicity and accumulation of heavy metals in aquatic animals. Period. Biol. 82:25-30.

Biesinger, K.E. and G.M. Christensen. 1972. Effects of various metals on survival, growth, reproduction, and metabolism of Daphnia magna. J. Fish. Res. Board Can. 29:1691-1700.

Biesinger, K.E., R.W. Andrew and J.W. Arthur. 1974. Chronic toxicity of NTA (nitrilotriacetate) and metal-NTA complexes to Daphnia magna. J. Fish. Res. Board Can. 31:486-490.

Biesinger, K.E., G.M. Christensen and J.T. Fiandt. 1986. Effects of metal salt mixtures on Daphnia magna reproduction. Ecotoxicol. Environ. Safety 11:9-14.

Billard, R. and P. Roubaud. 1985. The effect of metals and cyanide on fertilization in rainbow trout (Salmo gairdneri). Water Res. 19:209-214.

Birge, W.J. 1978. Aquatic toxicology of trace elements of coal and fly ash. In: Energy and environmental stress in aquatic systems. Thorp, J.H. and J.W. Gibbons (Eds.). CONF-771114. National Technical Information Service, Springfield, VA. pp. 219-240.

Birge, W.J. and J.J. Just. 1973. Sensitivity of vertebrate embryos to heavy metals as a criterion of water quality. PB-226850. National Technical Information Service, Springfield, VA.

Birge, W.J. and J.J. Just. 1975. Sensitivity of vertebrate embryos to heavy metals as a criterion of water quality. Phase II. Bioassay procedures using developmental stages as test organisms. PB240978. National Technical Information Service, Springfield, VA.

Birge, W.J., J.E. Hudson, J.A. Black and A.G. Westerman. 1978. Embryo-larval bioassays on inorganic coal elements and in situ biomonitoring of coal-waste effluents. In: Surface mining and fish/wildlife needs in the eastern United States. Samuel, D.E., J.R. Stauffer, C.H. Hocutt and W.T. Mason (Eds.). PB298353. National Technical Information Service, Springfield, VA. pp. 97-104.

Birge, W.J., J.A. Black and A.G. Westerman. 1979. Evaluation of aquatic pollutants using fish and amphibian eggs as bioassay organisms. In: Animals as monitors of environmental pollutants. Nielson, S.W., G. Migaki and D.G. Scarrelli (Eds.). National Academy of Sciences, Washington, DC. pp. 108-118.

Birge, W.J., J.A. Black, A.G. Westerman and J.E. Hudson. 1980. Aquatic toxicity tests on inorganic elements occurring in oil shale. In: Oil shale symposium: Sampling, analysis and quality assurance. Gale, C. (Ed.). EPA-600/9-80-022. National Technical Information Service, Springfield, VA. pp. 519-534.

Birge, W.J., J.A. Black and B.A. Ramey. 1981. The reproductive toxicology of aquatic contaminants. In: Hazard assessment of chemicals: Current development. Vol. I. Saxena, J. and F. Fisher (Eds.). Academic Press, New York, NY. pp. 59-115.

Birge, W.J., W.H. Benson and J.A. Black. 1983. Induction of tolerance to heavy metals in natural and laboratory populations of fish. PB84111756. National Technical Information Service, Springfield, VA.

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

Bohn, A. and B.W. Fallis. 1978. Metal concentrations (As, Cd, Cu, Pb and Zn) in shorthorn sculpins, Myoxocephalus scorpius (Linnaeus), and Arctic char, Salvelinus alpinus (Linnaeus), from the vicinity of Strathcona Sound, Northwest Territories. Water Res. 12:659-663.

Borgmann, U. 1980. Interactive effects of metals in mixtures on biomass production kinetics of freshwater copepods. Can. J. Fish. Aquat. Sci. 37:1295-1302.

Bosnak, A.D. and E.L. Morgan. 1981. Acute toxicity of cadmium, zinc, and total residual chlorine to epigean and hypogean isopods (Asellidae). Natl. Speleological Soc. Bull. 43:12-18.

Bosserman, R.W. 1985. Distribution of heavy metals in aquatic macrophytes from Okefenokee Swamp. Symp. Biol. Hung. 29:31-40.

Boyce, N.P. and S.B. Yamada. 1977. Effects of a parasite, Eubothrium salvelini (Cestoda: Pseudophyllidea), on the resistance of juvenile sockeye salmon, Oncorhynchus nerka, to zinc. J. Fish. Res. Board Can. 34:706-709.

Boyden, C.R., H. Watling and I. Thornton. 1975. Effect of zinc on the settlement of the oyster, Crassostrea gigas. Mar. Biol. (Berl.) 31:227-234.

Bradley, R.W. and J.R. Morris. 1986. Heavy metals in fish from a series of metal contaminated lakes near Sudbury, Ontario. Water Air Soil Pollut. 27:341-354.

Bradley, R.W. and J.B. Sprague. 1983. The influence of pH, hardness and alkalinity on the acute toxicity of zinc to rainbow trout. In: Proceedings of the eighth annual aquatic toxicity workshop. Kaushik, N.K. and K.R.

Solomon (Eds.). Canadian Technical Report of Fisheries and Aquatic Sciences No. 1151. Department of Fisheries and Oceans, Ottawa, Ontario, Canada. pp. 172-173.

Bradley, R.W. and J.B. Sprague. 1985. Accumulation of zinc by rainbow trout as influenced by pH, water hardness and fish size. Environ. Toxicol. Chem. 4:685-694.

Bradley, R.W., C. Dequesnay and J.B. Sprague. 1985a. Acclimation of rainbow trout to zinc - kinetics and mechanism of tolerance induction. In: Proceedings of the tenth annual aquatic toxicity workshop. Wells, P.G. and R.F. Addison (Eds.). Canadian Technical Report of Fisheries and Aquatic Sciences No. 1368. Fisheries and Oceans, Ottawa, Ontario, Canada. pp. 159-160.

Bradley, R.W., C. DuQuesnay and J.B. Sprague. 1985b. Acclimation of rainbow trout, _Salmo gairdneri_ Richardson, to zinc: Kinetics and mechanism of enhanced tolerance induction. J. Fish Biol. 27:367-379.

Braek, G.S., A. Jensen and A. Mohus. 1976. Heavy metal tolerance of marine phytoplankton. III. Combined effects of copper and zinc ions on cultures of four common species. J. Exp. Mar. Biol. Ecol. 25:37-50.

Braek, G.S., D. Malnes and A. Jensen. 1980. Heavy metal tolerance of marine phytoplankton. IV. Combined effect of zinc and cadmium on growth and uptake in some marine diatoms. J. Exp. Mar. Biol. Ecol. 42:39-54.

Brafield, A.E. and P. Matthiessen. 1976. Oxygen consumption by sticklebacks (_Gasterosteus aculeatus_ L.) exposed to zinc. J. Fish Biol. 9:359-370.

Braginskiy, L.P. and E.P. Shcherban. 1978. Acute toxicity of heavy metals to aquatic invertebrates at different temperatures. Hydrobiol. J. 14(6):78-82.

Brauwers, C. 1982. Comparison of Zn and Cd toxicity on Chlorella pyrenoidosa. Bull. Soc. R. Bot. Belg. 115:78-90; Aquat. Sci. Fish. Abst. 13(5):161. Abstr. No. 7167-1Q13. 1983.

Brereton, A., H. Lord, I. Thornton and J.S. Webb. 1973. Effect of zinc on growth and development of larvae of the Pacific oyster, Crassostrea gigas. Mar. Biol. (Berl.) 19:96-101.

Brezina, E.R. and M.Z. Arnold. 1977. Levels of heavy metals in fishes from selected Pennsylvania waters. Bureau of Water Quality Management Publication No. 50. Pennsylvania Department of Environmental Resources.

Bringmann, G. and R. Kuhn. 1959a. The toxic effects of waste water on aquatic bacteria, algae, and small crustaceans. Gesund.-Ing. 80:115-120.

Bringmann, G. and R. Kuhn. 1959b. Water toxicology studies with protozoans as test organisms. Gesund.-Ing. 80:239-242.

Bringmann, G. and R. Kuhn. 1977. Results of the damaging effect of water pollutants on Daphnia magna. Z. Wasser Abwasser Forsch. 10:161-166.

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. 13:65-72.

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. 13:93-98.

Broberg, A. 1984. Effects of heavy metals on nitrification in laboratory experiments with freshwater sediments. Ecol. Bull. 36:135-142.

Broderius, S.J. and L.L. Smith, Jr. 1979. Lethal and sublethal effects of binary mixtures of cyanide and hexavalent chromium, zinc, or ammonia to the fathead minnow, (*Pimephales promelas*), and rainbow trout, (*Salmo gairdneri*). J. Fish. Res. Board Can. 36:164-172.

Bromage, N.R. and A. Fuchs. 1976. A histological study of the response of the interrenal cells of the goldfish (*Carassius auratus*) to treatment with sodium lauryl sulphate. J. Fish Biol. 9:529-535.

Brooks, R.R., J.R. Lewis and R.D. Reeves. 1976. Mercury and other heavy metals in trout of Central North Island, New Zealand. N. Z. J. Mar. Freshwater Res. 10:233-244.

Brown, B. and M. Ahsanullah. 1971. Effect of heavy metals on mortality and growth. Mar. Pollut. Bull. 2:182-187.

Brown, B.E. 1977. Effects of mine drainage on the River Hayle, Cornwall. A) Factors affecting concentrations of copper, zinc and iron in water, sediments and dominant invertebrate fauna. Hydrobiologia 52:221-233.

Brown, B.T. and B.M. Rattigan. 1979. Toxicity of soluble copper and other metal ions to *Elodea canadensis*. Environ. Pollut. 20:303-314.

Brown, G.W., Jr. 1976. Effects of polluting substances on enzymes of aquatic organisms. J. Fish. Res. Board Can. 33:2018-2022.

Brown, J.R. and L.Y. Chow. 1977. Heavy metal concentrations in Ontario fish. Bull. Environ. Contam. Toxicol. 17:190-195.

Brown, V.M. 1968. The calculation of the acute toxicity of mixtures of poisons to rainbow trout. Water Res. 2:723-733.

Brown, V.M. and R.A. Dalton. 1970. The acute lethal toxicity to rainbow trout of mixtures of copper, phenol, zinc and nickel. J. Fish Biol. 2:211-216.

Brown, V.M., V.V. Mitrovic and G.T.C. Stark. 1968. Effects of chronic exposure to zinc on toxicity of a mixture of detergent and zinc. Water Res. 2:255-263.

Brown, V.M., D.H.M. Jordan and B.A. Tiller. 1969. The acute toxicity to rainbow trout of fluctuating concentrations and mixtures of ammonia, phenol and zinc. J. Fish Biol. 1:1-9.

Brungs, W.A. 1969. Chronic toxicity of zinc to the fathead minnow, *Pimephales promelas* Rafinesque. Trans. Am. Fish. Soc. 2:272-279.

Bryan, G.W. 1969. The absorption of zinc and other metals by the brown seaweed, *Laminaria digitata*. J. Mar. Biol. Assoc. U.K. 49:225-243.

Bryan, G.W. and L.G. Hummerstone. 1973. Adaptation of the polychaete, *Nereis diversicolor* to estuarine sediments containing high concentrations of zinc and cadmium. J. Mar. Biol. Assoc. U.K. 53:839-857.

Bryan, G.W., W.J. Langston, L.G. Hummerstone, G.R. Burt and Y.B. Ho. 1983. An assessment of the gastropod, *Littorina littorea* as an indicator of heavy metal contamination in United Kingdom estuaries. J. Mar. Biol. Assoc. U.K. 63:327-345.

Bryant, V., D.M. Newbery, D.S. McKlusky and R. Campbell. 1985. Effect of temperature and salinity on the toxicity of nickel and zinc to two estuarine invertebrates (*Corophium volutator*, *Macoma balthica*). Mar. Ecol. Prog. Ser. 24:139-153.

Buikema, A.L., Jr., J. Cairns, Jr. and G.W. Sullivan. 1974a. Rotifers as monitors of heavy metal pollution in water. Bulletin 71. Virginia Water Resources Research Center, Blacksburg, VA.

Buikema, A.L., Jr., J. Cairns, Jr. and G.W. Sullivan. 1974b. Evaluation of Philodina acuticornis (Rotifera) as a bioassay organism for heavy metals. Water Resour. Bull. 10:648-661.

Buikema, A.L., Jr., C.L. See and J. Cairns, Jr. 1977. Roitifer sensitivity to combinations of inorganic water pollutants. Bulletin 92. Virginia Water Resources Research Center, Blacksburg, VA.

Burrows, I.G. and B.A. Whitton. 1983. Heavy metals in water, sediments and invertebrates from a metal contaminated river free of organic pollution. Hydrobiologia 106:263-273.

Burton, D.T., E.L. Morgan and J. Cairns, Jr. 1972a. Mortality curves of bluegills (Lepomis macrochirus Rafinesque) simultaneously exposed to temperature and zinc stress. Trans. Am. Fish. Soc. 101:435-441.

Burton, D.T., A.H. Jones and J. Cairns, Jr. 1972b. Acute zinc toxicity to rainbow trout (Salmo gairdneri): Confirmation of the hypothesis that death is related to tissue hypoxia. J. Fish. Res. Board Can. 29:1463-1466.

Burton, M.A.S. and P.J. Peterson. 1979a. Studies on zinc localization in aquatic bryophytes. Bryologist 82:594-598.

Burton, M.A.S. and P.J. Peterson. 1979b. Metal accumulation by aquatic bryophytes from polluted mine streams. Environ. Pollut. (Series A) 19:39-46.

Bussey, R.E., D.E. Kidd and L.D. Potter. 1976. The concentration of ten heavy metals in some selected Lake Powell game fishes. NSF/RA-761133. National Technical Information Service, Springfield, VA.

Caines, L.A., A.W. Watt and D.E. Wells. 1985. The uptake and release of some trace metals by aquatic bryophytes in acidified waters in Scotland. Environ. Pollut. (Series B) 10:1-18.

Cairns, J., Jr. 1957. Environment and time in fish toxicity. Ind. Wastes 2:1-5.

Cairns, J., Jr. 1972. Application of biological monitoring systems to stimulated industrial waste discharge situation. PB213468. National Tecnnical Information Service, Springfield, VA.

Cairns, J., Jr. and K.L. Dickson. 1970. Reduction and restoration of the number of fresh-water protozoan species following acute exposure to copper and zinc. Trans. Kans. Acad. Sci. 73:1-10.

Cairns, J., Jr. and A. Scheier. 1957. The effects of temperature and hardness of water upon the toxicity of zinc to the common bluegill (Lepomis macrochirus Raf.). Notulae Naturae, No. 299:1-12.

Cairns, J., Jr. and A. Scheier. 1958a. The effects of periodic low oxygen upon the toxicity of various chemicals to aquatic organisms. Proc. Ind. Waste Conf. Purdue Univ. 12:165-176.

Cairns, J., Jr. and A. Scheier. 1958b. The effects of temperature and hardness of water upon the toxicity of zinc to the pond snail, Physa heterostropha (Say). Notulae Naturae, No. 308-1-11.

Cairns, J., Jr. and A. Scheier. 1959. The relationship of bluegill sunfish body size to tolerance for some common chemicals. Proc. Ind. Waste Conf. Purdue Univ. 13:243-252.

Cairns, J., Jr. and A. Scheier. 1964. The effects of sublethal levels of zinc and of high temperature upon the toxicity of a detergent to the sunfish *Lepomis gibbosus* (Linn.). Notulae Naturae, No. 367:1-3.

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. 30:3-8.

Cairns, J., Jr. and R.E. Sparks. 1971. The use of bluegill breathing to detect zinc. PB211332. National Technical Information Service, Springfield, VA.

Cairns, J., Jr. and W.T. Waller. 1971. The use of fish movement patterns to monitor zinc. PB211333. National Technical Information Service, Springfield, VA.

Cairns, J., Jr., W.T. Waller and J.C. Smrchek. 1969. Fish bioassays contrasting constant and fluctuating input of toxicants. Rev. Biol. (Lisb.) 7:75-91.

Cairns, J., Jr., T.K. Bahns, D.T. Burton, K.L. Dickson, R.E. Sparks and W.T. Waller. 1971. The effects of pH, solubility and temperature upon the acute toxicity of zinc to the bluegill sunfish (*Lepomis macrochirus* Raf.). Trans. Kans. Acad. Sci. 74:81-92.

Cairns, J., Jr., R.E. Sparks and W.T. Waller. 1973a. The use of fish as sensors in industrial waste lines to prevent fish kills. Hydrobiologia 41:151-167.

Cairns, J., Jr., J.W. Hall, E.L. Morgan, R.E. Sparks, W.T. Waller and G.F. Westlake. 1973b. The development of an automated biological monitoring system for water quality. PB238492. National Technical Information Service, Springfield, VA.

Cairns, J., Jr., A.G. Heath and B.C. Parker. 1975a. The effects of temperature upon the toxicity of chemicals to aquatic organisms. Hydrobiologia 47:135-171.

Cairns, J., Jr., W.H. van der Schalie and G.F. Westlake. 1975b. The effects of lapsed time since feeding upon the toxicity of zinc to fish. Bull. Environ. Contam. Toxicol. 13:269-274.

Cairns, J., Jr., D.L. Messenger and W.F. Calhoun. 1976. Invertebrate response to thermal shock following exposure to acutely sub-lethal concentrations of chemicals. Arch. Hydrobiol. 77:1[illegible]75.

Cairns, J., Jr., A.L. Buikema, Jr., A.G. Heath and B.C. Parker. 1978. Effects of temperature on aquatic organism sensitivity to selected chemicals. Bulletin 106. Virginia Water Resources Research Center, Blacksburg, VA.

Cairns, J., Jr., K.W. Thompson and A.C. Hendricks. 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, VA.

Cairns, M.A., R.R. Garton and R.A. Tubb. 1982. Use of fish ventilation frequency to estimate chronically safe toxicant concentrations. Trans. Am. Fish. Soc. 111:70-77.

Calabrese, A. and D.A. Nelson. 1974. Inhibition of embryonic development of the hard clam, Mercenaria mercenaria by heavy metals. Bull. Environ. Contam. Toxicol. 11:92-97.

Calabrese, A., R.S. Collier, D.A. Nelson and J.R. MacInnes. 1973. The toxicity of heavy metals to embryos of the American oyster, Crassostrea virginica. Mar. Biol. (Berl.) 18:162-166.

Calabrese, A., J.R. MacInnes, D.A. Nelson and J.E. Miller. 1977. Survival and growth of bivalve larvae under heavy-metal stress. Mar. Biol. (Berl.) 41:179-184.

Callahan, M.A., M.W. Slimak, N.W. Gabel, I.P. May, C.F. Fowler, J.R. Freed, P. Jennings, R.L. Durfee, F.C. Whitmore, B. Maestri, W.R. Mabey, B.R. Holt and C. Gould. 1979. Water related environmental fate of 129 priority pollutants. Vol. 1. EPA-440/4-79-029a. National Technical Information Service, Springfield, VA. pp. 19-1 to 19-21.

Cammarota, V.A., Jr. 1980. Production and uses of zinc. In: Zinc in the environment. Part I: Ecological cycling. J.O. Nriagu (Ed.). Wiley, New York, NY. p. 1-38.

Campbell, P.G. and P.M. Stokes. 1985. Acidification and toxicity of metals to aquatic biota. Can. J. Fish. Aquat. Sci. 42:2034-2049.

Cancalon, P. 1982. Degeneration and regeneration of olfactory cells induced by $ZnSO_4$ and other chemicals. Tissue & Cell 14:717-733.

Cardin, J.A. 1985. Acute toxicity data for zinc and the saltwater fish, Fundulus heteroclitus, Menidia menidia and Pseudopleuronectes americanus. (Memorandum to D.J. Hansen, U.S. EPA, Narragansett, RI.)

Carlson, A.R. and T.H. Roush. 1985. Site-specific water quality studies of the Straight River, Minnesota: Complex effluent toxicity, zinc toxicity, and biological survey relationships. EPA-600/3-85-005. National Technical Information Service, Springfield, VA.

Carlson, A.R., H. Nelson and D. Hammermeister. 1986. Evaluation of site-specific criteria for copper and zinc: An integration of metal addition toxicity, effluent and receiving water toxicity, and ecological survey data. EPA-600/3-86-026. National Technical Information Service, Springfield, VA.

Carpenter, K.E. 1927. The lethal action of soluble metallic salts of fishes. Br. J. Exp. Biol. 4:378-390.

Carson, W.G. and W.V. Carson. 1972. Toxicity of copper and zinc to juvenile Atlantic salmon in the presence of humic acid and lignosulfonates. Fisheries Research Board of Canada Manuscript Report Series No. 1181. Biological Station, St. Andrews, N.B., Canada.

Carter, J.G.T. and W.L. Nicholas. 1978. Uptake of zinc by the aquatic larvae of Simulium ornatipes (Diptera: Nematocera). Aust. J. Mar. Freshwater Res. 29:299-309.

Carter, J.W. and I.L. Cameron. 1973. Toxicity bioassay of heavy metals in water using Tetrahymera pyriformis. Water Res. 7:951-961.

Cearley, J.E. 1971. Toxicity and bioconcentration of cadmium, chromium, and silver in Micropterus salmoides and Lepomis macrochirus. Ph.D. thesis. University of Oklahoma, Oklahoma City, OK. Available from: University Microfilms, Ann Arbor, MI. Order No. 72-9023.

Cenci, G., G. Morozzi and G. Caldini. 1985. Injury by heavy metals in Escherichia coli. Bull. Environ. Contam. Toxicol. 34:188-195.

Cenini, P. and R.J. Turner. 1983. In vitro effects of zinc on lymphoid cells of the carp, Cyprinus carpio L. J. Fish Biol. 23:579-583.

Chaisemartin, C., Y. Lapouge and P.N. Martin. 1976. Reactional behavior of young crayfish to metallic ions zinc, copper, lead and chronium effect of temperature and sediment. C.R. Seances Soc. Biol. 170:880-885.

Chang, P.S., D.F. Malley, N.E. Strange and J.F. Klaverkamp. 1983. The effects of low pH, selenium and calcium on the bioaccumulation of ^{203}Hg by seven tissues of the crayfish, Orconectes virilis. In: Proceedings of the eighth annual aquatic toxicity workshop. Karishik, N.K. and K.R. Solomon (Eds.). Canadian Technical Report of Fisheries and Aquatic Sciences No. 1151. Department of Fisheries and Oceans, Ottawa, Ontario, Canada. pp. 45-62.

[illegible]apman, G. and S. Dunlop. 1981. Detoxication of zinc and cadmium to the freshwater protozoan Tetrahymena pyriformis. I. The effect of water hardness. Environ. Res. 26:81-86.

Chapman, G.A. 1975. Toxicity of copper, cadmium and zinc to Pacific northwest salmonids. Interim Report. U.S. EPA, Corvallis, OR. Available from: C.E. Stephan, U.S. EPA, Duluth, MN.

Chapman, G.A. 1978a. Effects of continuous zinc exposure on sockeye salmon during adult-to-smolt freshwater residency. Trans. Am. Fish. Soc. 107:828-836.

Chapman, G.A. 1978b. Toxicities of cadmium, copper and zinc to four juvenile stages of chinook salmon and steelhead. Trans. Am. Fish. Soc. 107:841-847.

Chapman, G.A. and D.G. Stevens. 1978. Acutely lethal levels of cadmium, copper and zinc to adult male coho salmon and steelhead. Trans. Am. Fish. Soc. 107:837-840.

Chapman, G.A., S. Ota and F. Recht. Manuscript. Effects of water hardness on the toxicity of metals to *Daphnia magna*. Available from: C.E. Stephan, U.S. EPA, Duluth, MN.

Chapman, P.M. 1985. Effets of gut sediment contents on measurements of metal levels in benthic invertebrates - a cautionary note. Bull. Environ. Contam. Toxicol. 35:345-347.

Chapman, W.H., H.L. Fisher and M.W. Pratt. 1968. Concentration factors of chemical elements in edible aquatic organisms. UCRL-50564. National Technical Information Service, Springfield, VA.

Chassard, B.C. and G. Balvay. 1978. Application of electron probe x-ray microanalysis to the detection of metal pollutants in freshwater zooplankton. Microsc. Acta Suppl. 2:185-192.

Cherry, D.S., R.K. Guthie, F.F. Sherberger and S.R. Larrick. 1979. The influence of coal ash and thermal discharges upon the distribution and bioaccumulation of aquatic invertebrates. Hydrobiologia 62:257-267.

Cherry, D.S., J.H. Rodgers, Jr., R.L. Graney and J. Cairns, Jr. 1980. Dynamics and control of the Asiatic clam in the New River, Virginia. Bulletin 123. Virginia Water Resources Research Center, Blacksburg, VA.

Christensen, E.R., C.Y. Chen and J. Kannall. 1985. The response of aquatic organisms to mixtures of toxicants. Water Sci. Technol. 17:1445-1446.

Clarke, G.L. 1947. Poisoning and recovery of barnacles and mussels. Biol. Bull. (Woods Hole) 92:73-91.

Clendenning, K.A. and W.J. North. 1959. Effects of wastes on the giant kelp, Macrocystis pyrifera. In: International conference on waste disposal in the marine environment. Pearson, E.A. (Ed.). Berkeley, CA. pp. 82-91.

Coburn, C.B. and A.A. Friedman. 1976. Conventional bioassay and tissue bioassay of zinc cyanide, sodium cyanide and malathion. J. Tenn. Acad. Sci. 51:59.

Coleman, R.D., R.L. Coleman and E.L. Rice. 1971. Zinc and cobalt bioconcentration and toxicity in selected algal species. Bot. Gaz. 132:102-109.

Connolly, J.P. 1985. Predicting single-species toxicity in natural water systems. Environ. Toxicol. Chem. 4:573-582.

Connor, P.M. 1972. Acute toxicity of some heavy metals to some marine larvae. Mar. Pollut. Bull. 3:190-192.

Cotter, A.J.R., D.J.H. Phillips and M. Ahsanullah. 1982. The significance of temperature, salinity and zinc as lethal factors for the mussel Mytilus edulis in a polluted estuary. Mar. Biol. (Berl.) 68:135-141.

Coughtrey, P.J. and M.H. Martin. 1977. The uptake of lead, zinc, cadmium, and copper by the pulmonate mollusc, Helix aspersa Mueller, and its relevance to the monitoring of heavy metal contamination of the environment. Oecologia 27:65-74.

Cover, E. and J. Wilhm. 1982. Effect of artificial destratification on iron, managnese, and zinc in the water, sediments, and two species of benthic macroinvertebrates in an Oklahoma lake. Hydrobiologia 87:11-16.

Cowgill, U.M., H.W. Emmel and I.T. Takahashi. 1985. Inorganic chemical composition of trout food pellets and alfalfa used to sustain Daphnia magna Straus. Bull. Environ. Contam. Toxicol. 34:890-896.

Cowgill, U.M., H.W. Emmel, D.L. Hopkins, S.L. Applegath and I.T. Takahashi. 1986. The influence of water on reproductive success and chemical composition of laboratory reared populations of *Daphnia magna*. Water Res. 20:317-323.

Cowx, I.O. 1982. Concentrations of heavy metals in the tissues of trout, *Salmo trutta*, and char, *Salvelinus alpinus* from two lakes in North Wales. Environ. Pollut. (Series A) 29:101-110.

Crandall, C.A. and C.J. Goodnight. 1962. Effects of sublethal concentrations of several toxicants on growth of the common guppy, *Lebistes reticulatus*. Limnol. Oceanogr. 7:233-239.

Crandall, C.A. and C.J. Goodnight. 1963. The effects of sublethal concentrations of several toxicants to the common guppy, *Lebistes reticulatus*. Trans. Am. Microsc. Soc. 82:59-73.

Crespo, S. 1984. An in vitro study of the effects of zinc on osmoregulatory processes. Mar. Pollut. Bull. 15:341-342.

Crist, R.H., K. Oberholser, N. Shank and M. Nguyen. 1981. Nature of bonding between metallic ions and algal cell walls. Environ. Sci. Technol. 15:1212-1217.

Cushing, C.E. and F.L. Rose. 1970. Cycling of zinc-65 by Columbia River periphyton in a closed lotic microcosm. Limnol. Oceanogr. 15:762-767.

Cushing, C.E. and D.G. Watson. 1971. Cycling of ^{55}Zn in a simple food-web. Nucl. Sci. Abstr. 25:39806.

Cushing, C.E., J.M. Thomas and L.L. Eberhardt. 1975. Modelling mineral cycling by periphyton in a simulated stream system. Int. Ver. Theor. Angew. Limnol. Verh. 19:1593-1598.

Cusimano, R.F., D.F. Brakke and G.A. Chapman. 1986. Effects of pH on the toxicities of cadmium, copper, and zinc to steelhead trout (*Salmo gairdneri*). Can. J. Fish. Aquat. Sci. 43:1497-1503.

Dabrowski, K., K. Krasnicki and H. Kozlowska. 1981. Rapeseed meal in the diet for common carp reared in heated waters. III. Metal concentrations in tissues. Z. Tierphysiol. Tierernaehr. Futtermittelkd. 46:273-282.

Dallinger, R. and H. Kautzky. 1985. The importance of contaminated food for the uptake of heavy metals by rainbow trout (*Salmo gairdneri*): A field study. Oecologia 67:82-89.

Dallinger, R. and W. Wieser. 1984. Molecular fractionation of Zn, Cu, Cd and Pb in the midgut gland of *Helix pomatia* L. Comp. Biochem. Physiol. 79C:125-129.

Danil'chenko, O.P. 1977. The sensitivity of fish embryos to the effect of toxicants. J. Ichthyol. (Engl. Transl. Vopr. Ikhtiol.) 17:455-463.

Danil'chenko, O.P. and N.S. Stroganov. 1975. Evaluation of toxicity to the early ontogeny of fishes of substances discharged into a body of water. J. Ichthyol. (Engl. Transl. Vopr. Ikhtiol.) 15:311-319.

Darnall, D.W., B. Green, M.T. Henzl, H. Hosea, R.A. McPherson, J. Sneddon and M.D. Alexander. 1986. Selective recovery of gold and other metal ions from an algal biomass. Environ. Sci. Technol. 20:206-208.

Davies, P.E. 1985. The toxicology and metabolism of chlorothalonil in fish. IV. Zinc coexposure and the significance of metallothionein in detoxication in *Salmo gairdneri*. Aquat. Toxicol. 7:301-306.

Davies, P.H. and J.D. Woodling. 1980. Importance of laboratory-derived metal toxicity results in predicting in-stream response of resident salmonids. In: Aquatic toxicology. Eaton, J.G., P.R. Parrish and A.C. Hendricks (Eds.). ASTM STP 707. American Society of Testing and Materials, Philadelphia, PA. pp. 281-299.

Davis, G.E. and D.S. Negilski. 1972. Independent and joint toxicity of cyanide, pentachlorophenol and zinc in model stream communities. Progress Report. Environmental Health Science Center, Oregon State University, Corvallis, OR. pp. 218-219.

Dean, J.M. 1974. The accumulation of ^{65}Zn and other radionuclides by tubificid worms. Hydrobiologia 45:33-38.

De Filippis, L.F. and C.K. Pallaghy. 1976. The effect of sub-lethal concentrations of mercury and zinc on Chlorella. III. Development and possible mechanisms of resistance to metals. Z. Pflanzenphysiol. 79:323-335.

Dilling, W.J. and C.W. Healy. 1927. Influence of lead on the metallic ions of copper, zinc, thorium, beryllium and thallium on the germination of frogs' spawn and the growth of tadpoles. Ann. Appl. Biol. 13:177-188.

Dinnel, P.A., Q.J. Slober, J.M. Link, M.W. Letourneau, W.E. Roberts, S.P. Felton and R.E. Nakatani. 1983. Methodology and validation of a sperm cell toxicity test for testing toxic substances in marine waters. FRI-UW-8306. Fisheries Research Institute, School of Fisheries, University of Washington, Seattle, WA.

Dixon, C. and K. Compher. 1977. The protective action of zinc against the deleterious effects of cadmium in the regenerating forelimb of the adult newt, Notophthalmus viridescens. Growth 41:95-103.

Dixon, W.J. and M.B. Brown (Eds.). 1979. BMDP biomedical computer programs, P-series. University of California, Berkeley, CA. p. 521.

Dorfman, D. 1977. Tolerance of Fundulus heteroclitus to different metals in saltwater. Bull. N.J. Acad. Sci. 22:21-23.

Doudoroff, P. 1956. Some experiments on the toxicity of complex cyanides to fish. Sewage Ind. Wastes 28:1020-1025.

Doudoroff, P. and M. Katz. 1953. Critical review of literature on the toxicity of industrial wastes and their components to fish. II. The metals, as salts. Sewage Ind. Wastes 25:802-839.

Doudoroff, P., G. Leduc and C.R. Schneider. 1966. Acute toxicity to fish of solutions containing complex metal cyanides in relation to concentration of molecular hydrocyanic acid. Sewage Ind. Wastes 95:6-22.

Doyle, M.J., M.P. Price and E. Frieden. 1981. Stabilization of amphibian and mammalian liver nuclei by zinc and other metal ions. Comp. Biochem. Physiol. 68C:115-120.

Drendel, G.H. 1981. The toxicity of zinc to the fathead minnow in soft, hard, and very hard waters. In: Water pollution studies. Project F-33-R, Colorado Division of Wildlife, Fish Research Station, Ft. Collins, CO.

Dugan, P.R. 1975. Bioflocculation and the accumulation of chemicals by floc-forming organisms. EPA-600/2-75-032. National Technical Information Service, Springfield, VA.

Duncan, D.A. and J.F. Klaverkamp. 1980. Induced tolerance to cadmium in white suckers (Catostomus commersoni) by exposure to sublethal concentrations of heavy metals. In: Proceedings of the sixth annual aquatic toxicity workshop. Klaverkamp, J.F., S.L. Leonard and K.E. Marshall (Eds.). Canandian Technical Report of Fisheries and Aquatic Sciences No. 975. Department of Fisheries and Oceans, Winnepeg, Manitoba, Canada. pp. 108-109.

Duncan, D.A. and J.F. Klaverkamp. 1983. Tolerance and resistance to cadmium in white suckers (Catostomus commersoni) previously exposed to cadmium, mercury, zinc or selenium. Can. J. Fish. Aquat. Sci. 40:128-138.

Dunlop, S. and G. Chapman. 1981. Detoxiciation of zinc and cadmium by the freshwater protozoan, Tetrahymena pyriformis. II. Growth experiments and ultrastructural studies on sequestration of heavy metals. Environ. Res. 24:264-274.

Duxbury, T. 1985. Ecological aspects of heavy metal responses in microorganisms. Adv. Microb. Ecol. 8:185-235.

Eaton, J.G. 1973. Chronic toxicity of a copper, cadmium and zinc mixture to the fathead minnow (Pimephales promelas Rafinesque). Water Res. 7:1723-1736.

Eddy, F.B. and J.E. Fraser. 1982. Sialic acid and mucus production in rainbow trout (Salmo gairdneri Richardson) in response to zinc and seawater. Comp. Biochem. Physiol. 73C:357-359.

Eddy, F.B. and C. Talbot. 1985. Sodium balance in eggs and dechorionated embryos of the Atlantic salmon Salmo salar L. exposed to zinc, aluminum and acid waters. Comp. Biochem. Physiol. 81C:259-266.

Eichenberger, E., F. Schlatter, H. Weilenmann and K. Wuhrmann. 1981. Toxic and eutrophicating effects of Co, Cu, and Zn on algal benthic communities in rivers. Int. Ver. Theor. Angew. Limnol. Verh. 21:1131.

EIFAC. 1977. The effect of zinc and copper pollution on the salmonid fisheries in a river and lake system in central Norway. EIFAC Technical Paper No. 29. United Nations Environmental Programme, Rome, Italy.

Eisler, R. 1967. Acute toxicity of zinc to the killifish, Fundulus heteroclitus. Chesapeake Sci. 8:262-264.

Eisler, R. 1977a. Toxicities of selected heavy metals to the soft-shell clam, Mya arenaria. Bull. Environ. Contam. Toxicol. 17:137-145.

Eisler, R. 1977b. Toxicity evaluation of a complex metal mixture to the soft-shell clam, Mya arenaria. Mar. Biol. (Berl.) 43:265-276.

Eisler, R. 1981. Trace metal concentrations in marine organisms. Pergamon Press, New York, NY.

Eisler, R. and G.R. Gardner. 1973. Acute toxicity to an estuarine teleost of mixtures of cadmium, copper and zinc salts. J. Fish Biol. 5:131-142.

Eisler, R. and R.J. Hennekey. 1977. Acute toxicities of Cd^{2+}, Cr^{6+}, Hg^{2+}, Ni^{2+}, and Zn^{2+} to estuarine macrofauna. Arch. Environ. Contam. Toxicol. 6:315-323.

Elder, J.F. and H.C. Mattraw, Jr. 1984. Accumulation of trace elements, pesticides, and polychlorinated biphenyls in sediments and the clam Corbicula manilensis of the Apalachicola River, Florida. Arch. Environ. Contam. Toxicol. 13:453-469.

Elliott, S.E., C. Burns-Flett, R.H. Hesslein, G.J. Brunskill and A. Lutz. 1981. Cesium-137, radium-226, potassium-40 and selected stable elements in fish populations from Great Slave Lake (N.W.T.), Louis Lake (Saskatchewan), Lake Winnipeg (Manitoba), and experimental lakes area (Northwestern Ontario). Data Report No. 293. Department of Fisheries and Oceans, Winnipeg, Manitoba, Canada.

Ellis, M.M. 1937. Detection and measurement of stream pollution. Bulletin No. 22. Bureau of Fisheries, U.S. Department of Commerce, Washington, DC.

Elwood, J.W., S.G. Hildebrand and J.J. Beauchamp. 1976. Contribution of gut contents to the concentration and body burden of elements in Tipula spp. from a spring fed stream. J. Fish. Res. Board Can. 33:1930-1938.

Estabrook, G.F., D.W. Burk, D.R. Inman, P.B. Kaufman, J.R. Wells, J.D. Jones and N. Ghosheh. 1985. Comparison of heavy metals in aquatic plants on Charity Island, Saginaw Bay, Lake Huron, U.S.A. with plants along the shoreline of Saginaw Bay. Amer. J. Bot. 72:209-216.

Everaarts, J.M., W.K. Osborne and E. Verhaaf. 1979. Effects of copper and zinc on some oxygen binding properties of the haemoglobin of the polychaete Arinicola marina. Neth. J. Sea Res. 13:571-580.

Evtushenko, N.Y., V.D. Romanenko and T.D. Malyzheva. 1984. Metabolic role of zinc in carp, Cyprinus carpio (Cyprinidae). J. Ichthyol. (Engl. Transl. Vopr. Ikhtiol.) 24(4):134-140.

Farmer, G.J., D. Ashfield and H.S. Samant. 1979. Effects of zinc on juvenile Atlantic salmon Salmo salar: Acute toxicity, food intake, growth and bioaccumulation. Environ. Pollut. 19:103-117.

Fayed, S.E. and H.I. Abd-El-Shafy. 1985. Accumulation of Cu, Zn, Cd, and Pb by aquatic macrophytes. Environ. Int. 11:77-87.

Fayed, S.E., H.I. Abdel-Shafy and N.M. Khalifa. 1983. Accumulation of Cu, Zn, Cd, and Pb by Scenedesmus obliquus under nongrowth conditions. Environ. Int. 9:409-414.

Feldt, W. and M. Melzer. 1978. Bioconcentration of the elements cobalt, manganese, iron, zinc and silver in fish. Arch. Fischwiss. 29:105-112.

Ferguson, J. and B. Bubela. 1974. The concentration of CU(II), Pb(II) and Zn(II) from aqueous solutions by particulate algal matter. Chem. Geol. 13:163-186.

Finlayson, B.J. and S.H. Ashuckian. 1979. Safe zinc and copper levels from the Spring Creek drainage for steelhead trout in the upper Sacramento River, California. Calif. Fish Game 65:80-99.

Finlayson, B.J. and K.M. Verrue. 1980. Estimated safe zinc and copper levels for chinook salmon, Oncorhynchus tshawytscha, in the upper Sacramento River, California. Calif. Fish Game 66:68-82.

Finlayson, B.J. and K.M. Verrue. 1982. Toxicities of copper, zinc and cadmium mixtures to juvenile chinook salmon. Trans. Am. Fish. Soc. 111:645-650.

Fisher, N.S., M. Bohe and J.L. Teussie. 1984. Accumulation and toxicity of Cd, Zn, Ag and Hg in four marine phytoplankters. Mar. Ecol. Prog. Ser. 18:201-213.

Fleming, T.P. and K.S. Richards. 1982. Uptake and surface adsorption of zinc by the freshwater tubificid oligochaete, Tubifex tubifex. Comp. Biochem. Physiol. 71C:69-75.

Fleming, T.P., M.K. Pratten and K.S. Richards. 1982. Subcellular localization of zinc in experimentally polluted Tubifex tubifex (Annelida: Oligochaeta). Comp. Biochem. Physiol. 73C:187-193.

Fletcher, G.L. and M.J. King. 1978. Copper, zinc, cadmium, magnesium and phosphate in the gonads and livers of sockeye salmon (Oncorhynchus nerka) during spawning migration. Comp. Biochem. Physiol. 60A:127-130.

Fletcher, G.L., E.G. Watts and M.J. King. 1975. Copper, zinc, and total protein levels in the plasma of sockeye salmon (Oncorhynchus nerka) during their spawning migration. J. Fish. Res. Board Can. 32:78-82.

Forstner, U. 1984. Metal pollution of terrestrial waters. In: Changing metal cycles and human health. Nriagu, J.O. (Ed.). Springer-Verlag, New York, NY. pp. 71-94.

Foster, P. 1976. Concentrations and concentration factors of heavy metals in brown algae. Environ. Pollut. 10:45-53.

Foster, P.L. 1982a. Species associations and metal contents of algae from rivers polluted by heavy metals. Freshwater Biol. 12:17-39.

Foster, P.L. 1982b. Metal resistances of Chlorophyta from rivers polluted by heavy metals. Freshwater Biol. 12:41-61.

Franzin, W.G. and G.A. McFarlane. 1980. Fallout, distribution and some effects of Zn, Cd, Pb, Cu, and As in aquatic ecosystems near a base metal smelter on Canada's precambrian shield. In: Ecological impact of acid precipitation. Drablos, D. and A. Tollan (Eds.). Sandefjord, Norway. pp. 302-303.

Frazier, J.M. 1975. The dynamics of metals in the American oyster, Crassostrea virginica. I. Seasonal effects. Chesapeake Sci. 16:162-171.

Frazier, J.M. 1976. The dynamics of metals in the American oyster, Crassostrea virginica. II. Environmental effects. Chesapeake Sci. 17:188-197.

Friant, S.L. and H. Koerner. 1981. Use of an in situ artificial substrate for biological accumulation and monitoring of aqueous trace metals. A preliminary field investigation. Water Res. 15:161-167.

Friant, S.L. and J.W. Sherman. 1980. The use of algae as biological accumulators for monitoring aquatic pollutants. Second interagency workshop on in situ water quality sensing and biological sensing. pp. 185-206.

Gale, N.L., M.G. Hardie, J.C. Jennett and A. Aleti. 1973a. Transport of trace pollutants in lead mining wastewaters. In: Trace substances in environmental health-VI. Hemphill, D.D. (Ed.). Univeristy of Missouri, Columbia, MO. pp. 95-106.

Gale, N.L., B.G. Wixson, M.G. Hardie and J.C. Jennett. 1973b. Aquatic organisms and heavy metals in Missouri's new lead belt. Water Resour. Bull. 9:673-688.

Galtsoff, P.S. and V.L. Loosanoff. 1937. Natural history and method of controlling the starfish (Asterias forbesi Desor.). Bull. Bur. Fish. 49:75-133.

Gardner, G.R. 1975. Chemically induced lesions in estuarine or marine teleosts. In: The pathobiology of fishes. Ribelin, W.E. and G. Migaki (Eds.). University of Wisconsin Press, Madison, WI. pp. 657-693.

Garton, R.B. 1972. Biological effects of cooling tower blowdown. Am. Inst. Chem. Eng. Symp. Ser. 69:284-292.

Gatlin, D.M., III and R.P. Wilson. 1983. Dietary zinc requirement of fingerling channel catfish. J. Nutr. 113:630-635.

Gatlin, D.M., III and R.P. Wilson. 1984. Zinc supplementation of practical channel catfish diets. Aquaculture 41:31-36.

George, S.G. 1983. Heavy metal detoxication in Mytilus kidney - an in vitro study of Cd- and Zn-binding to isolated tertiary lysosomes. Comp. Biochem. Physiol. 76C:59-65.

Giesy, J.P., Jr. and J.G. Wiener. 1977. Frequency distributions of trace metal concentrations in five freshwater fishes. Trans. Am. Fish. Soc. 106:393-403.

Giesy, J.P., J.W. Bowling and H.J. Kania. 1980. Cadmium and zinc accumulation and elimination by freshwater crayfish. Arch. Environ. Contam. Toxicol. 9:683-697.

Goettl, J.P., J.R. Sinley and P.H. Davies. 1974. Water pollution studies. In: Colorado fisheries research review. Review No. 9. Colorado Division of Wildlife, Fort Collins, CO. pp. 36-44.

Goettl, J.P., P.H. Davies and J.R. Sinley. 1976. Water pollution studies. In: Colorado fisheries research review 1972-1975. Cope, O.B. (Ed.). Review No. 8. Colorado Division of Wildlife, Fort Collins, CO. pp. 68-75.

Goodman, J.R. 1951. Toxicity of zinc for rainbow trout (Salmo gairdneri). Calif. Fish Game 37:191-194.

Graham, G.A., G. Byron and R.H. Norris. 1986. Survival of Salmo gairdneri (rainbow trout) in the zinc polluted Molonglo River near Captains Flat, New South Wales, Australia. Bull. Environ. Contam. Toxicol. 36:186-191.

Grande, M. 1966. Effect of copper and zinc on salmonid fishes. Adv. Water Pollut. Res. 1:97-111.

Graney, R.L., Jr., D.S. Cherry and J. Cairns, Jr. 1983. Heavy metal indicator potential of the Asiatic clam, (Carbicula fluminea) in artificial stream systems. Hydrobiologia 102:81-88.

Gray, J.S. 1974. Synergistic effects of three heavy metals on growth rates of a marine ciliate protozoan. In: Pollution and physiology of marine organisms. Vernberg, F.J. and W.B. Vernberg (Eds.). Academic Press, New York, NY. pp. 465-485.

Gray, J.S. and R.J. Ventilla. 1973. Growth rates of sediment-living marine protozoan as a toxicity indicator for heavy metals. Ambio 2:118-121.

Greene, J.C., W.E. Miller, T. Shiroyama and E. Merwin. 1975. Toxicity of zinc to the green alga Selenastrum capricornutum as a function of phosphorus or ionic strength. EPA-660/3-75-034. National Technical Information Service, Springfield, VA.

Greenwood, J.G. and D.R. Fielder. 1983. Acute toxicity of zinc and cadmium to zoeae of three species of portunid crabs (Crustacea: Brachyura). Comp. Biochem. Physiol 75C:141-144.

Greichus, Y.A., A. Greichus, H.A. Draayer and B. Marshall. 1978. Insecticides, polychlorinated biphenyls and metals in African lake ecosystems. II. Lake McIiwaine, Rhodesia. Bull. Environ. Contam. Toxicol. 19:444-453.

Grushko, Y.M., O.M. Kozhova and L.M. Mamontova. 1986. Accumulation of toxic substances by hydrobionts after sewage water discharge. Hydrobiol. J. 16(3):80-83.

Guilizzoni, P. 1980. Heavy metals distribution and their effects on photosynthetic rates of two submersed macrophytes of Lake Mezzola (N. Italy). In: Environment and quality of life. Second Environmental Research Programme 1976-1980. Commission of the European Communities. pp. 34-38.

Guth, D.J., H.D. Blankespoor and J. Cairns, Jr. 1977. Potentiation of zinc stress caused by parasitic infection of snails. Hydrobiologia 55:225-229.

Guthrie, R.K., F.L. Singleton and D.S. Cherry. 1977. Aquatic bacterial populations and heavy metals - II. Influence of chemical content of aquatic environments on bacterial uptake of chemical elements. Water Res. 11:643-646.

Haider, G. 1979. Histopathological effects of sublethal poisoning by heavy metals upon the lateral line system in rainbow trout (Salmo gairdneri Rich.). Zool. Anz. 203:378-394.

Haider, G. and W. Wunder. 1983. Experiments with young spawners of rainbow trout (Salmo gairdneri Rich.) to evaluate vertebral and muscular damage after long-time exposure to heavy metals (zinc). Zool. Anz. 210:296-314.

Hakanson, L. 1984. Metals in fish and sediments from the River Kolbacksan water system, Sweden. Arch. Hydrobiol. 101:373-400.

Hale, J.G. 1977. Toxicity of metal mining wastes. Bull. Environ. Contam. Toxicol. 17:66-73.

Hansen, D.J. 1983. U.S. EPA, Gulf Breeze, FL. (Memorandum to W.A. Brungs, U.S. EPA, Narragansett, RI.)

Harding, J.P.C. and B.A. Whitton. 1978. Zinc, cadmium and lead in water sediments and submerged plants of the Derwent Reservoir, Northern England. Water Res. 12:307-316.

Harding, J.P., P.J. Say and B.A. Whitton. 1981. River Etherow: Plants and animals of a river recovering form pollution. Naturalist 106:15-31.

Hardy, J.K. and N.B. Raber. 1985. Zinc uptake by the water hyacinth: Effects of solution factors. Chemosphere 14:1155-1166.

Haritonides, S., H.J. Jager and H.O. Schwantes. 1983. Accumulation of cadmium, zinc, copper and lead by marine macrophyceae under culture conditions. Angew. Bot. 57:311-330.

Harney, P.J. 1974. Loss of zinc-65 and manganese-54 from the freshwater mollusc Anodonta. Nucl. Sci. Abst. 30:21126.

Harrison, F.L. 1969. Accumulation and distribution of ^{54}Mn and ^{65}Zn in freshwater clams. Nucl. Sci. Abst. 23:17895.

Hartmann, L. 1980. Synergistic effects of heavy metal ions on the activity of bacteria and other aquatic microorganisms. In: Environmental and quality of life. Second Environmental Research Programme 1976-1980. Commission of the European Communities, pp. 16-20.

Havas, M. and T.C. Hutchinson. 1982. Aquatic invertebrates from the Smoking Hills, N.W.T.: Effect of pH and metals on mortality. Can. J. Fish. Aquat. Sci. 39:890-903.

Haya, K., B.A. Waiwood and D.W. Johnston. 1983. Adenylate energy charge and ATPase activity of lobster (Homarus americanus) during sublethal exposure to zinc. Aquat. Toxicol. 3:115-126.

Hedtke, J.L. and L.J. Weber. 1975. Weight-dependent quantal responses of salmonid fishes to heavy metals. Effects of age. Pharmacologist 17:212.

Hedtke, J.L., E.F. Robinson-Wilson and L.J. Weber. 1976. Changing sensitivity of salmon to several environmental toxicants with size and stage of development. Pharmacologist 18:247.

Hedtke, S.F. and F.A. Puglisi. 1980. Effects of waste oil on the survival and reproduction of the American flagfish, Jordanella floridae. Can. J. Fish. Aquat. Sci. 37:757-764.

Heit, M. and C.S. Klusek. 1985. Trace element concentrations in the dorsal muscle of white suckers and brown bullheads from two acidic Adirondack lakes. Water Air Soil Pollut. 25:87-96.

Helz, G.R., R.J. Huggett and J.M. Hill. 1975. Behavior of Mn, Fe, Cu, Zn, Cd, and Pb discharged from a wastewater treatment plant into an estuarine environment. Water Res. 9:631-636.

Hem, J.D. 1972. Chemistry and occurrence of cadmium and zinc in surface water and groundwater. Water Resour. Res. 8:661-679.

Hendricks, A.C. 1978. Response of Selenastrum capricornutum to zinc sulfides. J. Water Pollut. Control Fed. 50:163-168.

Henry, M.G. and G.J. Atchison. 1979a. Behavioral changes in bluegill (Lepomis macrochirus) as indicators of sublethal effects of metals. Environ. Biol. Fish. 4:37-42.

Henry, M.G. and G.J. Atchison. 1979b. Influence of social rank on the behaviour of bluegill, Lepomis macrochirus Rafinesque exposed to sublethal concentrations of cadmium and zinc. J. Fish Biol. 15:309-315.

Herbert, D.W.M. and D.S. Shurben. 1964. The toxicity to fish of mixtures of poisons. I. Salts of ammonia and zinc. Ann. Appl. Biol. 53:33-41.

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. 53:415-421.

Herbert, D.W.M. and A.C. Wakeford. 1964. The susceptibility of salmonid fish to poisons under estuarine conditions. I. Zinc sulphate. Int. J. Air Water Pollut. 8:251-256.

Hibiya, T. and M. Oguri. 1961. Gill absorption and tissue distribution of some radionuclides (Cr-51, Hg-203, Zn-65 and Ag-110m. 110) in fish. Bull. Jpn. Soc. Sci. Fish. 27:996-1000.

Hiller, J.M. and A. Perlmutter. 1971. Effect of zinc on viral-host interactions in a rainbow trout cell line, RTG-2. Water Res. 5:703-710.

Hiltibran, R.C. 1971. Effects of cadmium, zinc, manganese, and calcium on oxygen and phosphate metabolism of bluegill liver mitochondria. J. Water Pollut. Control Fed. 43:818-823.

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. 17:409-414.

Hodson, P.V. 1976. Temperature effects on lactate-glycogen metabolism in zinc intoxicated rainbow trout (Salmo gairdneri). J. Fish. Res. Board Can. 33:1393-1397.

Holcombe, G.W. and R.W. Andrew. 1978. The acute toxicity of zinc to rainbow and brook trout. Comparison in hard and soft water. EPA-600/3-78-094. National Technical Information Service, Springfield, VA.

Holcombe, G.W., D.A. Benoit and E.N. Leonard. 1979. Long-term effects of zinc exposures on brook trout (Salvelinus fontinalis). Trans. Am. Fish. Soc. 108:76-87.

Holm, J. 1980. Lead, cadmium, arsenic, and zinc contents in fish from uncontaminated and contaminated inland waters. Sonderdruck aus Fleischwirtschaft 5:1076-1083.

Hopkins, R. and J.M. Kain (Jones). 1971. The effect of marine pollutants on Laminaria hyperboria. Mar. Pollut. Bull. 2:75-77.

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. (Berl.) 78:87-97.

Howell, R. 1985. Effects of zinc on cadmium toxicity to the amphipod Gammarus pulex. Hydrobiologia 123:245-249.

Huang, C.P., H.A. Elliot and R.M. Ashmead. 1977. Interfacial reaction and the fate of heavy metals in soil water systems. J. Water Pollut. Control Fed. 49:745-756.

Hublou, W.F., J.W. Wood and E.R. Jeffries. 1954. The toxicity of zinc or cadmium for chinook salmon. Fish Commission Oregon Research Briefs 5:1-7.

Huggett, R.J., M.E. Bender and H.D. Slone. 1973. Utilizing metal concentration relationships in the eastern oyster (Crassostrea virginica) to detect heavy metal pollution. Water Res. 7:451-460.

Hughes, G.M. 1975. Coughing in the rainbow trout (Salmo gairdneri) and the influence of pollutants. Rev. Suisse Zool. 82:47-64.

Hughes, G.M. and R.J. Adeney. 1977. The effects of zinc on the cardiac and ventilatory rhythms of rainbow trout (Salmo gairdneri Richardson) and their responses to environmental hypoxia. Water Res. 11:1069-1077.

Hughes, G.M. and R. Flos. 1978. Zinc content of the gills of rainbow trout (S. gairdneri) after treatment with zinc solutions under normoxic and hypoxic conditions. J. Fish Biol. 13:717-728.

Hughes, G.M. and L. Tort. 1985. Cardio-respiratory responses of rainbow trout during recovery from zinc treatment. Environ. Pollut. (Series A) 37:255-266.

Hughes, G.M., S.F. Perry and V.M. Brown. 1979. A morphometric study of effects of nickel, chromium and cadmium on the secondary lamellae of rainbow trout gills. Water Res. 13:665-679.

Hughes, J.S. 1968. Toxicity of some chemicals to striped bass (Roccus saxatilis). Proc. Annu. Conf. Southeast. Assoc. Game Fish Comm. 22:230-234.

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, UT. July.

Hughes, R.M. 1985. Use of watershed characteristics to select control streams for estimating effects of metal mining wastes on extensively disturbed streams. Environ. Manage. 9:253-262.

Hutchinson, N.J. and J.B. Sprague. 1983. Chronic toxicity of a mixture of 7 metals to flagfish in soft acid water. In: Proceedings of the eighth annual aquatic toxicity workshop. Kaushik, N.K. and K.R. Solomon (Eds.). Canadian Technical Report of Fisheries and Aquatic Sciences No. 1151. Department of Fisheries and Oceans, Ottawa, Ontario, Canada. p. 191.

Hutchinson, N.J. and J.B. Sprague. 1985. Trace metal toxicity to fish in acid waters: Modification by organic acids and alkalization. In: Proceedings of the tenth annual aquatic toxicity workshop. Wells, P.G. and R.F. Addison (Eds). Canadian Technical Report of Fisheries and Aquatic Sciences No. 1368. Fisheries and Oceans, Ottawa, Ontario, Canada. pp. 225-226.

Hutchinson, T.C. and H. Czyrska. 1972. Cadmium and zinc toxicity and synergism to floating aquatic plants. In: Water pollution research in Canada 1972. Proc. 7th Canadian Symp. Water Pollut. Res., Inst. Environ. Sci. Eng. Publ. No. EI-3. pp. 59-65.

Ishizaka, O., Y. Iko and S. Yamamoto. 1966. Determination of the toxicity of food additives by their effects on the life cycle of Chlorella. I. Cultures and method. Nagoya Shiritsu Daigaku Yakugukuba Kenkyu Nenpo 14:66-78; Chem. Abstr. 1968. 68:20600. Abstr. No. 20598.

Jackim, E. 1973. Influence of lead and other metals on fish d-aminolevulinate dehydrase activity. J. Fish. Res. Board Can. 30:560-562.

Jaroensastraraks, J. and E. McLaughlin. 1974. The effects of different metallic compounds on the embryonic development of the freshwater snail, Helisoma. J. Ala. Acad. Sci. 45:231.

Jay, F.B. and R.J. Muncy. 1979. Toxicity to channel catfish of wastewater from an Iowa coal benefication plant. Iowa State J. Res. 54:45-50.

Jeng, S.S. and H.W. Lo. 1974. High zinc concentration in common carp viscera. Bull. Jpn. Soc. Sci. Fish. 40:509.

Jeng, S.S. and L.T. Sun. 1981. Effects of dietary zinc levels on zinc concentrations in tissues of common carp. J. Nutr. 111:134-140.

Jennett, J.C., B.G. Wixson and R.L. Kramer. 1981. Some effects of century old abandoned lead mining operations on streams in Missouri, USA. Miner. Environ. 3:17-20.

Jennett, J.C., J.E. Smith and J.M. Hassett. 1982. Factors influencing metal accumulation by algae. EPA-600/2-82-100. National Technical Information Service, Springfield, VA.

Jensen, A., B. Rystad and S. Melsom. 1974. Heavy metal tolerance of marine phytoplankton. I. The tolerance of three algal species to zinc in coastal sea water. J. Exp. Mar. Biol. Ecol. 15:145-157.

Jiang, L. and B. Pan. 1982. Avoidance reaction of fishes to some heavy metals and pesticides. Huanjing Kexue 3:1-7; CA Selects: Environ. Pollut. 1983. 98:84526K.

Johannesson, T., G. Lunde and E. Steinnes. 1981. Mercury, arsenic, cadmium, selenium and zinc in human hair and salmon fries in Iceland. Acta Pharmacol. Toxicol. 48:185-189.

Johnson, G.D., A.W. McIntosh and G. Atchison. 1978. The use of periphyton as a monitor of trace metals in two contaminated Indiana lakes. Bull. Environ. Contam. Toxicol. 19:733-740.

Johnson, M. 1985. Acute toxicity data for zinc and larvae of the American lobster, Homarus americanus. (Memorandum to D.J. Hansen, U.S. EPA, Narragansett, RI.)

Jones, A.R., M. Taylor and K. Simkiss. 1984. Regulation of calcium, cobalt and zinc by Tetrahymena elliotti. Comp. Biochem. Physiol. 78A:493-500.

Jones, J.R.E. 1935. The toxic action of heavy metal salts on the three-spined stickleback (Gastrosteus oculeatus). J. Exp. Biol. 12:165-173.

Jones, J.R.E. 1938. The relative toxicity of salts of lead, zinc and copper to the stickleback (Gasterosteus aculeatus L.) and the effect of calcium on the toxicity of lead and zinc salts. J. Exp. Biol. 15:394-407.

Jones, J.R.E. 1939. The relation between the electrolytic solution pressures of the metals and their toxicity to the stickleback (Gasterosteus aculeatus L.). J. Exp. Biol. 16:425-437.

Jones, K.C., P.J. Peterson and B.E. Davies. 1985. Silver and other metals in some aquatic bryophytes from streams in the lead mining district of mid-Wales, Great Britain. Water Air Soil Pollut. 24:329-338.

Jones, M.B. 1975. Synergistic effects of salinity, temperature and heavy metals on mortality and osmoregulation in marine and estuarine isopods (Crustacea). Mar. Biol. (Berl.) 30:13-20.

Jones, W.G. and K.F. Walker. 1979. Accumulation of iron, manganese, zinc and cadmium by the Australian freshwater mussel Velesunio ambiguus (Phillipi) and its potential as a biological monitor. Aust. J. Mar. Freshwater Res. 30:741-751.

Joyner, T. 1961. Exchange of zinc with environmental solutions by the brown bullhead. Trans. Am. Fish. Soc. 90:444-448.

Joyner, T. and R. Eisler. 1961. Retention and translocation of radioactive zinc by salmon fingerlings. Growth 25:151-156.

Judy, R.D., Jr. and P.H. Davies. 1979. Effects of calcium addition as $Ca(NO_3)_2$ on zinc toxicity to fathead minnows, Pimephales promelas Rafinesque. Bull. Environ. Contam. Toxicol. 22:88-94.

Kaiser, K.L.E. 1980. Correlation and prediction of metal toxicity to aquatic biota. Can. J. Fish. Aquat. Sci. 37:211-218.

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. 10:517-522.

Karbe, L., N. Antonacopoulos and C. Schnier. 1975. The influence of water quality on accumulation of heavy metals in aquatic organisms. Int. Ver. Theor. Angew. Limnol. Verh. 19:2094-2101.

Kawamata, S., Y. Yamaura, H. Hayashi and S. Komiyama. 1982. Contents of heavy metals in fishes in Nagano prefecture. Nagano-ken Eisei Kogai Kenkyusho Kenkyu Hokoku 5:30-32; CA Selects: Environ. Pollut. 1983. Issue 7:4. Abstr. No. 98:105850.

Kayser, H. 1977. Effects of zinc sulfate on the growth of mono- and multi-species cultures of some marine plankton algae. Helgol. Wiss. Meeresunters. 30:682-696.

Kearns, P.K. and G.J. Atchison. 1979. Effects of trace metals on growth of yellow perch (*Perca flavescens*) as measured by RNA-DNA ratios. Environ. Biol. Fishes 4:383-387.

Keeney, W.L., W.G. Breck, G.W. Vanloon and J.A. Page. 1976. The determination of trace metals in *Cladophora glomerata* - *C. glomerata* as a potential biological indicator. Water Res. 10:981-984.

Ketola, H.G. 1979. Influence of dietary zinc on cataracts in rainbow trout (*Salmo gairdneri*). J. Nutr. 109:965-969.

Khangarot, B.S. 1981a. Lethal effects of zinc and nickel on freshwater teleosts. Acta Hydrochim. Hydrobiol. 9:297-302.

Khangarot, B.S. 1981b. Effect of zinc, copper and mercury on *Channa marulius* (Hamilton). Acta Hydrochim. Hydrobiol. 9:639-649.

Khangarot, B.S. 1982. The effects of time intervals before feeding since the tolerance of common guppy (*Lebistes reticulatus* Peters) to zinc. Acta Hydrochim. Hydrobiol. 10:405-408.

Khangarot, B.S. 1984. Effect of zinc on acid phosphatase activity in the gills of *Channa punctatus* (Bloch). Acta Hydrochim. Hydrobiol. 12:103-105.

Khangarot, B.S., V.S. Durve and V.K. Rajbanshi. 1981. Toxicity of interactions of zinc-nickel, copper-nickel and zinc-nickel-copper to a freshwater teleost, *Lebistes reticulatus* (Peters). Acta Hydrochim. Hydrobiol. 9:495-503.

Khangarot, B.S., S. Mathur and V.S. Durve. 1982. Comparative toxicity of heavy metals and interaction of metals on a freshwater pulmonate snail *Lymnaea acuminata* (Lamarck). Acta Hydrochim. Hydrobiol. 10:367-375.

Khangarot, B.S., A. Sehgal and M.K. Bhasin. 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. 11:667-673.

Khangarot, B.S., A. Sehgal and M.K. Bhasin. 1984. "Man and biosphere"-studies on Sikkim Himalayas. Part 2: Acute toxicity of mixed copper-zinc solutions on common carp, *Cyprinus carpio* (Linn.). Acta Hydrochim. Hydrobiol. 12:131-135.

Khangarot, B.S., A. Sehgal and M.K. Bhasin. 1985. "Man and biosphere" - Studies on the Sikkim Himalayas. Part 5. Acute toxicity of selected heavy metals on the tadpoles of *Rana hexadactyla*. Acta Hydrochim. Hydrobiol. 13:259-263.

Kito, H., T. Tawawa, Y. Ose, T. Sato and T. Ishikawa. 1982. Formation of metallothionein in fish. Comp. Biochem. Physiol. 73C:129-134.

Klaverkamp, J.F., M.A. Turner, S.E. Harrison and R.H. Hesslein. 1983. Fates of metal radiotracers added to a whole lake; Accumulation in slimy sculpin (Cottus cognatus) and white sucker (Catostomus commersoni). Sci. Total Environ. 28:119-128.

Klaverkamp, J.F., W.A. MacDonald, L.J. Wesson and A. Lutz. 1985. Metallothionein and resistance to cadmium toxicity in white suckers (Catostomus commersoni) impacted by atmospheric emissions for a base-metal smelter. In: Proceedings of the tenth annual aquatic toxicity workshop. Wells, P.G. and R.F. Addison (Eds.). Canadian Technical Report of Fisheries and Aquatic Sciences No. 1368. Fisheries and Oceans, Ottawa, Ontario, Canada. pp. 163-164.

Kleinert, S.J., P.E. Degurse and J. Ruhland. 1974. Concentration of metals in fish. Technical Bulletin No. 74. Wisconsin Department of Natural Resources, Madison, WI.

Knittel, M.D. 1980. Heavy metal stress and increased susceptibility of steelhead trout (Salmo gairdneri) to Yersinia ruckeri infection. In: Aquatic toxicology. Eaton, J.G., P.R. Parrish and A.C. Hendricks (Eds.). ASTM STP 707. American Society for Testing and Materials, Philadelphia, PA. pp. 321-327.

Knox, D., C.B. Cowey and J.W. Adron. 1982. Effects of dietary copper and copper zinc ratio on rainbow trout, Salmo gairdneri. Aquaculture 27:111-119.

Knox, D., C.B. Cowey and J.W. Adron. 1984. Effects of dietary zinc intake upon copper metabolism in rainbow trout (Salmo gairdneri). Aquaculture 40:199-207.

Kodama, M., T. Ogata and K. Yamamori. 1982a. Hemolysis of erythrocytes of rainbow trout Salmo gairdneri exposed to zinc polluted water. Bull. Jpn. Soc. Sci. Fish. 48:593.

Kodama, M., T. Ogata and K. Yamamori. 1982b. Acute toxicity of zinc to rainbow trout Salmo gairdneri. Bull. Jpn. Soc. Sci. Fish. 48:1055-1058.

Kojima, Y. and J.H.R. Kagi. 1978. Metallothionein. Trends Biochem. Sci. 3:90-93.

Koli, A.K., S.S. Sandhu, W.T. Canty, K.L. Felix, R.J. Reed and R. Whitmore. 1978. Trace metals in some fish species of South Carolina. Bull. Environ. Contam. Toxicol. 20:328-331.

Korda, R.J., Y.E. Henzler, P.A. Helmke, M.M. Jimenez, L.A. Haskin and E.M. Larsen. 1977. Trace elements in samples of fish, sediment and taconite from Lake Superior. J. Great Lakes Res. 3:148-154.

Kormondy, E.J. 1965. Uptake and loss of zinc-65 in the dragonfly Plathemis lydia. Limnol. Oceanogr. 109:427-433.

Krantzberg, G. 1983. The role of the benthos in Cu and Zn dynamics in freshwater microcosms. In: Heavy metals in the environment. Vol. 2. CEP Consultants, Ltd., Edinburgh, U.K. pp. 806-809.

Krantzberg, G. and P.M. Stokes. 1985. Benthic macroinvertebrates modify copper and zinc partitioning in freshwater - sediment microcosms. Can. J. Fish. Aquat. Sci. 42:1465-1473.

Kumar, S. and S.C. Pant. 1984. Comparative effects of the sublethal poisoning of zinc, copper and lead on the gonads of the teleost Puntius conchonius Ham. Toxicol. Lett. 23:189-194.

Kuwabara, J.S. 1985. Phosphorus-zinc interactive effects on growth by Selenastrum capricornutum (Chlorophyta). Environ. Sci. Technol. 19:417-421.

Labat, R., C. Roqueplo, J. Ricard, P. Lim and M. Burgat. 1977. The ecotoxicological action of some metals (Cu, Zn, Pb, Cd) on freshwater fish in the river lot. Ann. Limnol. 13:191-207.

Lalande, M. and B. Pinel-Alloul. 1986. Acute toxicity of cadmium, copper, mercury and zinc to Tropocyclops prasinus mexicanus (Cyclopoida, Copepoda) from three Quebec lakes. Environ. Toxicol. Chem. 5:95-102.

Lang, C. and B. Lang-Dobler. 1979. The chemical environment of tubificid and lumbriculid worms according to the pollution level of the sediment. Hydrobiologia 65:273-282.

Laskowski-Hoke, R.A. and B.L. Prater. 1984. Multivariate statistical analyses of 96-hour sediment bioassay and chemistry data. Bull. Environ. Contam. Toxicol. 33:400-409.

Lauhachinda, N. and W.H. Mason. 1979. ^{65}Zn excretion as an indirect measurement of Q_{10} in the isopod, Armadillidium vulgare (Latreille). J. Ala. Acad. Sci. 50:27-34.

LeBlanc, G.A. 1982. Laboratory investigation into the development of resistance of Daphnia magna (Straus) to environmental pollutants. Environ. Pollut. (Series A) 27:309-322.

LeBlanc, G.A. 1984. Interspecies relationships in acute toxicity of chemicals to aquatic organisms. Environ. Toxicol. Chem. 3:47-60.

Lee, J., I.R. Jonasson and W.D. Goodfellow. 1984. Metal accumulation by bryophytes in some zinc-rich blanket bogs, Selwyn mountains, Yukon Territory. Can. J. Bot. 62:722-728.

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. 2:353-368.

Leland, H.V. and J.S. Kuwabara. 1985. Heavy metals. In: Fundamentals of aquatic toxicology. Rand, G.M. and S.R. Petrocelli (Eds.). Hemisphere Publishing Corp., Washington, DC. pp. 374-415.

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. 23:129-139.

Lewis, M. 1978. Acute toxicity of copper, zinc and manganese in single and mixed salt solutions to juvenile longfin dace, Agosia chrysogaster. J. Fish Biol. 13:695-700.

Lewis, M.A. 1980. Selected heavy metals in sediments and biota from desert streams of the Gila River drainage (Arizona). In: Aquatic toxicology. Eaton, J.G., P.R. Parrish and A.C. Hendricks (Eds.). ASTM STP 707. American Society for Testing and Materials. Philadelphia, PA. pp. 191-204.

Lewis, M.A. 1986. Impact of a municipal wastewater effluent on water quality, periphyton, and invertebrates in the Little Miami River near Xenia, Ohio. Ohio J. Sci. 86:2-8.

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, *Notemigonus crysoleucas* Mitchill. Trans. Am. Fish. Soc. 4:639-643.

Lewis, T. and A. McIntosh. 1984. Accumulation of the trace elements lead and zinc by *Asellus communis* at three different pH levels. PB84202514. National Technical Information Service, Springfield, VA.

Lewis, T.E. and A.W. McIntosh. 1986. Uptake of sediment-bound lead and zinc by the freshwater isopod *Asellus communis* at three different pH levels. Arch. Environ. Contam. Toxicol. 15:495-504.

Ley, H.L., III, M.L. Failla and D.S. Cherry. 1983. Isolation and characterization of hepatic metallothionein from rainbow trout (*Salmo gairdneri*). Comp. Biochem. Physiol. 74B:507-513.

Lim, B.H. 1972. Hazards of zinc in the environment with particular reference to the aquatic environment. (Available from C.E. Stephan, U.S. EPA, Duluth, MN.)

Lloyd, R. 1960. The toxicity of zinc sulphate to rainbow trout. Ann. Appl. Biol. 48:84-94.

Lloyd, R. 1961a. Effect of dissolved oxygen concentrations on the toxicity of several poisons to rainbow trout (*Salmo gairdneri* Richardson). J. Exp. Biol. 38:447-455.

Lloyd, R. 1961b. The toxicity of mixtures of zinc and copper sulphates to rainbow trout (*Salmo gairdneri* Richardson). Ann. Appl. Biol. 49:535-538.

Lloyd, R. 1965. Factors that affect the tolerance of fish to heavy metal poisoning. In: Biological problems in water pollution. Third seminar. Tarzwell, C.M. (Ed.). U.S. Department of Health, Education and Welfare, Division of Water Supply and Pollution Control. Cincinnati, OH. pp. 181-187.

Lobel, P.B. and D.A. Wright. 1983. Frequency distribution of zinc concentrations in the common mussel, *Mytilus edulis* (L.). Estuaries 6:154-159.

Lomte, V.S. and M.L. Jadahav. 1982. Effects of toxic compounds on oxygen consumption in the fresh water bivalve, *Corbicula regularis*. (Prime, 1960). Comp. Physiol. Ecol. 7:31-33.

Lord, D.A., J.W. McLaren and R.C. Wheeler. 1977. Determination of trace metals in fresh water mussels by atomic absorption spectrometry with direct solid sample injection. Anal. Chem. 49:257-261.

Lorz, H.W. and B.P. McPherson. 1976. Effects of copper or zinc in fresh water and the adaptation to sea water and ATPase activity, and the effects of copper on migratory disposition of coho salmon (*Oncorhynchus kisutch*). J. Fish. Res. Board Can. 33:2023-2030.

Lorz, H.W. and B.P. McPherson. 1977. Effects of copper and zinc on smoltification of coho salmon. EPA-600/3-77-032. National Technical Information Service, Springfield, VA.

Lovegrove, S.M. and B. Eddy. 1982. Uptake and accumulation of zinc in juvenile rainbow trout, *Salmo gairdneri*. Environ. Biol. Fishes 7:285-289.

Lowe, T.P., T.W. May, W.G. Brumbaugh and D.A. Kane. 1985. National contaminant biomonitoring program: Concentrations of seven elements in freshwater fish, 1978-1981. Arch. Environ. Contam. Toxicol. 14:363-388.

Lu, J.C.S. and K.Y. Chen. 1977. Migration of trace metals in interfaces of seawater and polluted surficial sediments. Environ. Sci. Technol. 11:174-182.

Lu, P., R.L. Metcalf, R. Furman, R. Vogel and J. Hassett. 1975. Model ecosystem studies of lead and cadmium and of urban sewage sludge containing these elements. J. Environ. Qual. 4:505-509.

Lubinski, K.S. and R.E. Sparks. 1981. Use of bluegill toxicity indexes in Illinois. In: Aquatic toxicology and hazard assessment: Fourth conference. Branson, D.R. and K.L. Dickson (Eds.). ASTM STP 737. American Society for Testing and Materials, Philadelphia, PA. pp. 324-337.

Lucas, H.F., Jr. and D.N. Edgington. 1970. Concentrations of trace elements in Great Lakes fishes. J. Fish. Res. Board Can. 27:677-684.

Lundholm, C.E. and L. Anderson. 1985. Biosphere levels of cadmium, zinc and copper around an old Swedish copper mine. Ambio 14:167-172.

Luoma, S.N. and G.W. Bryan. 1979. Trace metal bioavailability: Modeling chemical and biological interactions of sediment-bound zinc. In: Chemical modeling in aqueous systems. Speciation, sorption, solubility and kinetics. Jenne, E.A. (Ed.). ACS Symposium Series 93. American Chemical Society, Washington, DC. pp. 579-609.

Luoma, S.N. and G.W. Bryan. 1981. A statistical assessment of the form of trace metals in oxidized estuarine sediments employing chemical extractants. Sci. Total Environ. 17:165-196.

Luoma, S.N. and E.A. Jenne. 1977. The availability of sediment-bound cobalt, silver, and zinc to a deposit-feeding clam. In: Biological implications of metals in the environment. Drucker, H. and R.E. Wildung (Eds.). ERDA Symposium Series 42. CONF-750929. National Technical Information Service, Springfield, VA. pp. 213-230.

Lussier, S. and J. Cardin. 1985. Results of acute toxicity tests conducted with zinc at ERL-Narragansett. (Memorandum to D.J. Hansen, U.S. EPA, Narragansett, RI.)

Lussier, S. and J.H. Gentile. 1985. Acute toxicity data for zinc and the mysids, Mysidopsis bahia and Mysidopsis bigelowi. (Memorandum to D.J. Hansen, U.S. EPA, Narragansett, RI.)

Lussier, S.M., J.H. Gentile and J. Walker. 1985. Acute and chronic effects of heavy metals and cyanide on Mysidopsis bahia (Crustacea: Mysidacea). Aquat. Toxicol. 7:25-35.

Lyngby, J.E., H. Brix and H.H. Schierup. 1982. Absorption and translocation of zinc in eelgrass (Zostera marina L.). J. Exp. Mar. Biol. Ecol. 58:259-270.

Lyon, R., M. Taylor and K. Simkiss. 1983. Metal-binding proteins in the hepatopancreas of the crayfish, (Austropotamobius pallipes). Comp. Biochem. Physiol. 74C:51-54.

Lyon, R., M. Taylor and K. Simkiss. 1984. Ligand activity in the clearance of metals from the blood of the crayfish (Austropotamobius pallipes). J. Exp. Biol. 113:19-27.

Maas, R.P. 1978. A field study of the relationship between heavy metal concentrations in stream water and selected benthic macroinvertebrate species. PB297284. National Technical Information Service, Springfield, VA.

MacDonald, C.R., T.R. Jack and J.E. Zajic. 1980. Metal ion toxicity to Daphnia magna: A novel approach to data plotting. In: Proceedings of the sixth annual aquatic toxicity workshop. Klaverkamp. J.F., S.L. Leonard and K.E. Marshall (Eds.). Canadian Technical Report of Fisheries and Aquatic

Sciences No. 975. Department of Fisheries and Oceans, Winnipeg, Manitoba, Canada. pp. 91-107.

Macek, K.J. and B.H. Sleight. 1977. Utility of toxicity tests with embryos and fry of fish in evaluating hazards associated with chronic toxicity of chemicals to fishes. In: Aquatic toxicology and hazard evaluation. Mayer, F.L. and J.L. Hamelink (Eds.). ASTM STP 634. American Society for Testing and Materials, Philadelphia, PA. pp. 137-146.

MacInnes, J.R. and A. Calabrese. 1978. Response of embryos of the American oyster, *Crassostrea virginica* to heavy metals at different temperatures. In: Physiology and behavior of marine organisms. McLusky, D.S. and A.J. Berry (Eds.). Pergamon Press, New York, NY. 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. 4:185-187.

Malueg, K.W., G.S. Schuytema, J.H. Gakstatter and D.F. Krawczyk. 1984. Toxicity of sediments from three metal-contaminated areas. Environ. Toxicol. Chem. 3:279-291.

Mancini, J.L. 1983. A method for calculating effects, on aquatic organisms, of time varying concentrations. Water Res. 17:1355-1362.

Manley, A.R., L.O. Gruffydd and P.C. Almada-Villela. 1984. The effect of copper and zinc on the shell growth of *Mytilus edulis* measured by a laser diffraction technique. J. Mar. Biol. Assoc. U.K. 64:417-427.

Mansouri-Aliobadi, M. and R.E. Sharp. 1985. Passage of selected heavy metals from *Sphaerotilus* (Bacteria: Chlamydobacteriales) to *Paramecium caudatum* (Protozoa: Ciliata). Water Res. 19:697-699.

Marafante, E. 1976. Binding of mercury and zinc to cadmium-binding protein in liver and kidney of goldfish (*Carassius auratus* L.). Experientia 32:149-150.

Markarian, R.K., M.C. Matthews and L.T. Connor. 1980. Toxicity of nickel, copper, zinc and aluminum mixtures to the white sucker (*Catostomus commersoni*). Bull. Environ. Contam. Toxicol. 25:790-796.

Marking, L.L. and T.D. Bills. 1985. Effects of contaminants on toxicity of the lampricides TFM and Bayer 73 to three species of fish. J. Great Lakes Res. 11:171-178.

Marshall, J.S., D.L. Mellinger, and J.I. Parker. 1981. Combined effects of cadmium and zinc on a Lake Michigan zooplankton community. Int. Assoc. Great Lakes Res. 7:215-223.

Marshall, J.S., J.I. Parker, D.L. Mellinger and C. Lei. 1983. Bioaccumulation and effects of cadmium and zinc in a Lake Michigan plankton community. Can. J. Fish. Aquat. Sci. 40:1469-1479.

Martin, J.H. and G.A. Knauer. 1972. A comparison of inshore vs. offshore levels of 21 trace and major elements in marine plankton. In: Baseline studies of pollutants in the marine environment (heavy metals, halogenated hydrocarbons and petroleum). Goldberg, E.D. (Ed.). Workshop sponsored by the National Science Foundation - International Decade of Ocean Exploration at Brookhaven National Laboratory, Brookhaven, NY. pp. 35-66.

Martin, J.L., A. Van Wormhoudt and J.H. Ceccaldi. 1977. Zinc-hemocyanin binding in the hemolymph of *Carcinus maenas* (Crustacea, Decapoda). Comp. Biochem. Physiol. 58A:193-195.

Martin, J.M., F.M. Piltz and D.J. Reish. 1975. Studies on the Mytilus edulis community in Alamitos Bay, California. V. The effects of heavy metals on byssal thread production. Veliger 18:183-187.

Martin, T.R. and D.M. Holdich. 1986. The acute lethal toxicity of heavy metals to percarid crustaceans (with particular reference to fresh-water asellids and gammarids). Water Res. 20:1137-1147.

Mathis, B.J. and T.F. Cummings. 1973. Selected metals in sediments, water and biota in the Illinois River. J. Water Pollut. Control Fed. 45:1573-1583.

Mathur, S., B.S. Khangarot and V.S. Durve. 1981. Acute toxicity of mercury, copper and zinc to a freshwater pulmonate snail, Lymnaea luteola (Lamarck). Acta Hydrochim. Hydrobiol. 9:381-389.

Matthiessen, P. and A.E. Brafield. 1973. The effects of dissolved zinc on the gills of the stickleback Gasterosteus aculeatus (L). J. Fish Biol. 5:607-613.

Matthiessen, P. and A.E. Brafield. 1977. Uptake and loss of dissolved zinc by the stickleback Gasterosteus aculeatus (L.). J. Fish Biol. 10:399-410.

McFarlane, G.A. and W.G. Franzin. 1978. Elevated heavy metals: A stress on a population of white suckers, Catostomus commersoni, in Hamell Lake Saskatchewan. J. Fish. Res. Board Can. 35:963-970.

McFeters, G.A., P.J. Bond, S.B. Olson and Y.T. Tchan. 1983. A comparison of microbial bioassays for the detection of aquatic toxicants. Water Res. 17:1757-1762.

McHardy, B.M. and J.J. George. 1985. The uptake of selected heavy metals by the green alga Cladophora glomerata. Symp. Biol. Hung. 29:3-19.

McIntosh, A. and W. Bishop. 1976. Distribution and effects of heavy metals in a contaminated lake. PB264037. National Technical Information Service, Springfield, VA.

McKenney, C.M., Jr. 1979. Ecophysiological studies on the ontogeny of euryplasticity in the caridean shrimp, Palaemonetes pugio and modifications by zinc. Ph.D. thesis. Texas A & M University, College Station, TX. Available from: University Microfilms, Ann Arbor, MI. Order No. 80-11973.

McKenney, C.M., Jr. and J.M. Neff. 1979. Individual effects and interactions of salinity, temperature and zinc on larval development of the grass shrimp, Palaemonetes pugio. I. Survival and development duration through metamorphosis. Mar. Biol. (Berl.) 52:177-188.

McKenney, C.M., Jr. and J.M. Neff. 1981. The ontogeny of resistance adaptation and metabolic compensation to salinity and temperature by the caridean shrimp, Palaemonetes pugio, and modification by sublethal zinc exposure. In: Biological monitoring of marine pollutants. Vernberg, J., A. Calabrese, F.P. Thurberg and W.B. Vernberg (Eds.). Academic Press, New York, NY. pp. 205-240.

McKim, J.M. 1977. Evaluation of tests with early life stages of fish for predicting long-term toxicity. J. Fish. Res. Board Can. 34:1148-1154.

McLeay, D.J. 1975. Sensitivity of blood cell counts in juvenile coho salmon (Oncorhynchus kisutch) to stressors including sublethal concentrations of pulp mill effluent and zinc. J. Fish. Res. Board Can. 32:2357-2364.

McLeay, D.J. 1976. A rapid method for measuring the acute toxicity of pulp mill effluents and other toxicants to salmonid fish at ambient room temperature. J. Fish. Res. Board Can. 33:1303-1311.

McLeay, D.J. and J.R. Munro. 1979. Photoperiodic acclimation and circadian variations in tolerance of juvenile rainbow trout (Salmo gairdneri) to zinc. Bull. Environ. Contam. Toxicol. 23:552-557.

McLeese, D.W. 1976. Toxicity studies with lobster larvae and adults and a freshwater crayfish in 1975. Manuscript Report Series No. 1384. Fisheries Research Board of Canada. Environment Canada, St. Andrews, New Brunswick, Canada. pp. 1-15.

McLeese, D.W. and S. Ray. 1984. Uptake and excretion of cadmium, CdEDTA, and zinc by Macoma balthica. Bull. Environ. Contam. Toxicol. 32:85-92.

McMurtry, M.J. 1984. Avoidance of sublethal doses of copper and zinc by tubificid oligochaetes. J. Great Lakes Res. 10:267-272.

Mecham, J.A. and R.B. Holliman. 1975. Toxicity of zinc to Schistosoma mansoni cercariae in a chemically defined water medium. Hydrobiologia 46:391-404.

Melhuus, A., K.L. Seip, H.M. Seip and S. Myklestad. 1978. A preliminary study of the use of benthic algae as biological indicators of heavy metal pollution in Sorfjorden, Norway. Environ. Pollut. 15:101-107.

Mellinger, P.J. 1972. The comparative metabolism of cadmium, mercury and zinc as environmental contaminants in the freshwater mussel, Margaritifera margaritifera. Ph.D. thesis. Oregon State University, Corvallis, OR. Available from: University Microfilms, Ann Arbor, MI. Order No. 72-27637.

Meyer, R.L. 1978. The effects of heavy metals on algae populations in a south central reservoir. Publication No. 61. Arkansas Water Resources Research Center, University of Arkansas, Fayetteville, AR.

Michnowicz, C.J. and T.E. Weaks. 1984. Effects of pH on toxicity of As, Cr, Cu, Ni and Zn to Selenastrum capricornutum Printz. Hydrobiologia 118:299-305.

Miller, W.E., S.A. Petersen, J.C. Greene and C.A. Callahan. 1985. Comparative toxicology of laboratory organisms for assessing hazardous waste sites. J. Environ. Qual. 14:569-574.

Millington, P.J. and K.F. Walker. 1983. Australian freshwater mussel, Velesunio ambiguus (Philippi) as a biological monitor for zinc, iron and magnanese, Aust. J. Mar. Freshwater Res. 34:873-892.

Mills, W.L. 1976a. Water quality bioassay using selected protozoa. J. Environ. Sci. Health 11A:491-500.

Mills, W.L. 1976b. Water quality bioassay using selected protozoa, II. The effects of zinc on population growth Euglena gracilis. J. Environ. Sci. Health 11A:567-572.

Millward, G.E. and R.M. Moore. 1982. The adsorption of Cu, Mn and Zn by iron oxyhydrate in model estuarine solution. Water Res. 16:981-985.

Milner, N.J. 1982. The accumulation of zinc by o-group plaice, Pleuronectes platessa (L.), from high concentrations in sea water and food. J. Fish. Biol. 21:325-336.

Mirenda, R.J. 1986. Acute toxicity and accumulation of zinc in the crayfish, Orconectes virilis (Hagen). Bull. Environ. Contam. Toxicol. 37:387-394.

Moreau, G., C. Barbeau, J.J. Frenette, J. Saint-Onge and M. Simoneau. 1983. Zinc, manganese, and strontium in opercula and scales of brook trout (Salvelinus fontinalis) as indicators of lake acidification. Can. J. Fish. Aquat. Sci. 40:1685-1691.

Morris, A.W. and A.J. Bale. 1975. The accumulation of cadmium, copper, manganese and zinc by Fucus vesiculosus in the Bristol Channel. Estuarine Coastal Mar. Sci. 3:153-163.

Morrison, P.F., J.F. Leatherland and R.A. Sonstegard. 1985. Proximate composition and organochlorine and heavy metal contamination of eggs from Lake Ontario, Lake Erie and Lake Michigan coho salmon (Oncorhynchus kisutch Walbaum) in relation to egg survival. Aquat. Toxicol 6:73-86.

Mount, D.I. 1966. The effect of total hardness and pH on acute toxicity of zinc to fish. Int. J. Air Water Pollut. 10:49-56.

Mount, D.I. and T.J. Norberg. 1984. A seven-day life-cycle cladoceran toxicity test. Environ. Toxicol. Chem. 3:425-434.

Mukhopadhyay, M.K. and S.K. Konar. 1984. Toxicity of copper, zinc and iron to fish, plankton and worm. Geobios 11:204-207.

Muller, K.W. and J. Payer. 1980. The influence of zinc and light conditions on the cadmium-repressed growth of the green alga Coelastrum proboscideum. Physiol. Plant. 50:265-268.

Munawar, M., R.L. Thomas, W. Norwood and A. Mudroch. 1985. Toxicity of Detroit River sediment-bound contaminants to ultraplankton. J. Great Lakes Res. 11:264-274.

Munda, I.M. 1979. Temperature dependence of zinc uptake in Fucus virsoides (Don.) J. Ag. and Enteromorpha prolifera (O.F. Mull.) J. Ag. from the Adriatic Sea. Bot. Mar. 22:149-152.

Munda, I.M. 1984. Salinity dependent accumulation of Zn, Co and Mn in Scytosiphon lomentaria (Lyngb.) Link and Enteromorpha intestinalis (L.) Link from the Adriatic Sea. Bot. Mar. 27:371-376.

Muramoto, S. 1978. Removal of heavy-metal toxicity by complexanes. I. Effect of complexanes on the accumulation and toxicity in high concentration heavy-metal solutions (cadmium, zinc, copper, and lead) for aquatic animals. Nogaku Kenkyu 57:127-142.

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. 25:941-946.

Murphy, B.R., G.J. Atchison and A.W. McIntosh. 1978a. Cadmium and zinc content of fish from an industrially contaminated lake. J. Fish Biol. 13:327-335.

Murphy, B.R., G.J. Atchison and A.W. McIntosh. 1978b. Cadmium and zinc in muscle of bluegill (Lepomis macrochirus) and largemouth bass (Micropterus salmoides) from an industrially contaminated lake. Environ. Pollut. 17:253-257.

Murti, R. and G.S. Shukla. 1984. Toxicity of copper sulphate and zinc sulphate to Macrobrachium lamarrei (H. Milne Edwards) (Decapoda, Palaemonidae). Crustaceana 47:168-173.

Muska, C.F. 1977. Evaluation of an approach for studying the quantitative responses of whole organisms to mixtures of environmental toxicants. Thesis. Oregon State University, Corvallis, OR. Available from: University Microfilms, Ann Arbor, MI. Order No. 7729421.

Nabrzyski, M. 1975. Mercury, copper and zinc content in the meat tissue of some fresh water fish. Bromatol. Chem. Toksykol. 8:313-319.

Nabrzyski, M. and R. Gajewska. 1978. Occurrence of zinc and cadmium in saltwater and freshwater fish. Bromatol. Chem. Toksykol. 11:259-264.

Nagy-Toth, F. and A. Barna. 1982. Algal-physiological analysis of some metal-polluted waters. Stud. Cercet. Biol., Ser. Biol. Veg. 34:134-9; C.A. Selects: Environ. Pollut. 1983. Issue 12:2. Abstr. No. 98-192930.

Namminga, H. and J. Wilhm. 1977. Heavy metals in water, sediments and chironomids. J. Water Pollut. Control Fed. 49:1725-1731.

Natarajan, G.M. 1982. Effect of zinc sulphate on the tissue glycogen content of air-breathing climbing-perch, Anabas scandens (Cuvier). Comp. Physiol. Ecol. 7:37-39.

Nazarenko, L.D. 1970. Age-related changes of copper and zinc content in bream (Abramis brama (L.)) of Kuybyshev Reservoir. J. Ichthyol. (Engl. Transl. Vopr. Ikhtiol.) 10:150-152.

Nebeker, A.V., C. Savonen, R.J. Baker and J.K. McCrady. 1984. Effects of copper, nickel and zinc on the life cycle of the caddisfly Clistoronia magnifica (Limnephilidae). Environ. Toxicol. Chem. 3:645-649.

Nebeker, A.V., A. Stinchfield, C. Savonen and G.A. Chapman. 1986. Effects of copper, nickel and zinc on three species of Oregon freshwater snails. Environ. Toxicol. Chem. 5:807-811.

Nehring, R.B. 1976. Aquatic insects as biological monitors of heavy metal pollution. Bull. Environ. Contam. Toxicol. 15:147-154.

Nehring, R.B. and J.P. Goettl, Jr. 1974. Acute toxicity of a zinc-polluted stream to four species of salmonids. Bull. Environ. Contam. Toxicol. 12:464-469.

Nelson, V.A. 1972. Effects of strontium-90 + yttrium-90, zinc-65, and chromium-51 on the larvae of the Pacific oyster, *Crassostrea gigas*. In: The Columbia River Estuary and adjacent ocean water bioenvironmental studies. University of Washington Press, Seattle, WA. pp. 819-832.

Nemcsok, J. and L. Boross. 1982. Comparative studies on the sensitivity of different fish species to metal pollution. Acta Biol. Acad. Sci. Hung. 33:23-27.

Nemcsok, J., A. Nemeth, Z.S. Buzas and L. Boross. 1984. Effects of copper, zinc and paraquat on acetylcholinesterase activity in carp (*Cyprinus carpio* L.). Aquat. Toxicol. 5:23-31.

Neter, J. and W. Wasserman. 1974. Applied linear statistical models. Irwin, Inc., Homewood, IL.

Neufeld, R.D. and S. Wallach. 1984. Chemical and toxicity analysis of leachates from coal conversion solid wastes. J. Water Pollut. Control Fed. 56:266-273.

Newman, M.C., J.J. Alberts and V.A. Greenhut. 1985. Geochemical factors complicating the use of aufwuchs to monitor bioaccumulation of arsenic, cadmium, chromium, copper and zinc. Water Res. 19:1157-1165.

Ney, J.J. and M.G. Martin. 1985. Influence of prefreezing on heavy metal concentrations in bluegill sunfish. Water Res. 19:905-907.

Ney, J.J., M.G. Martin and J.M. Modre. 1982. Patterns of bioaccumulation of heavy metals in stream fishes. Va. J. Sci. 33:116.

Norris, R.H. and P.S. Lake. 1984. Trace metal concentrations in fish from the south Esk River, northeastern Tasmania, Australia. Bull. Environ. Contam. Toxicol. 33:348-354.

Oakden, J.M., J.S. Oliver and A.R. Flegal. 1984. Behavioral responses of a phoxocephalid amphipod to organic enrichment and trace metals in sediment. Mar. Ecol. Prog. Ser. 14:253-257.

O'Connor, T.P. 1976. Investigation of heavy metal concentrations of sediment and biota in the vicinity of the Morgantown steam electric generating station. Morgantown Monitoring Program Report Series Ref. No. MT-76-1. Martin Marietta Corp., Baltimore, MD. pp. 1-23.

Ogino, C. and G. Yang. 1978. Requirement of rainbow trout for dietary zinc. Bull. Jpn. Soc. Sci. Fish. 44:1015-1018.

Ogino, C. and G. Yang. 1979. Requirement of carp for dietary zinc. Bull. Jpn. Soc. Sci. Fish. 45:967-969.

O'Grady, K.T. 1981. The resorption of zinc from scales of sea trout (Salmo trutta) during the upstream spawning migration. Freshwater Biol. 11:561-565.

O'Grady, K.T. and M.I. Abdullah. 1985. Mobility and residence of Zn in brown trout, Salmo trutta: Results of environmentally induced change through transfer. Environ. Pollut. (Series A) 38:109-127.

Oladimeji, A.A. and J.W. Wade. 1984. Effects of effluents from a sewage treatment plant on the aquatic organisms. Water Air Soil Pollut. 23:309-316.

O'Rear, C.W., Jr. 1971. Some environmental influences on the zinc and copper content of striped bass, *Morone saxatilis* (Walbaum). Ph.D. thesis. Virginia Polytechnic Institute and State University, Blacksburg, VA. Available from University Microfilms, Ann Arbor, MI. Order No. 72-16294.

Overnell, J. 1975. The effect of heavy metals on photosynthesis and loss of cell potassium in two species of marine algae, *Dunaliella tertiolecta* and *Phaeodactylum tricornutum*. Mar. Biol. (Berl.) 29:99-103.

Overnell, J. 1976. Inhibition of marine algal photosynthesis by heavy metals. Mar. Biol. (Berl.) 38:335-342.

Ozimek, T. 1985. Heavy metal content in macrophytes from ponds supplied with post-sewage water. Symp. Biol. Hung. 29:41-50.

Pagenkopf, G.K. 1976. Zinc speciation and toxicity to fishes. In: Toxicity to biota of metal forms in natural water. Andrew, R.W., P.V. Hodson and D.E. Konasewich (Eds.). International Joint Commission, Windsor. Ontario. Canada. pp. 77-91.

Palawski, D., J.B. Hunn and F.J. Dwyer. 1985. Sensitivity of young striped bass to organic and inorganic contaminants in fresh and saline waters. Trans. Am. Fish. Soc. 114:748-753.

Pardue, W.J. and T.S. Wood. 1980. Baseline toxicity data for freshwater Bryozoa exposed to copper, cadmium, chromium and zinc. J. Tenn. Acad. Sci. 55:27-31.

Parker, H.I., K. Stanlaw, J.S. Marshall and C.W. Kennedy. 1982. Sorption and sedimentation of Zn and Cd by seston in southern Lake Michigan. J. Great Lakes Res. 8:520-531.

Parker, J.G. 1984. The effects of selected chemicals and water quality on the marine polychaete, *Ophryotrocha diadema*. Water Res. 18:865-868.

Patrick, F.M. and M. Loutit. 1976. Passage of metals in effluents through bacteria to higher organisms. Water Res. 10:333-335.

Patrick, F.M. and M.W. Loutit. 1978. Passage of metals to freshwater fish from their food. Water Res. 12:395-398.

Patrick, R., J. Cairns, Jr. and A. Scheier. 1968. The relative sensitivity of diatoms, snails, and fish to twenty common constituents of industrial wastes. Prog. Fish-Cult. 30:137-140.

Patrick, W.H., Jr., R.P. Gambrell and R.A. Khalid. 1977. Physicochemical factors regulating solubility and bioavailability of toxic heavy metals in contaminated dredged sediment. J. Environ. Sci. Health A12:475-492.

Paul, A.C. and K.C. Pillai. 1983. Trace metals in a tropical river environment - speciation and biological transfer. Water Air Soil Pollut. 19:75-86.

Pavicic, J. 1980. Interaction of cadmium and zinc in relation to oxygen consumption in early stages of marine bivalve molluscs. Ves Journees Etud. Pollutions. pp. 627-634.

Pennington, C.H., J.A. Baker and M.E. Potter. 1982. Contaminant levels in fishes from Brown's Lake, Mississippi. J. Miss. Acad. Sci. 27:139-147.

Pentreath, R.J. 1973. The accumulation and retention of ^{65}Zn and ^{54}Mn by the plaice. *Pleuronectes platessa* L. J. Exp. Mar. Biol. Ecol. 12:1-18.

Percy, K.E. and S.A. Borland. 1985. A multivariate analysis of element concentrations in *Sphagnum magellanicum* Brid. in the Maritime Provinces, Canada. Water Air Soil Pollut. 25:331-338.

Persoone, G. and G. Uyttersprot. 1975. The influence of inorganic and organic pollutants on the rate of reproduction of a marine hypotrichous ciliate: *Euplotes vannus* Muller. Rev. Int. Oceanogr. Med. 37-38:125-151.

Petersen, R. 1982. Influence of copper and zinc on the growth of a freshwater alga, *Scenedesmus quadricauda*: The significance of chemical speciation. Environ. Sci. Technol. 16:443-447.

Petry, H. 1982. The motility test, an early warning system for the biological control of waters. Zentralbl. Bakteriol. Mikrobiol. Hyg. Abt. B. 176:391-412; Aquat. Sci. Fish. Abstr. 1983. 13:180. Abstr. No. 2167-1Q13.

Peverly, J.H. 1985. Element accumulation and release by macrophytes in a wetland stream. J. Environ. Qual. 14:137-143.

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. (Berl.) 38:59-69.

Phillips, D.J.H. 1977. Effects of salinity on the net uptake of zinc by the common mussel *Mytilus edulis*. Mar. Biol. (Berl.) 41:79-88.

Phillips, G.R. and R.W. Gregory. 1980. Accumulation of selected elements (arsenic, copper, mercury, lead, selenium, zinc) by northern pike (*Esox lucius*) reared in surface coal mine decant water. Proc. Mont. Acad. Sci. 39:44-50.

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, VA.

Pickering, Q.H. 1968. Some effects of dissolved oxygen concentrations upon the toxicity of zinc to the bluegill, *Lepomis macrochirus*, Raf. Water Res. 2:187-194.

Pickering, Q.H. and C. Henderson. 1966. The acute toxicity of some heavy metals to different species to warmwater fishes. Air Water Pollut. Int. J. 10:453-463.

Pickering, Q.H. and W.N. Vigor. 1965. The acute toxicity of zinc to eggs and fry of the fathead minnow. Prog. Fish-Cult. 27:153-157.

Pierson, K.B. 1981. Effects of chronic zinc exposure on the growth, sexual maturity, reproduction, and bioaccumulation of the guppy, *Poecilia reticulata*. Can. J. Fish. Aquat. Sci. 38:23-31.

Pierson, K.B. 1985a. Isolation and partial characterization of a non-thionein, zinc-binding protein from the liver of rainbow trout (*Salmo gairdneri*). Comp. Biochem. Physiol. 80C:299-304.

Pierson, K.B. 1985b. Occurrence and synthesis of a non-thionein, zinc-binding protein in the rainbow trout (*Salmo gairdneri*). Comp. Biochem. Physiol. 81C:71-75.

Polikarpov, G.G. 1966. Radioecology of aquatic organisms. The accumulation and biological effect of radioactive substances. Reinhold Book Division, New York, NY.

Pommery, J., M. Imbenotte and F. Erb. 1985. Relationships between toxicities of free and complexed trace metals. Environ. Pollut. (Series B) 9:127-136.

Pope, D.H. 1981. Effect of biocides on algae and legionnaires disease bacteria. Final report DP-MS-81-63. Department of Biology, Rensselaer Polytechnic Institute, Troy, NY.

Porter, K.R. and D.E. Hakanson. 1976. Toxicity of mine drainage to embryonic and larval boreal toads (Bufonidae: *Bufo boreas*). Copeia 2:327-331.

Portmann, J.E. 1968. Progress report on a programme of insecticide analysis and toxicity-testing in relation to the marine environment. Helgol. Wiss. Meeresunters. 17:247-256.

Pringle, B.H., D.E. Hessong, E.L. Katz and S.T. Mulawka. 1968. Trace metal accumulation by estuarine mollusks. Am. Soc. Civ. Eng., J. Sanit. Eng. Div. 94:455-475.

Qureshi, S.A. and A.B. Saksena. 1980. The acute toxicity of some heavy metals to *Tilapia mossambica* (Peters). Aqua 1:19-20.

Qureshi, S.A., A.B. Saksena and V.P. Singh. 1980. Acute toxicity of four heavy metals to benthic fish food organisms from the River Khan, Ujjain. Int. J. Environ. Stud. 15:59-61.

Rabe, F.W. and S.B. Bauer. 1977. Heavy metals in lakes of the Coeur d'Alene River Valley, Idaho. Northwest Sci. 51:183-197.

Rabe, F.W. and C.W. Sappington. 1970. Biological productivity of the Coeur d'Alene Rivers as related to water quality. Project A-024-Ida. Water Resources Research Institute, Moscow, ID.

Rachlin, J.W. and M. Farran. 1974. Growth response of the green algae *Chlorella vulgaris* to selective concentrations of zinc. Water Res. 8:575-577.

Rachlin, J.W. and A. Perlmutter. 1968. Response of an inbred strain of platyfish and the fathead minnow to zinc. Prog. Fish-Cult. 30:203-207.

Rachlin, J.W. and A. Perlmutter. 1969. Response of rainbow trout cells in culture to selected concentrations of zinc sulfate. Prog. Fish-Cult. 31:94-98.

Rachlin, J.W., T.E. Jensen and B. Warkentine. 1982. The growth response of the green alga (Chlorella saccharophila) to selected concentrations of the heavy metals Cd, Cu, Pb and Zn. In: Trace substances in environmental health-XVI. Hemphill, D.D. (Ed.). University of Missouri, Columbia, MO. pp. 145-154.

Rachlin, J.W., T.E. Jensen and B. Warkentine. 1983. The growth response of the diatom Navicula incerta to selected concentrations of the metals: Cadmium, copper, lead and zinc. Bull. Torrey Bot. Club 110:217-223.

Rachlin, J.W., T.E. Jensen and B.E. Warkentine. 1985. Morphometric analysis of the response of Anabaena flos-aquae and Anabaena variabilis (Cyanophyceae) to selected concentrations of zinc. Arch. Environ. Contam. Toxicol. 14:395-402.

Rahel, F.J. 1981. Selection for zinc tolerance in fish: Results from laboratory and wild populations. Trans. Am. Fish. Soc. 110:19-28.

Rai, L.C., J.P. Gaur and H.D. Kumar. 1981a. Protective effects of certain environmental factors on the toxicity of zinc, mercury, and methylmercury to Chlorella vulgaris. Environ. Res. 25:250-259.

Rai, L.C., J.P. Gaur and H.D. Kumar. 1981b. Phycology and heavy-metal pollution. Biol. Rev. Camb. Philos. Soc. 56:99-151.

Rainbow, P.S., A.G. Scott, E.A. Wiggins and R.W. Jackson. 1980. Effect of chelating agents on the accumulation of cadmium by the barnacle Semibalanus balanoides, and complexation of soluble Cd, Zn and Cu. Mar. Ecol. Prog. Ser. 2:143-152.

Ramamoorthy, S. and K. Blumhagen. 1984. Uptake of Zn, Cd, and Hg by fish in the presence of competing compartments. Can. J. Fish. Aquat. Sci. 41:750-756.

Rana, B.C. and H.D. Kumar. 1974. The toxicity of zinc to Chlorella vulgaris and Plectonema boryanum and its protection by phosphate. Phykos 13:60-66.

Rana, B.C. and H.D. Kumar. 1975. Studies on chemical and biological treatment of a zinc smelter effluent and its evaluation through the growth of test algae. Nova Hedwigia 26:465-471.

Ranta, W.B., F.D. Tomassini and E. Nieboer. 1978. Elevation of copper and nickel levels in primaries from black and mallard ducks collected in the Sudbury district, Ontario. Can. Jour. Zool. 56:581-586.

Rao, D.S. and A.B. Saxena. 1981. Acute toxicity of mercury, zinc, lead, cadmium, manganese to the Chironomus sp. Int. J. Environ. Stud. 16:225-226.

Rao, V.N.R. and S.K. Subramanian. 1982. Metal toxicity tests on growth of some diatoms. Acta Bot. Indica 10:274-281.

Ray, S., D.W. McLeese, B.A. Waiwood and D. Pezzack. 1980. The disposition of cadmium and zinc in Pandalus montagui. Arch. Environ. Contam. Toxicol. 9:675-681.

Ray, S., D.W. McLeese and M.R. Peterson. 1981. Accumulation of copper, zinc, cadmium and lead from two contaminated sediments by three marine invertebrates - a laboratory study. Bull. Environ. Contam. Toxicol. 26:315-322.

Ray, S.N. and W.J. White. 1979. Equisetum arvense - an aquatic vascular plant as a biological monitor for heavy metal pollution. Chemosphere 3:125-128.

Reed, P., D. Richey and D. Roseboom. 1980. Acute toxicity of zinc to some fishes in high alkalinity water. Circular 142. Illinois Institute of National Resources, Urbana. IL.

Rehnberg, B.C. and C.B. Schreck. 1986. Acute metal toxicology of olfaction in coho salmon: Behavior, receptors, and odor-metal complexation. Bull. Environ. Contam. Toxicol. 36.579-586.

Rehwoldt, R., G. Bida and B. Nerrie. 1971. Acute toxicity of copper, nickel and zinc ions to some Hudson River fish species. Bull. Environ. Contam. Toxicol. 6:445-448.

Rehwoldt, R., G. Bida, B. Nerri and D. Alessandrello. 1972. The effect of increased temperature upon the acute toxicity of some heavy metal ions. Bull. Environ. Contam. Toxicol. 8 91-96.

Rehwoldt R., L. Lawrence, C. Shaw and E. Wirhowski. 1973. The acute toxicity of some heavy metal ions toward benthic organisms. Bull. Environ. Contam Toxicol. 10.291-294.

Rehwoldt. R., D. Karimian-Teherani and H. Altmann. 1976. Distribution of selected metals in tissue samples of carp. Cyprinus carpio. Bull. Environ. Contam. Toxicol. 15:374-377.

Reish, D.J. and R.S. Carr. 1978. The effect of heavy metals on the survival, reproduction, development and life cycles of two species of polychaetous annelids. Mar. Pollut. Bull. 9:24-29.

Reish. D.J., F. Piltz. J.M. Martin and J.Q. Word. 1974. Induction of abnormal polychaete larvae by heavy metals. Mar. Pollut. Bull. 4 125-126.

Reish, D.J., J.M. Martin, F.M. Piltz and J.Q. Word. 1976. The effect of heavy metals on laboratory populations of two polychaetes with comparisons to the water quality conditions and standards in southern California marine waters. Water Res. 10:299-302.

Renfro, W.C., S.W. Fowler, M. Heyraud and J. LaRosa. 1975. Relative importance of food and water in long-term zinc-65 accumulation by marine biota. J. Fish. Res. Board Can. 32:1339-1345.

Rice, R.G. 1977. The inter-relationships between selected trace metals and phytoplankton dynamics. J. Phycol. 13:58.

Richardson, N.L., D.A. Higgs, R.M. Beames and J.R. McBride. 1985. Influence of dietary calcium, phosphorus, zinc and sodium phytate level on cataract incidence, growth and histopathology in juvenile chinook salmon (Oncorhynchus tshawytscha). J. Nutr. 115:553-567.

Riordan, J.F. 1976. Biochemistry of zinc. Med. Clin. N. Am. 60:661-674.

Roch, M. and J.A. McCarter. 1984a. Hepatic metallothionein production and resistance to heavy metals by rainbow trout (Salmo gairdneri) - I. Exposed to an artificial mixture of zinc, copper and cadmium. Comp. Biochem. Physiol. 77C:71-75.

Roch, M. and J.A. McCarter. 1984b. Hepatic metallothionein production and resistance to heavy metals by rainbow trout (Salmo gairdneri) - II. Held in a series of contaminated lakes. Comp. Biochem. Physiol. 77C:77-82.

Roch, M. and J.A. McCarter. 1984c. Metallothionein induction, growth, and survival of chinook salmon exposed to zinc, copper, and cadmium. Bull. Environ. Contam. Toxicol. 32:478-485.

Roch, M. and J.A. McCarter. 1986. Survival and hepatic metallothionein in developing rainbow trout exposed to a mixture of zinc, copper, and cadmium. Bull. Environ. Contam. Toxicol. 36:168-175.

Roch, M., R.N. Nordin, A. Austin, C.J. McKean, J. Deniseger, R.D. Kathman, J.A. McCarter and M.J. Clark. 1985. The effects of heavy metal contamination on the aquatic biota of Bottle Lake and the Campbell River drainage (Canada). Arch. Environ. Contam. Toxicol. 14:347-362.

Roch, M., P. Noonan and J.A. McCarter. 1986. Determination of no effect levels of heavy metals for rainbow trout using hepatic metallothionein. Water Res. 20:771-774.

Rodgers, D.W. 1982. Dynamics of methylmercury accumulation in rainbow trout (Salmo gairdneri). University of Guelph, Guelph, Ontario, Canada. Dissertation Abstracts 43:1105-B.

Rodgers, D.W. and F.W.H. Beamish. 1983. Effects of water hardness, inorganic mercury and zinc on uptake of waterborne methylmercury in rainbow trout (Salmo gairdneri). In: Proceedings of the eighth annual aquatic toxicity workshop. Kaushik, N.K. and K.R. Solomon (Eds.). Canadian Technical Report of Fisheries and Aquatic Sciences No. 1151. Department of Fisheries and Oceans, Ottawa, Ontario, Canada. pp. 197-199.

Rodgers, J.H., Jr., D.S. Cherry, R.L. Graney, K.L. Dickson and J. Cairns, Jr. 1980. Comparison of heavy metal interactions in acute and artificial stream bioassay techniques for the Asiatic clam (Corbicula fluminea). In: Aquatic toxicology. Eaton, J.G., P.R. Parrish and A.C. Hendricks (Eds.). ASTM STP 707. American Society for Testing and Materials, Philadelphia, PA. pp. 266-280.

Roesijadi, G. 1981. The significance of low molecular weight, metallothionein-like proteins in marine invertebrates: Current status. Mar. Environ. Res. 4:167-179.

Roesijadi, G., J.S. Young, A.S. Drum and J.M. Gurtisen. 1984. Behavior of trace metals in Mytilus edulis during a reciprocal transplant field experiment. Mar. Ecol. Prog. Ser. 18:155-170.

Rohrer, T.K., J.C. Forney and J.H. Hartig. 1982. Organochlorine and heavy metal residues in standard fillets of coho and chinook salmon of the Great Lakes-1980. J. Great Lakes Res. 8:623-634.

Roline, R.A. and J.R. Boehmke. 1981. Heavy metals pollution of the upper Arkansas River, Colorado, and its effects on the distribution of the aquatic macrofauna. Report No. REC-ERC-81-15. Available from: National Technical Information Service, Springfield, VA.

Romberg, G.P. and W.C. Renfro. 1973. Radioactivity in juvenile Columbia River salmon: A model to distinguish differences in movement and feeding habits. Trans. Am. Fish. Soc. 2:317-322.

Rombough, P.J. 1985. The influence of the zonae radiata on the toxicities of zinc, lead, mercury, copper and silver ions to embryos of steelhead trout Salmo gairdneri. Comp. Biochem. Physiol. 82C:115-117.

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 102:100-106.

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 104:226-233.

Ruthven, J.A. and J. Cairns. 1973. Response of freshwater protozoan artificial communities to metals. J. Protozool. 20:127-135.

Sabodash, V.M. 1974. Survival rate of grass carp larvae after exposure to zinc sulfate. Hydrobiol. J. (Engl. Transl. Gidrobiol. Zh.) 10:77-80.

Saiki, M. and T. Mori. 1955. Studies on the distribution of administered radioactive zinc in the tissues of fishes-I. Bull. Jpn. Soc. Sci. Fish. 21:945.

Sailer, D., D. Shellenberger, R.H. Crist and K.M. Oberholser. 1980. Interactions of protons and metallic ions with algae. Proc. Pa. Acad. Sci. 54:85-88.

Sakanari, J.A., M. Moser, C.A. Reilly and T.P. Yoshino. 1984. Effects of sublethal concentrations of zinc and benzene on striped bass, *Morone saxatilis* (Walbaum), infected with larval *Aniskis* nematodes. J. Fish Biol. 24:553-563.

Salanki, J., K.V. Balogh and E. Berta. 1982. Heavy metals in animals of Lake Balaton. Water Res. 16:1147-1152.

Salomons, W. 1980. Adsorption processes and hydrodynamic conditions in estuaries. Environ. Technol. Lett. 1:356-365.

Salomons, W. 1985. Sediments and water quality. Environ. Technol. Lett. 6:315-326.

Salomons, W. and U. Forstner. 1984. Metals in the hydrocycle. Springer-Verlag, Berlin, Germany.

Saltes, J.G. and G.C. Bailey. 1984. Use of fish gill and liver tissue to monitor zinc pollution. Bull. Environ. Contam. Toxicol. 32:233-237.

Sartory, D.P. and B.J. Lloyd. 1976. The toxic effects of selected heavy metals on unadapted populations of Vorticella convallaria var. similis. Water Res. 10:1123-1127.

Sastry, K.V. and S. Subhadra. 1984. Effect of cadmium and zinc on intestinal absorption of xylose and tryptophan in the fresh water teleost fish, Heteropneustes fossilis. Chemosphere 13:889-898.

Satoh, S., H. Yamamoto, T. Takeuchi and T. Watanabe. 1983a. Effects on growth and mineral composition of rainbow trout of deletion of trace elements or magnesium from fish meal diet. Bull. Jpn. Soc. Sci. Fish. 49:425-429.

Satoh, S., H. Yamamoto, T. Takeuchi and T. Watanabe. 1983b. Effects on growth and mineral composition of carp of deletion of trace elements or magnesium from fish meal diet. Bull. Jpn. Soc. Sci. Fish. 49:431-435.

Satoh, S., T. Takeuchi, Y. Narabe and T. Watanabe. 1983c. Effects of deletion of several trace elements from fish meal diets on growth and mineral composition of rainbow trout fingerlings. Bull. Jpn. Soc. Sci. Fish. 49:1909-1916.

Sauer, G.R. and N. Watabe. 1984. Zinc uptake and its effect on calcification in the scales of the mummichog, Fundulus heteroclitus. Aquat. Toxicol. 5:51-56.

Saunders, R.L. and J.B. Sprague. 1967. Effects of copper-zinc mining pollution on a spawning migration of Atlantic salmon. Water Res. 1:419-432.

Saxena, O.P. and A. Parashari. 1983. Comparative study of the toxicity of six heavy metals to Channa punctatus. J. Environ. Biol. 4:91-94.

Say, P.J. and B.A. Whitton. 1977. Influence of zinc on lotic plants. II. Environmental effects on toxicity of zinc to Hormidium rivulare. Freshwater Biol. 7:377-384.

Say, P.J. and B.A. Whitton. 1983a. Accumulation of heavy metals by aquatic mosses. 1: *Fontinalis antipyretica* Hedw. Hydrobiologia 100:245-250.

Say, P.J. and B.A. Whitton. 1983b. Chemistry and plant ecology of zinc-rich streams in France. I. Massif Central. Ann. Limnol. 18:3-18(1982); Aquat. Sci. Fish. Abstr. 13:7224-1Q13.

Say, P.J., B.M. Diaz and B.A. Whitton. 1977. Influence of zinc on lotic plants. I. Tolerance of *Hormidium* species to zinc. Freshwater Biol. 7:357-376.

Schmitt, C.J., F.J. Dwyer and S.E. Finger. 1984. Bioavailability of Pb and Zn from mine tailings as indicated by erythrocyte d-aminolevulinic acid dehydratase (ALA-D) activity in suckers (Pisces: Catostomidae). J. Fish. Aquat. Sci. 41:1030-1040.

Seagle, S.M. and A.J. Ehlmann. 1974. Manganese, zinc and copper in water, sediments and mussels in north central Texas reservoirs. In: Trace substances in environmental health - VII. D.D. Hemphill (Ed.). University of Missouri, Columbia, MO. pp. 101-106.

See, C.L., A.L. Buikema and J. Cairns. 1974. The effects of selected toxicants on survival of *Dugesia tigrina* (Turbellaria). Assoc. Southeastern Biologists Bull. 21:82.

See, C.L., A.L. Buikema and J. Cairns. 1975. The effects of sublethal concentrations of zinc and nickel on the photonegative response of *Dugesia tigrina*. Va. J. Sci. 26:60.

Seelye, J.G., R.J. Hesselberg and M.J. Mac. 1982. Accumulation by fish of contaminants released from dredged sediments. Environ. Sci. Technol. 16:459-464.

Sehgal, R. and A.B. Saxena. 1986. Toxicity of zinc to a viviparous fish, Lebistes reticulatus (Peters). Bull. Environ. Contam. Toxicol. 36:888-894.

Seiffer, E.A. and H.F. Schoof. 1967. Tests of 15 experimental molluscicides against Australorbis glabratus. Publ. Health Rep. 82:833-839.

Seip, K.L. 1979. A mathematical model for the uptake of heavy metals in benthic algae. Ecol. Model. 6:183-197.

Sellers, C.M., Jr., A.G. Heath and M.L. Bass. 1975. The effect of sublethal concentrations of copper and zinc on ventilatory activity, blood oxygen and pH in rainbow trout (Salmo gairdneri). Water Res. 9:401-408.

Shaffi, S.A. 1979. Effect of zinc intoxication on fresh water fishes. II. Accumulation of metabolic products. Toxicol. Lett. 3:319-323.

Shaffi, S.A. 1980. Zinc intoxication in some freshwater fishes. I. Variations in tissue energy reserve. Ann. Limnol. 16:91-97.

Shazili, N.A. and D. Pascoe. 1986. Variable sensitivity of rainbow trout (Salmo gairdneri) eggs and alevins to heavy metals. Bull. Environ. Contam. Toxicol. 36:468-474.

Shcherban, E.P. 1977. Toxicity of some heavy metals for Daphnia magna Strauss, as a function of temperature. Hydrobiol. J. 13(4):75-80.

Shearer, K.D. 1984. Changes in elemental composition of hatchery-reared rainbow trout, Salmo gairdneri, associated with growth and reproduction. Can. J. Fish. Aquat. Sci. 41:1592-1600.

Sheehan, P.J. and A. W. Knight. 1985. A multilevel approach to the assessment of ecotoxicological effects in a heavy metal polluted stream. Int. Ver. Theor. Angew. Limnol. Verh. 22:2364-2370.

Shehata, F.H.A. and B.A. Whitton. 1981. Field and laboratory studies on blue-green algae from aquatic sites with high levels of zinc. Int. Ver. Theor. Angew. Limnol. Verh. 21:1466-1471.

Shimma, Y., H. Tanaka, Y. Furuta, H. Shimma and K. Ikeda. 1984. Protein carotenoid, and mineral contents and fatty acid composition on the sessile algae from Chikuma River. Bull. Jpn. Soc. Sci. Fish. 50:1223-1227.

Shukla, G.S., R. Murti and Omkar. 1983. Cadmium and zinc toxicity to an aquatic insect, *Ranatra elongata* (Fabr.). Toxicol. Lett. 15:39-41.

Shuman, M.S., L.A. Smock and C.L. Hayne. 1977. Metals in the water, sediments and biota of the Haw and New Hope Rivers, North Carolina. UNC-WRRI-77-124. Water Resources Research Institute, University of North Carolina, Chapel Hill, NC.

Shuster, C.N., Jr. and B.H. Pringle. 1968. Effects of marine trace metals on estuarine molluscs. Proceedings of the first mid-Atlantic industrial wastes conference, 13-15 Nov. 1967. pp. 285-303. Available from: Department of Civil Engineering, University of Delaware, Newark, DE.

Sicko-Goad, L. and D. Lazinsky. 1981. Accumulation and cellular effects of heavy metals in benthic and planktonic algae. Micron 22:289-290.

Simkiss, K., M. Taylor and Z.Z. Mason. 1982. Metal detoxification and bioaccumulation in molluscs. Mar. Biol. Lett. 3:187-201.

Simpson, R.D. 1979. Uptake and loss of zinc and lead by mussels (*Mytilus edulis*) and relationships with body weight and reproductive cycle. Mar. Poll. Bull. 10:74-78.

Sinley, J.R., J.P. Goettl, Jr. and P.H. Davies. 1974. The effects of zinc on rainbow trout (Salmo gairdneri) in hard and soft water. Bull. Environ. Contam. Toxicol. 12:193-201.

Sirover, M.A. and L.A. Loeb. 1976. Metal activation of DNA synthesis. Biochem. Biophys. Res. Comm. 7:812-817.

Skidmore, J.F. 1964. Toxicity of zinc compounds to aquatic animals, with special reference to fish. Q. Rev. Biol. 39:227-248.

Skidmore, J.F. 1970. Respiration and osmoregulation in rainbow trout with gills damaged by zinc sulphate. J. Exp. Biol. 52:481-494.

Skidmore, J.F. and I.C. Firth. 1983. Acute sensitivity of selected Australian freshwater animals to copper and zinc. Technical Paper No. 81. Australian Water Resources Council, Australian Government Publishing Service, Canberra, Australia.

Skidmore, J.F. and P.W.A. Tovell. 1972. Toxic effects of zinc sulphate on the gills of rainbow trout. Water Res. 6:217-230.

Skipnes, O., T. Roald and A. Naug. 1975. Uptake of zinc and strontium by brown algae. Physiol. Plant. 34:314-320.

Sklar, F.H. 1980. A preliminary comparison of the uptake of chromium-51 and zinc-65 by three species of aquatic plants from Louisiana. La. Acad. Sci. 43:46-51.

Slater, J.V. 1961. Comparative accumulation of radioactive zinc in young rainbow, cutthroat and brook trout. Copeia 2:158-161.

Slooff, W., J.A. Van Oers and D. DeZwart. 1986. Margins of uncertainty in ecotoxicological hazard assessment. Environ. Toxicol. Chem. 5:841-852.

Smith, K.L. and J.L. Harwood. 1984. Lipid metabolism in *Fucus serratus* as modified by environmental factors. J. Exp. Bot. 35:1359-1368.

Smith, M.A. 1983. The effect of heavy metals on the cytoplasmic fine structure of *Skeletonema costatum* (Bacillariophyta). Protoplasma 116:14-23.

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. 22:113-119.

Smith-Sonneborn, J., R.A. Palizzi, E.A. McCann and G.L. Fisher. 1983. Bioassay of genotoxic effects of environmental particles in a feeding ciliate. Environ. Health Perspect. 51:205-210.

Solbe, J.F. 1973. The relation between water quality and the status of fish populations in Willow Brook. Water Treat. Exam. 22:41-61.

Solbe, J.F. 1974. The toxicity of zinc sulphate to rainbow trout in very hard water. Water Res. 8:389-391.

Solbe, J.F. and V.A. Flook. 1975. Studies on the toxicity of zinc sulphate and of cadmium sulphate to stone loach, *Noemacheilus barbatulus* (L.) in hard water. J. Fish Biol. 7:631-637.

Somasundaram, B., P.E. King and S. Shackley. 1984a. The effects of zinc on postfertilization development in eggs of *Clupea harengus* L. Aquat. Toxicol. 5:167-178.

Somasundaram, B., P.E. King and S.E. Shackley. 1984b. The effects of zinc on the ultrastructure of the brain cells of the larvae of *Clupea harengus* L. Aquat. Toxicol. 5:323-330.

Somasundaram, B., P.E. King and S.E. Shackley. 1984c. Some morphological effects of zinc upon yolk-sac larvae of *Clupea harengus* L. J. Fish Biol. 25:333-343.

Somasundaram, B., P.E. King and S.E. Shackley. 1984d. The effect of zinc on the ultrastructure of the trunk muscle of the larva of *Clupea harengus* L. Comp. Biochem. Physiol. 79C:311-315.

Somasundaran, B., P.E. King and S.E. Shackley. 1985. The effect of zinc on the ultrastructure of the posterior gut and pronephric ducts of the larva of *Clupea harengus* L. Comp. Biochem. Physiol. 81C:29-37.

Sparks, R.E., J. Cairns, Jr. and A.G. Heath. 1972a. The use of bluegill breathing rates to detect zinc. Water Res. 6:895-911.

Sparks, R.E., W.T. Waller and J. Cairns, Jr. 1972b. Effect of shelters on the resistance of dominant and submissive bluegills (*Lepomis macrochirus*) to a lethal concentration of zinc. J. Fish. Res. Board Can. 29:1356-1358.

Sparks, R.E., J. Cairns, Jr., R.A. McNabb and G. Suter II. 1972c. Monitoring zinc concentrations in water using the respiratory response of bluegills (*Lepomis macrochirus* Rafinesque). Hydrobiologia 40:361-369.

Specht, W.L., D.S. Cherry, R.A. Lechleitner and J. Cairns, Jr. 1984. Structural, functional, and recovery responses of stream invertebrates to fly ash effluent. Can. J. Fish. Aquat. Sci. 41:884-896.

Spehar, R.L. 1976a. Cadmium and zinc toxicity to *Jordanella floridae*. EPA-600/3-76-096. National Technical Information Service, Springfield, VA.

Spehar, R.L. 1976b. Cadmium and zinc toxicity to flagfish, *Jordanella floridae*. J. Fish. Res. Board Can. 33:1939-1945.

Spehar, R.L., E.N. Leonard and D.L. DeFoe. 1978. Chronic effects of cadmium and zinc mixtures on flagfish (*Jordanella floridae*). Trans. Am. Fish. Soc. 107:354-360.

Speranza, A.W., R.J. Seeley, V.A. Seeley and A. Perlmutter. 1977. The effect of sublethal concentrations of zinc on reproduction in the zebrafish, *Brachydanio rerio* Hamilton-Buchanan. Environ. Pollut. 12:217-222.

Sprague, J.B. 1964a. Lethal concentrations of copper and zinc for young Atlantic salmon. J. Fish. Res. Board Can. 21:17-26.

Sprague, J.B. 1964b. Avoidance of copper-zinc solutions by young salmon in the laboratory. J. Water Pollut. Control Fed. 36:990-1004.

Sprague, J.B. 1965. Effects of sublethal concentrations of zinc and copper on migration of Atlantic salmon. In: Biological problems in water pollution. Third seminar. U.S. Department of Health, Education, and Welfare, Division of Water Supply and Pollution Control, Cincinnati, OH. pp. 332-333.

Sprague, J.B. 1968. Avoidance reactions of rainbow trout to zinc sulphate solutions. Water Res. 2:367-372.

Sprague, J.B. 1985. Factors that modify toxicity. In: Fundamentals of aquatic toxicology. Rand, G.M. and S.R. Petrocelli (Eds.). Hemisphere Publishing Corporation, New York, NY. pp. 124-163.

Sprague, J.B. and B.A. Ramsay. 1965. Lethal levels of mixed copper-zinc solutions for juvenile salmon. J. Fish. Res. Board Can. 22:425-432.

Sprague, J.B., P.F. Elson and R.L. Saunders. 1964. Sublethal copper-zinc pollution in a salmon river-a field and laboratory study. Adv. Water Pollut. Res. 1:61-82.

Spry, D.J. and C.M. Wood. 1984. Acid-base, plasma ion and blood gas changes in rainbow trout during short term toxic zinc exposure. J. Comp. Physiol. B 154:149-158.

Srivastava, D.K., S.S. Khanna, V.M. Sriwastwa and R. Kumar. 1985. Electron diffraction of the metallic elements in the pineal organ of a freshwater fish, Mystus vittatus (Bloch.) Experimentia 41:603-605.

Stanley, R.A. 1974. Toxicity of heavy metals and salts to Eurasian watermilfoil (Myriophyllum spicatum L.). Arch. Environ. Contam. Toxicol. 2:331-341.

Stary, J. and K. Kratzer. 1982. The cumulation of toxic metals on alga. Int. J. Environ. Anal. Chem. 12:65-71.

Stary, J., K. Kratzer, B. Havlik, J. Prasilova and J. Hanusova. 1982. The cumulation of zinc and cadmium in fish (Poecilia reticulata). Int. J. Environ. Anal. Chem. 11:117-120.

Stary, J., B. Havlik, K. Kratzer, J. Prasilova and J. Hanusova. 1983. Cumulation of zinc, cadmium and mercury on the alga Scenedesmus obliquus. Acta Hydrochim. Hydrobiol. 11:401-409.

Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman and W.A. Brungs. 1985. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. PB85-227049. National Technical Information Service, Springfield, VA.

Stillwell, E.F. 1977. Zinc effects on cell division and calcification in the coccolithophorid, Cricosphaera carterae. Sci. Biol. J. Nov.-Dec.:436-443.

Stokes, P.M., R.C. Bailey and G.R. Groulx. 1985. Effects of acidification on metal availability to aquatic biota, with special reference to filamentous algae. Envrion. Health Perspect. 63:79-87.

Stromgren, T. 1979. The effect of zinc on the increase in length of five species of intertidal fucales. J. Exp. Mar. Biol. Ecol. 40:95-102.

Stromgren, T. 1980. Combined effects of Cu, Zn, and Hg on the increase in length of Ascophyllum nodosum (L.) LeJollis. J. Exp. Mar. Biol. Ecol. 48:225-231.

Stromgren, T. 1982. Effect of heavy metals (Zn, Hg, Cu, Cd, Pb, Ni) on the length growth of Mytilus edulis. Mar. Biol. (Berl.) 72:69-72.

Strufe, R. 1968. Problems and results of residue studies after application of molluscicides. Residue Rev. 24:79-167.

Styron, C.E., T.M. Hagan, D.R. Campbell, J. Harvin, N.K. Whittenburg, G.A. Baughman, M.E. Bransford, W.H. Saunders, D.C. Williams, C. Woodle, N.K. Dixon and C.R. McNeil. 1976. Effects of temperature and salinity on growth and uptake of ^{65}Zn and ^{137}Cs for six marine algae. J. Mar. Biol. Assoc. U.K. 56:13-20.

Subhadra and K.V. Sastry. 1985. Alterations in the rate of intestinal absorption of some nutrients due to zinc in the freshwater catfish, Heteropneustes fossilis. J. Environ. Biol. 6:139-146.

Subramanian, A., B.R. Subramanian and V.K. Venugopalan. 1980. Toxicity of copper and zinc on cultures of Skeletonema costatus (Grev.) Cleve and Nitzschia longissima. Curr. Sci. 49:266-268.

Sullivan, G.W., A.L. Buikema and J. Cairns. 1973. Acute bioassays for the assessment of heavy metal pollution using the freshwater littoral rotifer, Philodina sp. Va. J. Sci. 24:120.

Suzuki, K.T. and Y. Ebihara. 1984. Distribution of cadmium, copper and zinc in the liver of spot salamander, Ambystoma maculatum and their binding to metallothionein. Comp. Biochem. Physiol. 78C:35-38.

Suzuki, K.T. and R. Kawamura. 1984. Metallothionein present or induced in the three species of frogs Bombina orientalis, Bufo bufo japonicus and Hyla arborea japonica. Comp. Biochem. Physiol. 79C:255-260.

Suzuki, K.T., Y. Tanaka and R. Kawamura. 1983. Properties of metallothionein induced by zinc, copper and cadmium in the frog, Xenopus laevis. Comp. Biochem. Physiol. 75C:33-37.

Suzuki, K.T., H. Akitomi and R. Kawamura. 1984. Cadmium, copper and zinc-binding protein (metallothionein) in the liver of the water lizard, Triturus pyrrhogaster. Toxicol. Lett. 21:179-184.

Swain, R. and R.W.G. White. 1985. Influence of a metal-contaminated tributary on the invertebrate drift fauna of the King River (Tasmania, Australia). Hydrobiologia 122:261-266.

Swift, M.C. 1985. Effects of coal pile runoff on stream quality and macroinvertebrate communities. Water Resour. Bull. 21:449-457.

Taban, C.H., M. Cathieni and P. Burkard. 1982. Changes in newt brain caused by zinc water-pollution. Experientia 38:683-685.

Takeda, H. and C. Shimizu. 1982. Existence of the metallothionein-like protein in various fish tissues. Bull. Jpn. Soc. Sci. Fish. 48:711-715.

Takeda, H. and Y. Shimma. 1977. Effects of toxic amounts of dietary zinc on the growth and body components of rainbow trout at two levels of calcium. Bull. Freshwater Fish. Res. Lab. (Tokyo) 27:103-110.

Taylor, J.L. 1978. Toxicity of copper and zinc in two Arkansas streams to mosquitofish (Gambusia affinis). Bios 49:99-106.

Taylor, M.C., A. Demayo and K.W. Taylor. 1982. Effects of zinc on humans, laboratory and farm animals, terrestrial plants, and freshwater aquatic life. Crit. Rev. Environ. Control 12:113-181.

Teherani, D.K., G. Stehlik, N. Tehrani and H. Schada. 1979. Concentrations of heavy metals and selenium in fishes in Upper Austrian Waters. Part 2: Lead, cadmium, scandium, chromium, cobalt, iron, zinc, and selenium. Environ. Pollut. 18:241-248.

Tessier, A., P.G.C. Campbell, J.C. Auclair and M. Bisson. 1984. Relationships between the partitioning of trace metals in sediments and their accumulation in the tissues of the freshwater mollusc, Elliptio complanata in a mining area. Can. J. Fish. Aquat. Sci. 41:1463-1472.

Thomas, D.G., M.W. Brown, D. Shurben, J.F. Solbe, A. Cryer and J. Kay. 1985. A comparison of the sequestration of cadmium and zinc in the tissues of rainbow trout (Salmo gairdneri) following exposure to the metals singly or in combination. Comp. Biochem. Physiol. 82C:55-62.

Thompson, K.W., A.C. Hendricks and J. Cairns, Jr. 1980. Acute toxicity of zinc and copper singly and in combination to the bluegill (*Lepomis macrochirus*). Bull. Environ. Contam. Toxicol. 25:122-129.

Thompson, K.W., A.C. Hendricks, G.L. Nunn and J. Cairns, Jr. 1983. Ventilatory responses of bluegill sunfish to sublethal, fluctuating exposures to heavy metals (Zn^{++} and Cu^{++}). Water Resour. Bull. 19:719-727.

Thompson, S.E., C.A. Burton, D.J. Quinn and Y.C. Ng. 1972. Concentration factors of chemical elements in edible aquatic organisms. UCRL-50564. Rev. 1. National Technical Information Service, Springfield, VA.

Thomson, R.L. and D.G. MacPhee. 1985. Biological monitoring of water quality in Australian inland waters. Water Qual. Bull. 10:40-45.

Thorp, V.J. and P.S. Lake. 1974. Toxicity bioassays of cadmium on selected freshwater invertebrates and the interaction of cadmium and zinc on the freshwater shrimp, *Paratya tasmaniensis* Riek. Aust. J. Freshwater Res. 25:95-104.

Timourian, H. and G. Watchmaker. 1977. Assay of sperm mobility to study the effects of metal ions. In: Biological implications of metals in the environment. Drucker, H. and R.E. Wildung (Eds.). CONF-750929. National Technical Information Service, Springfield, VA. pp. 523-536.

Tisa, M.S. and R.J. Strange. 1981. Zinc and cadmium residues in striped bass from Cherokee, Norris, and Watts Bar Reservoirs. J. Tenn. Acad. Sci. 56:134-137.

Tishinova, V. 1977. A study of the toxic effect of zinc on one-summer old carp; Part I. Lethal concentrations. ORNL-tr-4353. National Technical Information Service, Springfield, VA.

Tokunaga, T. and A. Kishikawa. 1982. Acute visible and invisible injuries to submerged plants by water pollutants. Seitai Kagaku 5:23-30; C.A. Selects: Environ. Pollut. 1982. Issue 21:1. Abstr. No. 97:121482.

Trefry, J.H. and B.J. Presley. 1976. Heavy metal transport from the Mississippi River to the Gulf of Mexico. In: Marine pollution transfer. Windom, H.L. and R.A. Duce (Eds.). Heath and Company, Lexington, MA. pp. 39-76.

Trollope, D.R. and B. Evans. 1976. Concentrations of copper, iron, lead, nickel and zinc in freshwater algal blooms. Environ. Pollut. 11:109-116.

Tsui, P.T.P. and P.J. McCart. 1981. Chlorinated hydrocarbon residues and heavy metals in several fish species from the Cold Lake area in Alberta, Canada. Int. J. Environ. Anal. Chem. 10:277-285.

Turbak, S.C., S.B. Olson and G.A. McFeters. 1986. Comparison of algal assay systems for detecting waterborne herbicides and metals. Water Res. 20:91-96.

Turner, D.R., M. Whitfield and A.G. Dickson. 1981. The equilibrium speciation of dissolved components in freshwater and sea water at 25°C and 1 atm. pressure. Geochim. Cosmochim. Acta 45:855-881.

Tuurala, H. and A. Soivio. 1982. Structural and circulatory changes in the secondary lamellae of Salmo gairdneri gills after sublethal exposures to dehydroabietic acid and zinc. Aquat. Toxicol. 2:21-29.

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

U.S. EPA. 1980. Ambient water quality criteria for zinc. EPA-440/4-80-079. National Technical Information Service, Springfield, VA.

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, VA.

U.S. EPA. 1983b. Water quality standards regulation. Fed. Regist. 48:51400-51413. November 8.

U.S. EPA. 1983c. Water quality standard handbook. Office of Water Regulations and Standards, Washington, DC.

U.S. EPA. 1985a. Appendix B - Response to public comments on "Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses." Fed. Regist. 50:30793-30796. July 19.

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

U.S. EPA. 1986. Chapter 1 - Stream design flow for steady-state modeling. In: Book VI - Design conditions. In: Technical guidance manual for performing waste load allocations. Office of Water, Washington, DC.

Uthe, J.F. and E.G. Bligh. 1971. Preliminary survey of heavy metal contamination of Canadian freshwater fish. J. Fish. Res. Board Can. 28:786-788.

Uviovo, E.J. and D.D. Beatty. 1979. Effects of chronic exposure to zinc on reproduction in the guppy (Poecilia reticulata). Bull. Environ. Contam. Toxicol. 23:650-657.

Van Coillie, R. and A. Rousseau. 1974. The mineral content of scales of Catostomus commersoni taken from two different environments: Results using electron microscopic analyses. J. Fish. Res. Board Can. 31:63-66.

Van der Werff, M. 1984. The effect of natural complexing agents on heavy metal toxicity in aquatic plants. In: Complexation of trace metals in natural waters. Kramer, C.J. and J.C. Duinker (Eds.). W. Junk Publishing Company, The Hague, Netherlands. pp. 441-444.

Van der Werff, M. and M.J. Pruyt. 1982. Long-term effects of heavy metals on aquatic plants. Chemosphere 11:727-739.

Van Hoof, F. and M. Van San. 1981. Analysis of copper, zinc, cadmium and chromium in fish tissues. A tool for detecting metal caused fish kills. Chemosphere 10:1127-1135.

Van Loon, J.C. and R.J. Beamish. 1977. Heavy-metal contamination by atmospheric fallout of several Flin Flon area lakes and the relation to fish populations. J. Fish. Res. Board Can. 34:899-906.

Vaughan, D., P.C. Dekock and B.G. Ord. 1982. The nature and localization of superoxide dismutase in fronds of Lemna gibba L. and the effect of copper and zinc deficiency on its activity. Physiol. Plant. 54:253-257.

Verma, S.R., I.P. Tonk, A.K. Gupta and M. Saxena. 1984. Evaluation of an application factor for determining the safe concentration of agricultural and industrial chemicals. Water Res. 18:111-115.

Vernon, E.H. 1954. The toxicity of heavy metals to fish with special reference to lead, zinc and copper. Can. Fish Cult.15:1-6.

Vijayamadhavan, K.T. and T. Iwai. 1975. Histochemical observations on the permeation of heavy metals into taste buds of goldfish. Bull. Jpn. Soc. Sci. Fish. 41:631-639.

Villarreal-Trevino, C.M., M.E. Obregon-Morales, J.F. Lozano-Morales and A. Villegas-Navarro. 1986. Bioaccumulation of lead, copper, iron, and zinc by fish in a transect of the Santa Catarina River in Cadereyte Jimenez, Nuevo Leon Mexico. Bull. Environ. Contam. Toxicol. 37:395-401.

Vinikour, W.S., R.M. Goldstein and R.V. Anderson. 1980. Bioconcentration patterns of zinc, copper, cadmium and lead in selected fish species from the Fox River, Illinois. Bull. Environ. Contam. Toxicol. 24:727-734.

Vinot, H. and J.P. Larpent. 1984. Water pollution by uranium ore treatment works. Hydrobiologia 112:125-129.

Vymazal, J. 1984. Short-term uptake of heavy metals by periphyton algae. Hydrobiologia 119:171-179.

Vymazal, J. 1985. Occurrence and chemistry of zinc in freshwaters - its toxicity and bioaccumulation with respect to algae: A review. Part 1: Occurrence and chemistry of zinc in freshwaters. Acta Hydrochim. Hydrobiol. 13:627-654.

Wachs, V. 1982. Concentration of heavy metals in fishes from the river Danube. Z. Wasser Abwasser Forsch. 15:43-48.

Wagh, S.B., K. Shareef and S. Shaikh. 1985. Acute toxicity of cadmium sulphate, zinc sulphate and copper sulphate to *Barbus ticto* (Ham.): Effect on oxygen consumption and gill histology. J. Environ. Biol. 6:287-293.

Wagner, G.F. and B.A. McKeown. 1982. Changes in plasma insulin and carbohydrate metabolism of zinc-stressed rainbow trout, *Salmo gairdneri*. Can. J. Zool. 60:2079-2084.

Walker, G., P.S. Rainbow, P. Foster and D.J. Crisp. 1975. Barnacles: Possible indicators of zinc pollution? Mar. Biol. (Berl.) 30:57-65.

Wallace, G.T., N. Dubek, R. Dulmage and O. Mahoney. 1983. Trace element distributions in the Gulf Stream adjacent to the southeastern Atlantic continental shelf - influence of atmospheric and shelf water inputs. Can. J. Fish. Aquat. Sci. 40(Suppl. 2):183-191.

Waller, W.T. and J. Cairns, Jr. 1972. The use of fish movement patterns to monitor zinc in water. Water Res. 6:257-269.

Wang, H. 1959. Analyses of a toxic factor lethal to paramecium present in non-glass-distilled water. Proc. Soc. Exp. Biol. Med. 101:682-685.

Wang, W. 1982. An algal assay technique for aquatic toxicants. Report of Investigation 101. Illinois State Water Survey, Champaign, IL.

Wang, W. 1986a. Toxicity tests of aquatic pollutants by using common duckweed. Environ. Pollut. (Series B) 11:1-14.

Wang, W. 1986b. Acclimation and response of algal communities from different sources to zinc toxicity. Water Air Soil Pollut. 28:335-349.

Warnick, S.L. and H.L. Bell. 1969. The acute toxicity of some heavy metals to different species of aquatic insects. J. Water Pollut. Control Fed. 41:280-284.

Warren, L.J. 1981. Contamination of sediments by lead, zinc and cadmium: A review. Environ. Pollut. (Series B) 2:401-436.

Watanabe, N., E. Sato and Y. Ose. 1985. Absorption and desorption of polydimethylsiloxane, PCBs, cadmium nitrate, copper sulfate, nickel sulfate and zinc nitrate by river surface sediments. Sci. Total Environ. 41:153-161.

Waterman, A.J. 1937. Effects of salts of heavy metals on development of the sea urchin, *Arbacia punctulata*. Biol. Bull. 73:401-420.

Watling, H.R. 1982. Comparative study of the effects of zinc, cadmium, and copper on the larval growth of three oyster species. Bull. Environ. Contam. Toxicol. 28:195-201.

Watling, H.R. 1983. Comparative study of the effects of metals on the settlement of *Crassostrea gigas*. Bull. Environ. Contam. Toxicol. 31:344-351.

Watson, T.A. and F.W.H. Beamish. 1980. Effects of zinc on branchial ATPase activity in vivo in rainbow trout, *Salmo gairdneri*. Comp. Biochem. Physiol. 66C:77-82.

Watson, T.A. and F.W.H. Beamish. 1981. The effects of zinc on branchial adenosine triphosphatase enzymes in vitro from rainbow trout, *Salmo gairdneri*. Comp. Biochem. Physiol. 68C: 167-173.

Watson, T.A. and B.A. McKeown. 1976a. The effect of sublethal concentrations of zinc on growth and plasma glucose levels in rainbow trout, *Salmo gairdneri* (Richardson). J. Wildl. Dis. 2:263-270.

Watson, T.A. and B.A. McKeown. 1976b. The activity of 5-3β-hydroxysteroid dehydrogenase enzyme in the interrenal tissue of rainbow trout (*Salmo gairdneri* Richardson) exposed to sublethal concentrations of zinc. Bull. Environ. Contam. Toxicol. 16:173-181.

Weatherley, A.H. and S.C. Rogers. 1980. Use of telemetry in monitoring intensity and energetics of activity in free-swimming fish with reference to zinc pollution. In: Proceedings of the sixth annual aquatic toxicity workshop. Klaverkamp, J.F., S.L. Leonhard and K.E. Marshall (Eds.). Canadian Technical Report of Fisheries and Aquatic Science No. 975. Department of Fisheries and Oceans, Winnipeg, Manitoba, Canada. pp. 162-170.

Weatherley, A. H., P.S. Lake and S.C. Rogers. 1980. Zinc pollution and the ecology of the freshwater environment. In: Zinc in the environment. Part I: Ecological cycling. Nriagu, J.O. (Ed.). Wiley, New York, NY. pp. 337-418.

Weber, W.J., Jr. and W. Stumm. 1963. Mechanism of hydrogen ion buffering in natural waters. J. Am. Water Works Assoc. 55:1553-1578.

Wehr, J.D. and B.A. Whitton. 1983a. Aquatic cryptograms of natural acid springs enriched with heavy metals: The Kootenay Paint Pots, British Columbia. Hydrobiologia 98:97-105.

Wehr, J.D. and B.A. Whitton. 1983b. Accumulation of heavy metals by aquatic mosses. 2: *Rhynchostegium riparioides*. Hydrobiologia 100:261-284.

Wehr, J.D. and B.A. Whitton. 1983c. Accumulation of heavy metals by aquatic mosses. 3: Seasonal changes. Hydrobiologia 100:285-291.

Wehr, J.D., A. Empain, C. Mouvet, P.J. Say and B.A. Whitton. 1983. Methods for processing aquatic mosses used as monitors of heavy metals. Water Res. 17:985-992.

Weis, J.S. 1980. Effect of zinc on regeneration in the fiddler crab, *Uca pugilator* and its interactions with methylmercury and cadmium. Mar. Environ. Res. 3:249-255.

Weis, J.S., P. Weis and J.L. Ricci. 1981. Effects of cadmium, zinc, salinity, and temperature on the teratogenicity of methylmercury to the killifish (*Fundulus heteroclitus*). Rapp. P.V. Reun. Cons. Int. Explor. Mer. 178:64-70.

Weis, P. and J.S. Weis. 1980. Effect of zinc on fin regeneration in the mummichog, Fundulus heteroclitus, and its interaction with methylmercury. Fish. Bull. 78:163-166.

Weise, G., G. Burger, S. Fuchs and L. Schurmann. 1985. The effects of zinc and lead in water on assimilation in Fontinalis antipyretica. Acta Hydrochim. Hydrobiol. 13:25-34.

Wentsel, R. and A. McIntosh. 1977. Sediment contamination and benthic macroinvertebrate distribution in a metal-impacted lake. Environ. Pollut. 14:187-193.

Wentsel, R., A. McIntosh, W.P. McCafferty, G. Atchison and V. Anderson. 1977. Avoidance response of midge larvae (Chironomus tentans) to sediments containing heavy metals. Hydrobiologia 55:171-175.

Westerman, A.G. and W.J. Birge. 1978. Accelerated rate of albinism in channel catfish exposed to metals. Prog. Fish-Cult. 40:143-146.

White, K.N. and G. Walker. 1981. Uptake, accumulation, and excretion of zinc by the barnacle, Balanus balanoides (L.). J. Exp. Mar. Biol. Ecol. 51:285-298.

White, S.L. and P.S. Rainbow. 1982. Regulation and accumulation of copper, zinc and cadmium by the shrimp, Palaemon elegans. Mar. Ecol. Prog. Ser. 8:95-101.

Whitley, L.S. 1968. The resistance of tubificid worms to three common pollutants. Hydrobiologia 32:193-205.

Whitton, B.A. 1970. Toxicity of heavy metals to freshwater algae: A review. Phykos 9:116-125.

Whitton, B.A., N.L. Gale and B.G. Wixson. 1981a. Chemistry and plant ecology of zinc-rich wastes dominated by blue-green algae. Hydrobiologia 83:331.

Whitton, B.A., P.J. Say and J.D. Wehr. 1981b. Use of plants to monitor heavy metals in rivers. In: Heavy metals in northern England: Environmental and biological aspects. Say, P.J. and B.A. Whitton (Eds.). University of Durham, Durham, U.K. pp. 135-145.

Whitton, B.A., P.J. Say and B.P. Jupp. 1982. Accumulation of zinc, cadmium and lead by the aquatic liverwort Scapania. Environ. Pollut. (Series B) 3:299-316.

Wiener, J.G. and J.P. Giesy, Jr. 1979. Concentrations of Cd, Cu, Mn, Pb, and Zn in fishes in a highly organic softwater pond. J. Fish. Res. Board Can. 36:270-279.

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. Prog. Ser. 7:191-206.

Williams, L.G. and D.I. Mount. 1965. Influence of zinc on periphytic communities. Am. J. Bot. 52:26-34.

Williamson, K.J. and P.O. Nelson. 1983. Bacterial bioassay for level 1 toxicity assessment. EPA-600/3-83-017. National Technical Information Service, Springfield, VA.

Willis, J.N. and W.G. Sunda. 1984. Relative contributions of food and water in the accumulation of zinc by two species of marine fish. Mar. Biol. (Berl.) 80:273-279.

Willis, M. 1983. A comparative survey of Ancylus fluviatilis (Muller) populations in the Afon Crafnant, N. Wales, above and below an input of zinc from mine-waste. Arch. Hydrobiol. 98:198-214.

Wilson, W.B. and L.R. Freeberg. 1980. Toxicity of metals to marine phytoplankton cultures. EPA-600/3-80-025. National Technical Information Service, Springfield, VA.

Windom, H.L., K.T. Tenore and D.L. Rice. 1982. Metal accumulation by the polychaete, Capitella capitata: Influences of metal content and nutritional quality of detritus. Can. J. Fish. Aquat. Sci. 39:191-196.

Winger, P.V. and J.K. Andreasen. 1985. Contaminant residues in fish and sediments from lakes in the Atchafalaya River basin (Louisiana). Arch. Environ. Contam. Toxicol. 14:579-586.

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) 26:33-37.

Winner, R.W. and J.D. Gauss. 1986. Relationship between chronic toxicity and bioaccumulation of copper, cadmium and zinc as affected by water hardness and humic acid. Aquat. Toxicol. 8:149-161.

Wissmar, R.C., A.H. Devol, A.E. Nevissi and J.R. Sedell. 1982. Chemical changes of lakes within the Mount St. Helens blast zone. Science 216:175-178.

Wolfe, D.A. 1970. Zinc enzymes in Crassostrea virginica. J. Fish. Res. Board Can. 27:59-69.

Wong, M.H. and S.H. Kwan. 1981. The uptake of zinc, lead, copper and manganese by carp fed with activated sludge. Toxicol. Lett. 7:367-372.

Wong, M.H. and F.Y. Tam. 1984a. Sewage sludge for cultivating freshwater algae and the fate of heavy metals at higher trophic organisms. II. Heavy metal contents of *Chlorella pyrenoidosa* cultivated in various extracts. Arch. Hydrobiol. 100:207-218.

Wong, M.H. and F.Y. Tam. 1984b. Sewage sludge for cultivating freshwater algal and the fate of heavy metals at higher trophic organisms. IV. Heavy metal contents in different trophic levels. Arch. Hydrobiol. 100:423-430.

Wong, M.H., S.H. Kwan and F.Y. Tam. 1979. Comparative toxicity of manganese and zinc on *Chlorella pyrenoidosa*, *Chlorella salina* and *Scenedesmus quadricauda*. Microbios Lett. 12:37-46.

Wong, P.T.S., Y.K. Chau and D. Patel. 1982. Physiological and biochemical responses of several freshwater algae to a mixture of metals. Chemosphere 11:367-376.

Wong, M.H., L.M. Chu and W.C. Chan. 1984a. The effects of heavy metals and ammonia in sewage sludge and animal manure on the growth of *Chlorella pyrenoidosa*. Environ. Pollut. (Series A) 34:55-71.

Wong, P.T.S., R.J. Maguire, Y.K. Chau and O. Kramar. 1984b. Uptake and accumulation of inorganic tin by a freshwater alga, *Ankistrodesmus falcatus*. Can. J. Fish. Aquat. Sci. 41:1570-1574.

Wood, K.G. 1975. Trace element pollution in streams of northwestern U.S.A. Int. Ver. Theor. Angew. Limnol. Verh. 19:1641-1645.

Wren, C.D., H.R. Maccrimmon and B.R. Loescher. 1983. Examination of bioaccumulation and biomagnification of metals in a precambrian shield lake. Water Air Soil Pollut. 19:277-291.

Wurtz, C.B. 1962. Zinc effects on fresh water mollusks. Nautilus 76:53-61.

Wurtz, C.B. and C.H. Bridges. 1961. Preliminary results from macroinvertebrate bioassays. Proc. Pa. Acad. Sci. 35:51-56.

Yamamoto, Y., M. Sato and S. Ikeda. 1977. Biochemical studies on L-ascorbic acid in aquatic animals. VIII. Purification and properties of dehydro-L-ascorbic acid reductase from carp hepatopancreas. Bull. Jpn. Soc. Sci. Fish. 43:59-67.

Yan, N.D., G.E. Miller, I. Wile and G.G. Hitchin. 1985. Richness of aquatic macrophyte floras of soft water lakes of differing pH and trace metal content in Ontario, Canada. Aquat. Bot. 23:27-40.

Yasuno, M., S. Hatakeyama and Y. Sugaya. 1985. Characteristic distribution of chironomids in the rivers polluted with heavy metals. Int. Ver. Theor. Angew. Limnol. Verh. 22:2371-2377.

Young, G.J. and R.D. Blevins. 1981. Heavy metal concentrations in the Holston River basin (Tennessee). Arch. Environ. Contam. Toxicol. 10:541-560.

Young, L.G. and L. Nelson. 1974. The effects of heavy metal ions on the motility of sea urchin spermatozoa. Biol. Bull. 147:236-246.

Young, M.L. 1975. The transfer of ^{65}Zn and ^{59}Fe along a *Fucus serratus* (L.)-*Littorina obtusata* (L.) food chain. J. Mar. Biol. Assoc. U.K. 55:583-610.

Young, M.L. 1977. The roles of food and direct uptake from water in the accumulation of zinc and iron in the tissues of the dogwhelk, *Nucella lapillus* (L.). J. Exp. Mar. Biol. Ecol. 30:315-325.

Zadory, L. 1984. Freshwater molluscs as accumulation indicators for monitoring heavy metal pollution. Z. Anal. Chem. 317:375-379.

Zanella, E.F. 1982. Shifts in caddisfly species composition in Sacramento River invertebrate communities in the presence of heavy metal contamination. Bull. Environ. Contam. Toxicol. 29:306-312.

Zirino, A. and S. Yamamoto. 1972. A pH-dependent model for the chemical speciation of copper, zinc, cadmium and lead in seawater. Limnol. Oceanogr. 17:661-671.

Zitko, P., W.V. Carson and W.G. Carson. 1973. Prediction of incipient lethal levels of copper to juvenile Atlantic salmon in the presence of humic acid by cupric electrode. Bull. Environ. Contam. Toxicol. 10:265-271.

Zitko, V. and W.G. Carson. 1976. A mechanism of the effects of water hardness on the lethality of heavy metals to fish. Chemosphere 5:299-303.

Zitko, V. and W.G. Carson. 1977. Seasonal and developmental variation in the lethality of zinc to juvenile Atlantic salmon (<u>Salmo salar</u>). J. Fish. Res. Board Can. 34:139-141.