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# AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR SILVER

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## NOTICES

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## FOREWORD

Section 304(a)(1) of the Clean Water Act 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. Pursuant to that end, this document proposes water quality criteria for the protection of aquatic life. These criteria do not involve consideration of effects on human health.

This document is a draft, distributed for public review and comment. After considering all public comments and making any needed changes, EPA will issue the criteria in final form, at which time they will replace any previously published EPA aquatic life criteria for the same pollutant.

The term "water quality criteria" is used in two sections of the Clean Water Act, section 304(a)(1) and section 303(c)(2). In section 304, the term represents a non-regulatory, scientific assessment of 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, then they become maximum acceptable pollutant concentrations that can be used to derive enforceable permit limits for discharges to such waters.

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 before incorporation into water quality standards. Guidance is available from EPA to assist States in the modification of section 304(a)(1) criteria, and in the development of water quality standards. It is not until their adoption as part of State water quality standards that the criteria become regulatory.

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## Introduction

Primary sources of anthropogenic silver in surface waters include industrial and smelting wastes, wastes in jewelry manufacture, or electrical supply, and most importantly, in the production and disposal of photographic materials. In a study of six water treatment facilities, however, Lytle (1984) found the highest influent concentrations of silver in plants receiving no known photoprocessing or industrial silver wastes. Silver, as silver iodide, is used in cloud seeding operations, and atmospheric transport can result in silver in precipitation great distances from target areas. Freeman (1979) suggested that influent ground water might also be an important source of silver in surface waters.

Silver cycling studies by Freeman (1979) showed a strong affinity of silver for aquatic sediments. Sediments contained approximately 1000 times the silver concentrations occurring in overlying waters. Organic sediments (silt, clay) contained two to three times more silver than inorganic sediments (sand, pebble). Dependent on the specific conditions (e.g., redox potential, pH, dissolved oxygen, organic content, etc.) in sediments, silver might be associated with materials such as manganese dioxide, clay minerals, organic ligands, sulfate, sulfite, or occur as elemental silver. Although silver can exist in the 0, +1, +2, and +3 oxidation states, only the 0 and +1 states occur to any great extent in the environment. The +1 state is the only one that occurs in substantial concentrations in natural waters. Due to the low solubility product constant ($Ksp = 1.8 \times 10^{-10}$) of silver chloride, chloride has a strong influence on the concentration of free ionic silver (Callahan et al. 1979). Free silver ions are photoreduced to elemental silver by natural sunlight at a rate that is dependent on such factors as the degree of radiation, water clarity, and differential penetration of photoreactive wavelengths.

Chambers and Proctor (1960) found that the germicidal action of silver in distilled water was related to the concentration of silver ions, rather than to the physical nature of the silver from which the ions were derived. Studies with saltwater species have shown that toxicity of silver is related to the concentration of the free +1 ion; however, chlorocomplexes appear to play an important role in the accumulation of silver by saltwater organisms (Engel et al. 1981).

Symptoms of silver intoxication in aquatic organisms appear to be similar to those caused by other heavy metals. Separátion and disruption of the gill epithelium is frequently observed, resulting in esphisia. Damage may be the result of silver ions reacting directly at the gill membrane, or as an indirect result of hematological osmotic imbalances (Katz 1979). Although working with a limited data set, Campbell and Stokes (1985) stated that biological responses to silver are generally pH independent.

Unless otherwise noted, all concentrations reported herein are expected to be essentially equivalent to acid-soluble silver concentrations. All concentrations are expressed as silver, not as the chemical tested. A comprehension of the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" (Stephan et al. 1985), hereinafter 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. Results of such intermediate calculations as recalculated LC50s and Species Mean Acute Values are given to four significant figures to prevent round-off error in subsequent calculations, not to reflect the precision of the value. The criteria presented herein supersede previous national aquatic life water quality criteria for silver (U.S. EPA 1976,1980a) because these new criteria were derived using improved procedures and additional information. 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

Acceptable data on the acute effects of silver in fresh water are available for twelve species of invertebrates and seven species of fish (Table 1). Although water hardness or associated factors probably influence silver toxicity and the previous freshwater criterion (U.S. EPA 1980) was based on hardness, it has been determined that insufficient data are available at medium and high hardnesses (> 75 mg/L as $CaCO_3$) upon which to derive national freshwater criterion based upon hardness. The lack of data on silver toxicity at higher hardnesses and the poor agreement between the few data that are available results in poor agreement between species on the regression slopes which were calculated but not presented. Because the freshwater criterion derived herein is weighted by toxicity data from soft waters, criterion concentrations might be overly protective of aquatic organisms in hard waters.

Freshwater Species Mean Acute Values (SMAV) for silver range from 0.9 μg/L for a cladoceran (*Daphnia magna*) to 560 μg/L for a crayfish (*Orconectes immunis*) (Table 1). Genus Mean Acute Values (GMAV) for the 15 most sensitive genera occur within a small range, 2.155 to 29 μg/L (Table 3). Although the five most sensitive genera are arthropods, freshwater fishes do not appear to be greatly more resistant to silver intoxication with SMAVs ranging from 8.163 μg/L for *Rhinichthys osculus* to 13 μg/L for *Lepomis macrochirus*. The Final Acute Value (FAV) in fresh water is 1.833 μg/L. This value exceeds the SMAV for *Daphnia magna* (0.9 μg/L).

The acute toxicity of silver to resident North American saltwater animals has been determined with ten species of invertebrates, including five molluscs, four crustaceans and a polychaete, and eleven species of fish (Table 1). The acute values range from 3 μg/L for the Eastern oyster, Crassostrea virginica (Zaroogian, Manuscript) to > 1,000,000 μg/L for the mummichog, a value in excess of silver's solubility (Dorfman 1977). Of the nine most resistant species, eight were fishes. The four most sensitive species include a fish, the summer flounder Paralichthys dentatus, and three bivalve molluscs, including the Eastern oyster; Pacific oyster, Crassostrea gigas and quahog, Mercenaria mercenaria.

The toxicity of silver to several saltwater species has been tested more than once in the same or different laboratories with generally reasonable agreement in acute values. Values ranged from 145 to > 357 μg/L for the polychaete, Neanthes arenaceodentata (Pesch and Hoffman 1983); from 3 to 37 μg/L for the Eastern and Pacific oysters (Calabrese et al. 1973; Coglianese 1982; Coglianese and Martin 1981; Dinnel et al. 1983; MacInnes and Calabrese 1978; Zaroogian, Manuscript); from 23.5 to 66 μg/L for the copepod Acartia tonsa (Lussier and Cardin 1985; Schimmel 1981); from 74.3 to 300 μg/L for static tests and from 65 to 313 μg/L for flow-through tests for the mysid Mysidopsis bahia (Schimmel 1981); from 640 to 58,000 μg/L for static tests and from 441 to 1,876 μg/L for flow-through tests with the sheepshead minnow, Cyprinodon variegatus (Heitmuller et al. 1981; Schimmel 1981); from 4.7 to 47.7 μg/L for summer flounder, Paralichthys dentatus (Cardin 1986); and from 196 μg/L to 503 μg/L for winter flounder Pseudopleuronectes americanus (Cardin 1986).

Data on the relative sensitivities of early life stages of summer and winter flounder to silver are contradictory. Acute values were similar, 196.3 to 503 μg/L, in tests which began with embryos just after fertilization, in early clevage, at blastula and one-day-old larvae of the winter flounder (Cardin 1986). In contrast, acute values from flow-through tests that began with embryos in early clevage were 15.5 and 47.7 μg/L. Acute values were 8 μg/L in tests that began with embryos at gastrulation and 4.7 μg/L with the larvae (Cardin 1986).

Of the 19 genera for which saltwater Genus Mean Acute Values are available (Table 3), the most sensitive genus, Crassostrea, is about 190 times more sensitive than the most resistant, Fundulus. Molluscs, including oysters, quahogs, scallops, and squid are particularly sensitive to silver. Certain crustaceans and fishes are similarly sensitive. Acute values are available for more than one species for two genera; the maximum difference in Species Mean Acute Values is a factor of 2.74. The saltwater Final Acute Value for silver was calculated to be 14.50 μg/L. This value is slightly higher than Species Mean Acute Values for the Eastern and Pacific oysters, and the copepod Acartia clausi and greater than acute values from nine individual tests with these three species and the summer flounder, Paralichthys dentatus.

## Chronic Toxicity to Aquatic Animals

Acceptable data on chronic toxicity of silver to freshwater organisms are available for a cladoceran and two species of fish (Table 2). Elnabarawy et al. (1986) conducted life-cycle tests with three cladoceran species, Ceriodaphnia reticulata, Daphnia magna, and D. pulex, but did not measure silver concentrations in test chambers. They reported chronic values of 1.3, < 0.56, and < 0.56 μg/L, respectively.

The chronic values for the two cladoceran species reported are close to or greater than 48-hr LC50s. Based on these values, most acute-chronic ratios for the cladocerans are less than 1.0. This is probably due to mitigating influence of the presence of food in the chronic tests. Chapman (1980) reported the 48-hr EC50 for Daphnia magna increased by a factor of 40 when organisms were fed. The mean 21-day LC50 for D. magna of 3.4 μg/L reported by Nebeker (1982) is greater than its Species Mean Acute Value, 2.557 μg/L. All studies reported high mortalities in chronic exposures in the first 24-hr period. Although having high acute toxicity in aquatic macroinvertebrates, silver does not appear to have significant cumulative effect in chronic exposures. Nebeker (1982) and co-workers (1983) reported chronic values for D. magna ranging from 2.6 to 28.6 μg/L, resulting in acute-chronic ratios from 0.3911 to 0.7507.

The effects of chronic exposure to silver have been studied with two fishes, the rainbow trout and fathead minnow. Nebeker et al. (1983) conducted a 60-day early life-stage test with rainbow trout (Salmo gairdneri); growth was reduced at a silver concentration of 1.06 μg/L. Although small, but statistically significant, growth reductions were observed at the lowest concentrations tested, intermediate concentrations did not produce growth reductions compared to the control. The most sensitive parameter appeared to be survival, which was reduced at 0.51 μg/L, but not at 0.36 μg/L. The chronic value for this study was 0.43 μg/L. Davies et al. (1978) reported a similar effect of silver on survival of rainbow trout. In an 18-month exposure, survival was reduced at 0.17 μg/L, but was not affected at 0.09 μg/L. Growth was affected in 18 months at 0.34 μg/L. The chronic value for this study was 0.12 μg/L.

Holcombe and co-workers (1983) conducted an early life-stage exposure with the fathead minnow, Pimephales promelas. Growth was reduced at a silver concentration of 1.07 μg/L, although no effects on growth were observed at 0.65 μg/L. Survival of fry was reduced at 0.65 μg/L, but not at 0.37 μg/L. The chronic value for the fathead minnow was 0.49 μg/L. The acute-chronic ratio was 13.66.

Theoretically, acute-chronic ratios should not be less than 1.0. The chronic value in any test must be equal to or less than the acute value. Although the Species Mean Acute-Chronic Ratio for Daphnia magna was calculated to be 0.4994, considering the mitigating influence of food, as reported by Chapman (1980) and Nebeker et al. (1983), this value might be artificially low. The Acute-Chronic Ratio (ACR) for this species may more realistically be in the range of 15 to 20, which is in general agreement with ACRs for other species tested. Therefore, the ACRs for Daphnia magna were omitted from the calculation of the Final Acute-Chronic Ratio.

The chronic toxicity of silver has been determined in five life-cycle toxicity tests with the saltwater mysid, Mysidopsis bahia (Table 2). Chronic values from these tests conducted at five laboratories ranged from 15.00 to 87.75 μg/L (McKenney 1982). Reproduction was reduced at 15, 19, and 53 μg/L in three tests, and both reproduction and survival were reduced at 16 μg/L in one test. For three of the tests, 96-hr LC50s from flow-through tests using the same dilution water are available. Acute-chronic ratios for these tests ranged from 5.273 to 13.29. The Species Mean Acute-Chronic Ratio for this mysid is 8.512.

The three useful Species Mean Acute-Chronic Ratios are 33.29, 13.66, and 8.512 (Table 3). The geometric mean of these values is 15.70, which is the Final Acute-Chronic Ratio. Division of the freshwater and saltwater Final Acute Values by 15.70 results in freshwater and saltwater Final Chronic Values of 0.1168 and 0.9236 μg/L, respectively, which are lower than the lowest available chronic values.

Toxicity to Aquatic Plants

Three acceptable tests are available with freshwater species exposed to silver (Table 4). The most sensitive species was the alga Selenastrum capricornutum for which the 96-hr EC50, based on chlorophyll a production, was 2.6 µg/L (U.S. EPA 1978). Brown and Rattigan (1979) exposed two freshwater vascular plants to silver for 28 days. EC50s for Elodea canadensis and Lemna minor were 7,500 and 270 µg/L, respectively.

Toxicity tests on silver have been conducted with eight species of saltwater plants (Tables 4 and 6). The 96-hr EC50 for the diatom, Skeletonema costatum, was 130 µg/L based on cell counts and 170 µg/L based on chlorophyll a (U.S. EPA 1978). Chlorophyll a was reduced after two days exposure to 5 µg/L for the dinoflagellate, Glenodinium halli (Wilson and Freeberg 1980). Formation of cystocarps, sexual fusion, in the red alga Champia parvula was reduced by 1.9 µg/L (Steele and Thursley 1983).

The effect of temperature and salinity on the toxicity of silver has been studied with three phytoplankton species (Wilson and Freeberg 1980). Salinity did not significantly affect the toxicity of silver to the diatom Thalassiosira pseudonana, whereas the dinoflagellate Gymnodinium splendens appeared to be more resistant at higher salinities (Table 6). T. pseudonana was most resistant at temperatures between 16 and 20°C, whereas G. splendens was most resistant at temperatures between 20 and 30°C. Chlorophyll a was reduced about 65% after two days exposure to from 15 to 110 µg/L for Isochrysis galbana for 13 temperature - salinity combinations; from 13 to 84 µg/L for T. pseudonana for 25 temperature - salinity combinations; and from 1.3 to 18 µg/L for G. splendens for 15 temperature - salinity combinations.

A Final Plant Value, as defined in the Guidelines, cannot be obtained because no test in which the concentrations of silver were measured has been conducted with any aquatic plant species.

Bioaccumulation

Two studies reported on silver uptake by freshwater fish (Table 5). Largemouth bass (Micropterus salmoides) muscle tissue had bioconcentration factors (BCF) of 11 and 19 after a 120-day exposure to 1 and 10 $\mu$g/L, respectively. Bluegills (Lepomis macrochirus) exposed for 180 days had whole body BCFs of 15 and 150 at water concentrations of 10 and 100 $\mu$g/L, respectively (Cearley 1971). Both species demonstrated a concentration-dependent BCF. In contrast, Barrows et al. (1980) reported no significant uptake of silver by bluegills in a 28-day exposure. No water concentration was given.

Bioconcentration tests have been conducted on silver with one saltwater species, the blue mussel, Mytilus edulis, (Table 5). The mussels were exposed to three concentrations of silver for 12 to 21 months (Calabrese et al. 1984). The highest BCF observed was 6,500. The BCF decreased with increasing concentration of silver in water and reached a maximum value after 12 months of exposure. Fisher et al. (1984) reported a BCF of 34,000 for the diatom Thalassiosira pseudonana, and 13,000 for the green alga Dunaliella tertiolecta exposed to silver cyanide for 12 hours (Table 6).

No U.S. FDA action level or other maximum acceptable concentration in tissue, as defined in the Guidelines, is available for silver; therefore, no Final Residue Value can be calculated.

Other Data

Other data on the lethal and sublethal effects of silver on aquatic organisms are found in Table 6. Two algal species were tested for onset of inhibition of cell multiplication (Bringman and Kuhn 1977a,1978a,b,1980b). The blue-green alga, Microcystis aeruginosa, was about 14 times more sensitive to silver than the green alga, Scenedesmus quadricauda. The blue-green alga was affected at 0.7 µg/L, whereas the green alga was not affected at concentrations less than 9.5 µg/L. Other tests on green algal species produced EC50s or reduced growth effects in 6- to 21-day exposures ranging from 6.4 to 100 µg/L. In general, bacteria were about as sensitive as algae to silver. However, the duration of exposures was much shorter (0.5 to 16 hr) for the bacteria tests than for the algal tests (6-21 day).

Bringmann and Kuhn (1959a,1980a,b,c) tested three species of protozoans for incipient inhibition. Results ranged from 2.6 µg/L for a 48-hr exposure of Chilomonas paramaecium to 580 µg/L for a 72-hr exposure of Entosiphon sulcatum.

Nehring (1976) ran 14-day exposures to silver with two species of immature insects. A mayfly nymph, Ephemerella grandis, was the most sensitive with a 14-day LC50 of < 1 µg/L and a stonefly naiad, Pteronarcys californica, was nearly as sensitive with a 14-day LC50 of 4 to 9 µg/L. Bioconcentration factors (BCF) were determined for each species at death in exposures of 1 to 14 days. BCFs varied inversely with exposure concentration. This may have been the result of increased bioconcentration with lower exposure levels or due to early deaths at the higher exposure concentrations. Mean BCFs of 37 to 84 were reported in the stonefly and mayfly, respectively.

Davies et al. (1978) exposed rainbow trout embryos and larvae for 5 and 22 weeks. They observed premature hatching at concentrations as low as 2.2 μg/L. Rombough (1985) exposed rainbow trout embryos to silver and reported median time to death (LT50). He also exposed a group of embryos with the zonae radiatae (egg capsule) removed. Median time to death was inversely related to exposure concentration for all embryos. Embryos without the zonae radiatae were more sensitive to silver.

Birge (1978) and Birge et al. (1978) exposed two species of fish and two species of amphibians to silver during early life stages. EC50s (dead and deformed larvae) ranged from 10 to 240 μg/L for 7 to 8-day exposures. These results are greater than most of the Species Mean Acute Values for fishes found in Table 1.

LaPoint et al. (1984) related silver concentrations in a Texas stream to benthic invertebrate community dynamics. Although silver levels were high, attaining a maximum of 79.9 μg/L, other factors, such as extreme nutrient loading, appeared to obscure any effects caused solely by silver.

Wilson and Freeberg (1980) studied the effects of temperature and salinity on the toxicity of silver to several species of saltwater unicellular algae. For the most extensively studied species, the diatom Thalassiosira pseudonana, silver was more toxic at temperatures above and below 20°C. For a particular temperature, the toxicity tended to decrease with increasing salinity, except for the combination of 20°C and 3 g/kg salinity, which was the least toxic combination tested. The dinoflagellate Gymnodinium splendens also was more resistant to silver at higher salinities.

Several studies have been conducted with macroalgae (Boney et al. 1959; Steele and Thursby 1983). A significant decrease in the growth of female gametophytes of the red alga Champia parvula was observed after two days of exposure to 3.2 µg/L. No cystocarp formation occurred at concentrations above 1.2 µg/L.

An interlaboratory comparison was performed with the polychaete Neanthes arenaceodentata (Pesch and Hoffman 1983). Ability to burrow was the effect tested. The geometric mean values for the 96-hr and 28-day EC50s were 158.6 and 158.7 µg/L, respectively, which indicates that no additional toxicity occurred during the last 24 days of the test. Windom et al. (1982) studied the uptake of silver from food by a polychaete.

A number of studies of physiological or biochemical effects have been conducted with polychaetes (Pereira and Kanungo 1981), snails (MacInnes and Thurberg 1973), bivalves (Calabrese et al. 1977a,1984; Thurberg et al. 1974,1975), crustaceans (Calabrese et al. 1977b) and fish (Calabrese et al. 1977b; Gould and MacInnes 1977; Jackim 1974; Jackim et al. 1970; Thurberg and Collier 1977). Ionic imbalances in the coelomic fluid and a significant decrease in respiration were observed with the blue mussel, Mytilus edulis, the Eastern oyster, Crassostrea virginica, the surf clam, Spisula solidissima, the quahog, Mercenaria mercenaria, and the soft-shell clam, Mya arenaria, after 96-hr exposures to silver concentrations of 50 to 100 µg/L.

Dinnel et al. (1982,1983) conducted tests with gametes and embryos of many species of echinoderms. The EC50s, based on sperm cell fertilization success after 60-min exposures, ranged from 29.8 to 115.3 µg/L for the four species tested. The most sensitive effect observed was the percentage of larvae developing to the pluteus stage after 5 days of exposure. The lowest EC50 based on this effect was 14.9 µg/L for the sea urchin Strongylocentrotus droebachiensis.

The effect of silver on the early life stages of winter flounder, Pseudopleuronectes americanus, was investigated by Klein-MacPhee et al. (1984)

and Voyer et al. (1982). A significant increase in larval mortality was observed after 18 days of exposure to 92 μg/L. Growth was significantly reduced by 180 μg/L.

Unused Data

Some data on the effects of silver on aquatic organisms were not used because the studies were conducted with species that are not resident in North America (e.g., Khangarot and Ray 1987a; Khangarot et al. 1985; Laroze 1955). McFeters et al. (1983) tested a brine alga, which is too atypical to be used in deriving national criteria. Doudoroff and Katz (1953), Engel et al. (1981), Ganther (1980), Goettl et al. (1976), Jenne et al. (Manuscript), Kay (1984), LeBlanc (1984), Lockhart (Manuscript), Phillips and Russo (1978), Whitton (1970), and the International Joint Commission (1976) compiled data from other sources.

Results were not used when the test procedures were not adequately described (Ding et al. 1982; Fitzgerald 1967; Goettl et al. 1974,1976; Hassell 1962; Ishizake et al. 1966; Palmer and Maloney 1955; Tanaka and Cleland 1978). Acute and chronic tests with fathead minnows from Davies (1976), Davies and Goettl (1978), LeBlanc et al. (1984) and EG & G, Bionomics (1979) were not used because silver concentrations were measured using a silver electrode (Chudd 1983), and it is expected that results would have been substantially different had they been reported in terms of acid-soluble silver.

Data were not used when silver was a component of an effluent or mixture (Bryan et al. 1983; Doudoroff et al. 1966; Greig 1979; Lewis 1986; Lopez-Avila et al. 1985; Luoma and Jenne 1975; Malins et al. 1984; Martin et al. 1984; McDermott et al. 1976; Parsons et al. 1973; Reynolds 1979; Roesijadi et al. 1984; Terhaar et al. 1972; Young and Lisk 1972). Data were not used when the organisms were exposed to silver by injection or gavage (Hibiya and Orguri 1961; Storebakken et al. 1981). Christensen (1971), Christensen and Tucker (1976), and Dalmon and Bayen (1976) only exposed enzymes, excised or homogenized tissue, or cell cultures.

Tests conducted without controls (Albright and Wilson 1974; Coleman and Clearley 1974) were not used. Data from Buikema et al. (1973, 1974a,b) were not used due to possible reproductive interactions. High control mortalities occurred in a life-cycle test reported by McKenney (1982). Data from Hale (1977) was not used because dilution water contained high concentrations of other heavy metals.

Results of some laboratory tests were not used because the tests were conducted in distilled or deionized water without addition of appropriate salts (Chambers and Proctor 1960; Jones 1939,1940; Mukai 1977; Shaw and Groshkin 1957; Shaw and Lowrance 1956). Watanabe and Takimoto (1977) tested silver toxicity in duckweed at a pH below 6.5. Dilution waters used by Hannan and Patouillet (1972) contained high organic levels. Results from Bringmann and Kuhn (1977b) were not used because organisms were cultured and tested in different waters.

Results of laboratory bioconcentration tests were not used when the concentration of silver in the test solution was not adequately measured (Goettl and Davies 1978). Reports of the concentrations of silver in wild aquatic organisms (Amiard 1978a,b,1979; Bryan et al. 1983; Eisler et al. 1978; Estabrook et al. 1985; Feldt and Melzer 1978; Hall et al. 1978; Jones et al. 1985; Lucas and Edgington 1970; Martin, Manuscript; Martin and Flegal 1975; Martin and Knauer 1972; Martin et al. 1984; Nelson et al. 1983; Reynolds 1979; Strong and Luoma 1981; Telitchenko et al. 1970; Tong et al. 1972; Van Coillie and Rousseau 1974) were not used to calculate bioaccumulation factors due to an insufficient number of measurements of the concentration of silver in water. BCFs obtained from microcosm or model ecosystem studies were not used when the concentration of silver in water decreased with time (Terhaar et al. 1977).

Summary

The toxicity of silver is probably influenced by water hardness or related factors, although insufficient data are available on which to base national freshwater criteria upon hardness. Silver is highly toxic to both freshwater macroinvertebrates and fishes in acute exposures. Acute values ranged from 0.9 μg/L to 29 μg/L for the 15 most sensitive species. A crayfish, Orconectes immunis, was the most resistant species to silver with a 96-hr LC50 of 560 μg/L. The six most sensitive species were arthropods.

Data are available for a cladoceran and two species of fish in chronic exposures. Chronic values for cladocerans were above acute values that were obtained in acute tests in which the organisms were not fed, but were below acute values obtained in acute tests in which the organisms were fed. Mean chronic values were 0.2272 and 0.49 μg/L for rainbow trout and fathead minnows, respectively. Their respective acute-chronic ratios were 33.29 and 13.66. Freshwater vascular plants appeared to be relatively insensitive to silver, although algae and other microorganisms were reported to be very sensitive. Uptake of silver was reported for several organisms. Bioconcentration factors ranged from less than detectable to 150.

Acute toxicity values for silver are available for 21 species of saltwater animals including ten species of invertebrates and eleven species of fish. Acute values range from 3 μg/L for the Eastern oyster to

> 1,000,000 for the mummichog. Fishes are generally resistant except for sensitive early life stages. The four most sensitive species include embryo and larval stages of the summer flounder, Eastern oyster, Pacific oyster, and quahog.

The chronic toxicity of silver has been determined in five life-cycle toxicity tests with the saltwater mysid, Mysidopsis bahia. Chronic values ranged from 15.00 to 87.75 µg/L based primarily on decreases in reproduction. Acute-chronic ratios for the three tests for which 96-hr LC50s were available ranged from 5.273 to 13.29. The toxicity of silver has been determined with eight species of saltwater plants. Four species, Thalassiosira pseudonana, Glenodinium halli, Gymnodinium splendens, and Champia parvula were affected in one or more tests at concentrations below the acute value for the most sensitive saltwater animal. The blue mussel can bioconcentrate silver from 1,056 to 6,500 times the concentration in water. Embryonic development of sea urchins and surf clam embryos was affected and physiological or histological changes occurred in American lobsters, surf clams, and blue mussels at concentrations below the acute value for the most sensitive saltwater animal.

## 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 of silver does not exceed 0.12 µg/L more than once every three years on the average and if the one-hour average concentration does not exceed 0.92 µg/L more than once every three years on the average.

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 silver does not exceed 0.92 $\mu$g/L more than once every three years on the average and if the one-hour average concentration does not exceed 7.2 $\mu$g/L more than once every three years on the average.

Implementation

Because of the variety of forms of silver in ambient water and the lack of definitive information about their relative toxicities to aquatic species, no available analytical measurement is known to be ideal for expressing aquatic life criteria for silver. Previous aquatic life criteria for metals and metalloids (U.S. EPA 1980b) were expressed in terms of the total recoverable measurement (U.S. EPA 1983a), but newer criteria for metals and metalloids have been expressed in terms of the acid-soluble measurement (U.S. EPA 1985b). Acid-soluble silver (operationally defined as the silver that passes through a 0.45 $\mu$m membrane filter after the sample has been acidified to a pH between 1.5 and 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 silver to, and bioaccumulation of silver by, aquatic organisms. It is expected that the results of tests used in the derivation of the criteria would not have been substantially different if they had been reported in terms of acid-soluble silver.
2. On samples of ambient water, measurement of acid-soluble silver will probably measure all forms of silver 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 silver 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 silver, such as the EDTA complex of silver, 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 silver in aqueous effluents. Measurement of acid-soluble silver is expected to be applicable to effluents because it will measure precipitates, such as carbonate and hydroxide precipitates of silver, 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 silver might be used to determine whether the receiving water can decrease the concentration of acid-soluble silver because of sorption.
4. The acid-soluble measurement is expected to be useful for most metals and metalloids, thus minimizing the number of samples and procedures that are necessary.
5. The acid-soluble measurement does not require filtration of the sample 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 a pH between 1.5 and 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. Ambient waters have much higher buffer intensities at a pH between 1.5 and 2.0 than they do at a pH between 4 and 9 (Stumm and Morgan 1981).
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 silver, 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 silver in terms of the acid-soluble measurement has both toxicological and practical advantages. The U.S. EPA is considering development and approval of a method for a measurement such as acid-soluble.

Metals and metalloids might be measured using the total recoverable method (U.S. EPA 1983a). This would have two major impacts because this method includes a digestion procedure. First, certain species of some metals and metalloids cannot be measured because the total recoverable method cannot distinguish between individual oxidation states. Second, in some cases these criteria would be overly protective when based on the total recoverable method because the digestion procedure will dissolve silver that is not toxic and cannot be converted to a toxic form under natural conditions. Because no measurement is known to be ideal for expressing aquatic life criteria for silver or for measuring silver in ambient water or aqueous effluents, measurement of both acid-soluble silver and total recoverable silver in ambient water or effluent or both might be useful. For example, there might be cause for concern when total recoverable silver is much above an applicable limit, even though acid-soluble silver is below the limit.

In addition, metals and metalloids might be measured using the dissolved method, but this would also have several impacts. First, in many toxicity tests on silver the test organisms were exposed to both dissolved and undissolved silver. If only the dissolved silver had been measured, the acute and chronic values would be lower than if acid-soluble or total recoverable silver had been measured. Therefore, water quality criteria expressed as dissolved silver would be lower than criteria expressed as acid-soluble or total recoverable silver. Second, not enough data are available concerning the toxicity of dissolved silver to allow derivation of a criterion based on dissolved silver. Third, whatever analytical method is specified for measuring silver in ambient surface water will probably also be used to monitor effluents. If effluents are monitored by measuring only the dissolved metals and metalloids, carbonate and hydroxide precipitates of metals would not be measured. Such precipitates might dissolve, due to dilution or change in pH or both, when the effluent is mixed with receiving water. Fourth, measurement of dissolved silver requires filtration of the sample at the time of collection. For these reasons, it is recommended that aquatic life criteria for silver not be expressed as dissolved silver.

As discussed in the Water Quality Standards Regulation (U.S. EPA 1983b) and the Foreword to this document, a water quality criterion for aquatic life has regulatory impact only after it has been adopted in a state water quality standard. Such a standard specifies a criterion for a pollutant that is consistent with a particular designated use. With the concurrence of the U.S. EPA, states designate one or more uses for each body of water or segment thereof and adopt criteria that are consistent with the use(s) (U.S. EPA

1983c,1987). In each standard a state may adopt the national criterion, if one exists, or, if adequately justified, a site-specific criterion.

Site-specific criteria may include not only site-specific criterion concentrations (U.S. EPA 1983c), but also site-specific, and possibly pollutant-specific, durations of averaging periods and frequencies of allowed excursions (U.S. EPA 1985c). The averaging periods of "one hour" and "four days" were selected by the U.S. EPA on the basis of data concerning how rapidly some aquatic species react to increases in the concentrations of some pollutants, and "three years" is the Agency's best scientific judgment of the average amount of time aquatic ecosystems should be provided between excursions (Stephan et al. 1985; U.S. EPA 1985c). However, various species and ecosystems react and recover at greatly differing rates. Therefore, if adequate justification is provided, site-specific and/or pollutant-specific concentrations, durations, and frequencies may be higher or lower than those given in national water quality criteria for aquatic life.

Use of criteria, which have been adopted in state water quality standards, for developing water quality-based permit limits and for designing waste treatment facilities requires selection of an appropriate wasteload allocation model. Although dynamic models are preferred for the application of these criteria (U.S. EPA 1985c), limited data or other considerations might require the use of a steady-state model (U.S. EPA 1986). Guidance on mixing zones and the design of monitoring programs is also available (U.S. EPA 1985c,1987).

Table 1. Acute Toxicity of Silver to Aquatic Animals

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| **FRESHWATER SPECIES** | | | | | | |
| Hydra, *Hydra* sp. | S, M | Silver nitrate | 46.6 | 26 | 26 | Brooke et al. 1986 |
| Leech, *Nephelopsis obscura* | S, M | Silver nitrate | 46.6 | 53 | - | Brooke et al. 1986 |
| Leech, *Nephelopsis obscura* | F, M | Silver nitrate | 44.7 | 29 | 29 | Holcombe et al. 1987 |
| Snail (adult), *Aplexa hypnorum* | R, M | Silver nitrate | 50.4 | 241 | - | Holcombe et al. 1983 |
| Snail, *Aplexa hypnorum* | F, M | Silver nitrate | 44.7 | 83 | 83 | Holcombe et al. 1987 |
| Cladoceran, *Ceriodaphnia reticulata* | S, U | - | 45. | 11 | - | Mount and Norberg 1984 |
| Cladoceran (<24 hr), *Ceriodaphnia reticulata* | S, U | Silver nitrate | 240 | 1.4 | 3.924 | Elnabarawy et al. 1986 |
| Cladoceran, *Daphnia magna* | S, M | Silver nitrate | 54 | 2.2 | - | Lemke 1981 |
| Cladoceran, *Daphnia magna* | S, M | Silver nitrate | - | 1.07 | - | Lemke 1981 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (μg/L)[b] | Species Mean Acute Value (μg/L) | Reference |
|---|---|---|---|---|---|---|
| Cladoceran, *Daphnia magna* | S, M | Silver nitrate | - | 0.64 | - | Lemke 1981 |
| Cladoceran, *Daphnia magna* | S, U | Silver nitrate | - | 0.39 | - | Lemke 1981 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 255 | 48. (45) | - | Nebeker 1982; Lemke 1981 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 255 | 55. (49) | - | Nebeker 1982; Lemke 1981 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 73 | 8.4 | - | Nebeker 1982; Lemke 1981 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 73 | 14.9 | - | Nebeker 1982; Lemke 1981 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 60 | 1.1 | - | Nebeker 1982; Lemke 1981 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 60 | 0.6 | - | Nebeker 1982; Lemke 1981 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 46 | 0.63 | - | Nebeker 1982; Lemke 1981 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 46 | 0.66 | - | Nebeker 1982; Lemke 1981 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 46 | 0.9 | - | Nebeker 1982; Lemke 1981 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 46 | 1.03 | - | Nebeker 1982; Lemke 1981 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 54 | 2.9 | - | Nebeker 1982; Lemke 1981 |
| Cladoceran (24 hr), *Daphnia magna* | S, M | Silver nitrate | 47 | 0.24 | - | Chapman 1980 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 60 | 1.1 | - | Nebeker et al. 1983 |
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 38-40 | 0.6 | - | Nebeker et al. 1983 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Cladoceran (<24 hr), *Daphnia magna* | S, M | Silver nitrate | 38-40 | - | - | Nebeker et al. 1983 |
| Cladoceran (<24 hr), *Daphnia magna* | S, U | - | 72 | 1.5 | - | LeBlanc 1980 |
| Cladoceran (adult), *Daphnia magna* | S, U | Silver nitrate | 240 | 10 | - | Khangarot and Ray 1987b |
| Cladoceran (<24 hr), *Daphnia magna* | S, U | Silver nitrate | 240 | 1.5 | - | Elnabarawy et al. 1986 |
| Cladoceran (<24 hr), *Daphnia magna* | F, M | Silver nitrate | 44.7 | 0.9 | 0.9 | Holcombe et al. 1987 |
| Cladoceran (<24 hr), *Daphnia pulex* | S, U | - | 45 | 14. | - | Mount and Norberg 1984 |
| Cladoceran (<24 hr), *Daphnia pulex* | S, U | Silver nitrate | 240 | 1.9 | 5.158 | Elnabarawy et al. 1986 |
| Cladoceran, *Simocephalus vetulus* | S, U | - | 45 | 15 | 15 | Mount and Norberg 1984 |
| Amphipod, *Crangonyx pseudogracilis* | R, U | Silver nitrate | 50 | 5 | 5 | Martin and Holdich 1986 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Amphipod (adult), *Gammarus pseudolimnaeus* | F, M | Silver nitrate | 48.1 | 4.5 | 4.5 | Lima et al. 1982; Call et al. 1983 |
| Mayfly (nymph), *Leptophlebia* sp. | S, M | Silver nitrate | 46.6 | 2.2 | 2.2 | Brooke et al. 1986 |
| Midge (3rd instar), *Tanytarsus dissimilis* | S, M | Silver nitrate | 47.9 | 3,160 | - | Lima et al. 1982; Call et al. 1983 |
| Midge (larva), *Tanytarsus dissimilis* | F, M | Silver nitrate | 44.7 | 420 | 420 | Holcombe et al. 1987 |
| Crayfish, *Orconectes immunis* | F, M | Silver nitrate | 44.7 | 560 | 560 | Holcombe et al. 1987 |
| Rainbow trout (larva), *Salmo gairdneri* | S, M | Silver nitrate | 48 | 19.92 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | S, M | Silver nitrate | 255 | 240 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | S, M | Silver nitrate | 54 | 48 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | S, M | Silver nitrate | 46.1 | 11.8 | - | Lemke 1981 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Rainbow trout (larva), *Salmo gairdneri* | S, M | Silver nitrate | 75 | 24.6 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | S, M | Silver nitrate | 48 | 31.80 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | S, M | Silver nitrate | 255 | 280 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | S, M | Silver nitrate | 54 | 54 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | S, M | Silver nitrate | 46 | 108.9 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | S, M | Silver nitrate | 75 | 22.5 | - | Lemke 1981 |
| Rainbow trout (juvenile), *Salmo gairdneri* | S, M | Silver nitrate | 40 | 72.9 | - | Nebeker et al. 1983 |
| Rainbow trout (juvenile), *Salmo gairdneri* | S, M | Silver nitrate | 37 | 84.4 | - | Nebeker et al. 1983 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Rainbow trout (juvenile), *Salmo gairdneri* | S, M | Silver nitrate | 26 | 10.9 | - | Nebeker et al. 1983 |
| Rainbow trout (juvenile), *Salmo gairdneri* | S, M | Silver nitrate | 35 | 8.5 | - | Nebeker et al. 1983 |
| Rainbow trout (larva), *Salmo gairdneri* | F, U | Silver nitrate | 54 | 16.38 | - | Lemke 1981 |
| Rainbow trout (69 mm), *Salmo gairdneri* | F, M | Silver nitrate | 31 | 5.3 | - | Davies et al. 1978; Goettl and Davies 1978 |
| Rainbow trout (146 mm), *Salmo gairdneri* | F, M | - | 20 | 6.2 | - | Davies et al. 1978; Goettl and Davies 1978 |
| Rainbow trout (173 mm), *Salmo gairdneri* | F, M | - | 26 | 8.1 | - | Davies et al. 1978; Goettl and Davies 1978 |
| Rainbow trout (167 mm), *Salmo gairdneri* | F, M | - | 350 | 13.0 | - | Davies et al. 1978; Goettl and Davies 1978 |
| Rainbow trout (juvenile), *Salmo gairdneri* | F, M | Silver nitrate | 36 | 9.2 | - | Nebeker et al. 1983 |
| Rainbow trout (juvenile), *Salmo gairdneri* | F, M | Silver nitrate | 29 | 8.6 | - | Nebeker et al. 1983 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Rainbow trout (juvenile), *Salmo gairdneri* | F, M | Silver nitrate | 42 | 9.7 | - | Nebeker et al. 1983 |
| Rainbow trout (larva), *Salmo gairdneri* | F, M | Silver nitrate | 48 | 17.87 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | F, M | Silver nitrate | 255 | 240 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | F, M | Silver nitrate | 54 | 14 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | F, M | Silver nitrate | 46.1 | 6.9 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | F, M | Silver nitrate | 75 | 11.5 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | F, M | Silver nitrate | 255 | 170 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | F, M | Silver nitrate | 46.1 | 8.4 | - | Lemke 1981 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Rainbow trout (larva), *Salmo gairdneri* | F, M | Silver nitrate | 75 | 9.7 | - | Lemke 1981 |
| Rainbow trout (larva), *Salmo gairdneri* | F, U | Silver nitrate | 54 | 16.38 | - | Lemke 1981 |
| Rainbow trout (juvenile), *Salmo gairdneri* | F, M | Silver nitrate | 44.7 | 6 | 13.38 | Holcombe et al. 1987 |
| Fathead minnow, *Pimephales promelas* | S, M | Silver nitrate | 48 | 30.43 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | S, M | Silver nitrate | 255 | 230 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | S, M | Silver nitrate | 54 | 13.8 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | S, M | Silver nitrate | 46.1 | 6.7 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | S, M | Silver nitrate | 75 | 10.3 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | S, M | Silver nitrate | 48 | 22.66 | - | Lemke 1981 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Fathead minnow, *Pimephales promelas* | S, M | Silver nitrate | 255 | 270 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | S, M | Silver nitrate | 54 | 19.6 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | S, M | Silver nitrate | 46.1 | 12.3 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | S, M | Silver nitrate | 75 | 8.7 | - | Lemke 1981 |
| Fathead minnow (juvenile), *Pimephales promelas* | F, M | Silver nitrate | 40 | 5.6 | - | Nebeker et al. 1983; Lemke 1981 |
| Fathead minnow (juvenile), *Pimephales promelas* | F, M | Silver nitrate | 36 | 7.4 | - | Nebeker et al. 1983; Lemke 1981 |
| Fathead minnow (juvenile), *Pimephales promelas* | S, M | Silver nitrate | 38 | 9.4 | - | Nebeker et al. 1983; Lemke 1981 |
| Fathead minnow (juvenile), *Pimephales promelas* | S, M | Silver nitrate | 39 | 9.7 | - | Nebeker et al. 1983; Lemke 1981 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Fathead minnow (0.15 g), *Pimephales promelas* | S, M | Silver nitrate | 44.8 | 14.0 | - | Holcombe et al. 1983 |
| Fathead minnow (37 mm), *Pimephales promelas* | F, U | Silver nitrate | 33 | 3.9 | - | Goettl and Davies 1978 |
| Fathead minnow (37 mm), *Pimephales promelas* | F, U | Silver nitrate | 274 | 4.8 | - | Goettl and Davies 1978 |
| Fathead minnow (juvenile), *Pimephales promelas* | F, M | Silver nitrate | 44.7 | 9 | - | Holcombe et al. 1987 |
| Fathead minnow, *Pimephales promelas* | F, M | Silver nitrate | 38 | 16 | - | EG & G Bionomics 1979; LeBlanc et al. 1984 |
| Fathead minnow (30 day old), *Pimephales promelas* | F, M | Silver nitrate | 46.0 | 10.7 | - | Lima et al. 1982; Call et al. 1983 |
| Fathead minnow, *Pimephales promelas* | F, M | Silver nitrate | 48 | 10.98 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | F, M | Silver nitrate | 255 | 150 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | F, M | Silver nitrate | 54 | 11.1 | - | Lemke 1981 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Fathead minnow, *Pimephales promelas* | F, M | Silver nitrate | 46.1 | 5.3 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | F, M | Silver nitrate | 75 | 6.3 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | F, M | Silver nitrate | 48 | 11.75 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | F, M | Silver nitrate | 255 | 110 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | F, M | Silver nitrate | 46.1 | 3.9 | - | Lemke 1981 |
| Fathead minnow, *Pimephales promelas* | F, M | Silver nitrate | 75 | 5.0 | - | Lemke 1981 |
| Fathead minnow (0.15 g), *Pimephales promelas* | F, M | Silver nitrate | 44.4 | 6.7 | 11.34 | Holcombe et al. 1983 |
| Speckled dace (68 mm), *Rhinichthys osculus* | F, U | Silver nitrate | 30 | 4.9 | - | Goettl and Davies 1978 |
| Speckled dace (68 mm), *Rhinichthys osculus* | F, U | Silver nitrate | 250 | 13.6 | 8.163 | Goettl and Davies 1978 |

Table 1. (continued)

| Species | Method[a] | Chemical | Hardness (mg/L as $CaCO_3$) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Mottled sculpin (81 mm), Cottus bairdi | F, U | Silver nitrate | 30 | 5.3 | - | Goettl and Davies 1978 |
| Mottled sculpin (81 mm), Cottus bairdi | F, U | Silver nitrate | 250 | 13.6 | 8.490 | Goettl and Davies 1978 |
| Channel catfish (14.2 g), Ictalurus punctatus | F, M | Silver nitrate | 44.4 | 17.3 | 17.3 | Holcombe et al. 1983 |
| Flagfish (30 day old), Jordonella floridae | F, M | Silver nitrate | 44.5 | 9.2 | 9.2 | Lima et al. 1982; Call et al. 1983 |
| Bluegill (young of the year) Lepomis macrochirus | S, U | Silver nitrate | 32-48 | 60 | - | Buccafusco et al. 1981 |
| Bluegill (juvenile), Lepomis macrocnirus | F, M | Silver nitrate | 44.7 | 13 | 13 | Holcombe et al. 1987 |
| | | | **SALTWATER SPECIES** | | | |
| Polychaete, Neanthes arenaceodentata | F, M | Silver nitrate | 30[c] | 151 | - | Pesch and Hoffman 1983 |
| Polychaete, Neanthes arenaceodentata | F, M | Silver nitrate | 30[c] | 145 | - | Pesch and Hoffman 1983 |

Table 1. (continued)

| Species | Method[a] | Chemical | Salinity (g/kg) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Polychaete, *Neanthes arenaceodentata* | F, M | Silver nitrate | 30 | 260 | - | Pesch and Hoffman 1983 |
| Polychaete, *Neanthes arenaceodentata* | F, M | Silver nitrate | 30 | > 357[d] | 178.6 | Pesch and Hoffman 1983 |
| Bay scallop (juvenile), *Argopectin irradians* | R, U | Silver nitrate | 25 | 33 | 33 | Nelson et al. 1976 |
| Pacific oyster (embryo, larva), *Crassostrea gigas* | S, U | Silver nitrate | 33.0 | 11.91 | - | Coglianese and Martin 1981 |
| Pacific oyster (embryo, larva), *Crassostrea gigas* | S, U | Silver nitrate | 33.0 | 15.10 | - | Coglianese and Martin 1981 |
| Pacific oyster (embryo, larva), *Crassostrea gigas* | S, U | Silver nitrate | 33.0 | > 18[c] | - | Coglianese 1982 |
| Pacific oyster (embryo, larva), *Crassostrea gigas* | S, U | Silver nitrate | 22.7 | > 11.94[e] | - | Coglianese 1982 |
| Pacific oyster (embryo, larva), *Crassostrea gigas* | S, M | Silver nitrate | 30 | 19.0 | 14.21 | Dinnel et al. 1983 |
| Eastern oyster (embryo, larva), *Crassostrea gigas* | S, U | Silver nitrate | 25 | 5.8 | - | Calabrese et al. 1973 |

Table 1. (continued)

| Species | Method[a] | Chemical | Salinity (g/kg) | LC50 or EC50 (μg/L)[b] | Species Mean Acute Value (μg/L) | Reference |
|---|---|---|---|---|---|---|
| Eastern oyster (embryo, larva), *Crassostrea virginica* | S, U | Silver nitrate | 26 (20°C) | 24.2 | - | MacInnes and Calabrese 1978 |
| Eastern oyster (embryo, larva), *Crassostrea virginica* | S, U | Silver nitrate | 26 (25°C) | 35.3 | - | MacInnes and Calabrese 1978 |
| Eastern oyster (embryo, larva), *Crassostrea virginica* | S, U | Silver nitrate | 26 (30°C) | 32.2 | - | MacInnes and Calabrese 1978 |
| Eastern oyster (embryo, larva), *Crassostrea virginica* | S, U | Silver nitrate | 30 | 13 | - | Zaroogian, Manuscript |
| Eastern oyster (embryo, larva), *Crassostrea virginica* | S, U | Silver nitrate | 30 | 7 | - | Zaroogian, Manuscript |
| Eastern oyster (embryo, larva), *Crassostrea virginica* | S, U | Silver nitrate | 30 | 3 | - | Zaroogian, Manuscript |
| Eastern oyster (embryo, larva), *Crassostrea virginica* | S, U | Silver nitrate | 30 | 37 | 14.15 | Zaroogian, Manuscript |
| Quahog clam (embryo, larva), *Mercenaria mercenaria* | S, U | Silver nitrate | 25 | 21 | 21 | Calabrese and Nelson 1974 |
| Squid (larva), *Loligo opalescens* | S, M | Silver nitrate | 30 | > 100, < 200 | > 100, < 200 | Dinnel et al. 1983 |

Table 1. (continued)

| Species | Method[a] | Chemical | Salinity (g/kg) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Copepod (adult), *Acartia clausi* | S, U | Silver nitrate | 30 | 13.3 | 13.3 | Lussier and Cardin 1985 |
| Copepod (adult), *Acartia tonsa* | S, M | Silver nitrate | 30 | 37.8 | - | Lussier and Cardin 1985 |
| Copepod (adult), *Acartia tonsa* | S, U | Silver nitrate | 28 | 30.9 | - | Schimmel 1981 |
| Copepod (adult), *Acartia tonsa* | S, U | Silver nitrate | 28 | 66.0 | - | Schimmel 1981 |
| Copepod (adult), *Acartia tonsa* | S, U | Silver nitrate | 28 | 35.8 | - | Schimmel 1981 |
| Copepod (adult), *Acartia tonsa* | S, U | Silver nitrate | 28 | 23.5 | - | Schimmel 1981 |
| Copepod (adult), *Acartia tonsa* | S, U | Silver nitrate | 28 | 36.4 | - | Schimmel 1981 |
| Copepod (adult), *Acartia tonsa* | S, U | Silver nitrate | 30 | 36.3 | 36.46 | Lussier and Cardin 1985 |
| Mysid (juvenile), *Mysidopsis bahia* | S, U | Silver nitrate | 28 | 264 | - | Schimmel 1981 |
| Mysid (juvenile), *Mysidopsis bahia* | S, U | Silver nitrate | 28 | 159.4 | - | Schimmel 1981 |
| Mysid (juvenile), *Mysidopsis bahia* | S, U | Silver nitrate | 28 | 203 | - | Schimmel 1981 |
| Mysid (juvenile), *Mysidopsis bahia* | S, U | Silver nitrate | 28 | 248 | - | Schimmel 1981 |

Table 1. (continued)

| Species | Method[a] | Chemical | Salinity (g/kg) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Mysid (juvenile), *Mysidopsis bahia* | S, U | Silver nitrate | 28 | 178 | - | Schimmel 1981 |
| Mysid (juvenile), *Mysidopsis bahia* | S, U | Silver nitrate | 28 | 74.3 | - | Schimmel 1981 |
| Mysid (juvenile), *Mysidopsis bahia* | S, U | Silver nitrate | 15-30 | 89.54 | - | McKenney 1982 |
| Mysid (juvenile), *Mysidopsis bahia* | S, U | Silver nitrate | 15-30 | 300 | - | McKenney 1982 |
| Mysid (juvenile), *Mysidopsis bahia* | S, U | Silver nitrate | 15-30 | 300 | - | McKenney 1982 |
| Mysid (juvenile), *Mysidopsis bahia* | S, U | Silver nitrate | 15-30 | 298 | - | McKenney 1982 |
| Mysid (juvenile), *Mysidopsis bahia* | F, U | Silver nitrate | 15-30 | 64 | - | McKenney 1982 |
| Mysid (juvenile), *Mysidopsis bahia* | F, M | Silver nitrate | 30 | 249 | - | Lussier et al. 1985 |
| Mysid (juvenile), *Mysidopsis bahia* | F, M | Silver nitrate | 28 | 256 | - | Schimmel 1981 |
| Mysid (juvenile), *Mysidopsis bahia* | F, M | Silver nitrate | 28 | 300 | - | Schimmel 1981 |
| Mysid (juvenile), *Mysidopsis bahia* | F, M | Silver nitrate | 28 | 86 | - | Schimmel 1981 |
| Mysid (juvenile), *Mysidopsis bahia* | F, M | Silver nitrate | 28 | 313 | - | Schimmel 1981 |

Table 1. (continued)

| Species | Method[a] | Chemical | Salinity (g/kg) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Mysid (juvenile), *Mysidopsis bahia* | F, M | Silver nitrate | 28 | 65 | - | Schimmel 1981 |
| Mysid (juvenile), *Mysidopsis bahia* | F, M | Silver nitrate | 28 | 132 | 171.8 | Schimmel 1981 |
| Sand shrimp (adult), *Crangon* spp. (mostly *Crangon franciscorum*) | F, M | Silver nitrate | 30.1 | > 838 | > 838 | Dinnel et al. 1983 |
| Dungeness crab (zoea), *Cancer magister* | S, M | Silver nitrate | 30 | 33.1 | 33.1 | Dinnel et al. 1983 |
| Coho salmon (smolt), *Oncorhynchus kisutch* | F, M | Silver nitrate | 28.6 | 487.5 | 487.5 | Dinnel et al. 1983 |
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | S, U | Silver nitrate | 10-31 | 58,000 | - | U.S. EPA 1978; Heitmuller et al. 1981 |
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | S, U | Silver nitrate | 28 | 640 | - | Schimmel 1981 |
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | S, U | Silver nitrate | 28 | 1,082 | - | Schimmel 1981 |
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | S, U | Silver nitrate | 28 | 1,182 | - | Schimmel 1981 |
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | S, U | Silver nitrate | 28 | 1,584 | - | Schimmel 1981 |

Table 1. (continued)

| Species | Method[a] | Chemical | Salinity (g/kg) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | S, M | Silver nitrate | 30 | 1,376 | - | Cardin 1986 |
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | F, M | Silver nitrate | 28 | 441 | - | Schimmel 1981 |
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | F, M | Silver nitrate | 28 | 898 | - | Schimmel 1981 |
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | F, M | Silver nitrate | 28 | 1,356 | - | Schimmel 1981 |
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | F, M | Silver nitrate | 28 | 1,510 | - | Schimmel 1981 |
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | F, M | Silver nitrate | 28 | 1,876 | 1,088 | Schimmel 1981 |
| Mummichog (adult), *Fundulus heteroclitus* | S, U | Silver nitrate | 7.2 | $> 1 \times 10^6$ | - | Dorfman 1977 |
| Mummichog (adult), *Fundulus heteroclitus* | S, U | Silver nitrate | 24.0 | 2,700 | 2,700 | Dorfman 1977 |
| Atlantic silverside (juvenile), *Menidia menidia* | S, U | Silver nitrate | 30 | 404 | - | Cardin 1986 |

Table 1. (continued)

| Species | Method[a] | Chemical | Salinity (g/kg) | LC50 or EC50 (μg/L)[b] | Species Mean Acute Value (μg/L) | Reference |
|---|---|---|---|---|---|---|
| Atlantic silverside (larva), *Menidia menidia* | F, M | Silver nitrate | 32 | 110.1 | 110.1 | Cardin 1986 |
| Fourspine stickleback (adult), *Apeltes quadracus* | S, U | Silver nitrate | 30 | 546.6 | 546.6 | Cardin 1986 |
| Shiner perch (adult), *Cymatogaster aggregata* | F, M | Silver nitrate | 29.3 | 355.6 | 355.6 | Dinnel et al. 1983 |
| Cabezon (larva), *Scorpaenichthys marmoratus* | S, M | Silver nitrate | 27 | > 800 | > 800 | Dinnel et al. 1983 |
| Summer flounder (embryo), *Paralichthys dentatus* | S, U | Silver nitrate | 30.2 | 140.8 | 140.8 | Cardin 1986 |
| Summer flounder (embryo), *Paralichthys dentatus* | F, M | Silver nitrate | 30 | 47.7 | - | Cardin 1986 |
| Summer flounder (larva), *Paralichthys dentatus* | S, U | Silver nitrate | 30 | 4.7 | - | Cardin 1986 |
| Summer flounder (embryo), *Paralichthys dentatus* | F, M | Silver nitrate | 30 | 8 | - | Cardin 1986 |
| Summer flounder (embryo), *Paralichthys dentatus* | F, M | Silver nitrate | 30 | 15.5 | 18.08 | Cardin 1986 |

Table 1. (continued)

| Species | Method[a] | Chemical | Salinity (g/kg) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| English sole (juvenile), *Paraphrys vetulus* | F, M | Silver nitrate | 29.5 | 800 | 800 | Dinnel et al. 1983 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | S, U | Silver nitrate | 30 | 447.0 | - | Cardin 1986 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | S, U | Silver nitrate | 30 | 295.6 | - | Cardin 1986 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | S, U | Silver nitrate | 30 | 272 | - | Cardin 1986 |
| Winter flounder (larva), *Pseudopleuronectes americanus* | S, U | Silver nitrate | 30 | 503 | - | Cardin 1986 |

Table 1. (continued)

| Species | Method[a] | Chemical | Salinity (g/kg) | LC50 or EC50 (µg/L)[b] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Winter flounder (embryo), *Pseudopleuronectes americanus* | F, M | Silver nitrate | 30 | 196.3 | 196.3 | Cardin 1986 |

[a] S = static; R = renewal; F = flow-through; M = measured; U = unmeasured.

[b] Results are expressed as silver, not as the chemical.

[c] Salinity (g/kg), not hardness.

[d] Not used in calculation of Species Mean Acute Value.

[e] LC50 calculated from author's data using the moving average method.

Table 2. Chronic Toxicity of Silver to Aquatic Animals

| Species | Test[a] | Chemical | Hardness (mg/L as $CaCO_3$) | Chronic Limits (µg/L)[b] | Chronic Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| **FRESHWATER SPECIES** | | | | | | |
| Cladoceran, *Daphnia magna* | LC | Silver nitrate | 73 | 10.5-21.2 | 14.92 | Nebeker 1982 |
| Cladoceran, *Daphnia magna* | LC | Silver nitrate | 73 | 20.0-41.0 | 28.64 | Nebeker 1982 |
| Cladoceran, *Daphnia magna* | LC | Silver nitrate | 46 | 2.7-3.9[c] | 3.245 | Nebeker 1982 |
| Cladoceran, *Daphnia magna* | LC | Silver nitrate | 60 | 1.6-4.1 | 2.561 | Nebeker et al. 1983; Nebeker 1982 |
| Cladoceran, *Daphnia magna* | LC | Silver nitrate | 75 | 8.8-19.4 | 13.07 | Nebeker et al. 1983; Nebeker 1982 |
| Cladoceran, *Daphnia magna* | LC | Silver nitrate | 180 | 3.4-8.0 | 5.215 | Nebeker et al. 1983; Nebeker 1982 |
| Rainbow trout, *Salmo gairdneri* | ELS | Silver nitrate | 28 | 0.09-0.17 | 0.1240 | Davies et al. 1978 |
| Rainbow trout, *Salmo gairdneri* | ELS | Silver nitrate | 36 | 0.36-0.51 | 0.4285 | Nebeker et al. 1983 |
| Fathead minnow, *Pimephales promelas* | ELS | Silver nitrate | 45.1 | 0.37-0.65 | 0.4904 | Holcombe et al. 1983 |

Table 2. (continued)

| Species | Test[a] | Chemical | Salinity (g/kg) | Chronic Limits (μg/L)[b] | Chronic Value (μg/L) | Reference |
|---|---|---|---|---|---|---|
| | | | **SALTWATER SPECIES** | | | |
| Mysid, *Mysidopsis bahia* | LC | Silver nitrate | 15-30 | 70-110[d] (60-110) | 87.75 | Breteler et al. 1982; McKenney 1982 |
| Mysid, *Mysidopsis bahia* | LC | Silver nitrate | 30 | 11-32 | 18.76 | McKenney 1982; Lussier et al. 1985 |
| Mysid, *Mysidopsis bahia* | LC | Silver nitrate | 15-30 | 9-25 | 15.00 | McKenney 1982 |
| Mysid, *Mysidopsis bahia* | LC | Silver nitrate | 15-30 | 14-19 | 16.31 | McKenney 1982 |
| Mysid, *Mysidopsis bahia* | LC | Silver nitrate | 15-30 | 30-93 | 52.82 | McKenney 1982 |

[a] LC = life-cycle or partial life-cycle; ELS = early life-stage.

[b] Results are based on measured concentrations of silver.

[c] Lower and upper chronic limits for this test were concentrations resulting in less than 50% reproductive impairment and greater than 50% reproductive impairment, respectively.

[d] Chronic limits from McKenney (1982) from the same test reported by Breteler et al. (1982).

Table 2. (continued)

## Acute-Chronic Ratio

| Species | Hardness (mg/L as $CaCO_3$) | Acute Value (μg/L) | Chronic Value (μg/L) | Ratio |
|---|---|---|---|---|
| Cladoceran, *Daphnia magna* | 73 | 11.2[a] | 14.92 | 0.7507 |
| Cladoceran, *Daphnia magna* | 73 | 11.2[a] | 28.64 | 0.3911 |
| Cladoceran, *Daphnia magna* | 60 | 1.1 | 2.561 | 0.4295 |
| Rainbow trout, *Salmo gairdneri* | 36 | 9.2 | 0.4285 | 21.47 |
| Rainbow trout, *Salmo gairdneri* | 28 | 6.4[a] | 0.1240 | 51.61 |
| Fathead minnow, *Pimephales promelas* | 44.8 | 6.7 | 0.4904 | 13.66 |
| Mysid, *Mysidopsis bahia* | 30[b] | 249.3 | 18.76 | 13.29 |
| Mysid, *Mysidopsis bahia* | 15-30[b] | 86 | 16.31 | 5.273 |
| Mysid, *Mysidopsis bahia* | 15-30[b] | 132 | 15.00 | 8.800 |

[a] Geometric mean of two or more values in Table 1.

[b] Salinity (g/kg), not hardness.

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

| Rank[a] | Genus Mean Acute Value (μg/L) | Species | Species Mean Acute Value (μg/L)[b] | Species Mean Acute-Chronic Ratio[c] |
|---|---|---|---|---|
| | | FRESHWATER SPECIES | | |
| 18 | 560 | Crayfish, *Orconectes immunis* | 560 | - |
| 17 | 420 | Midge, *Tanytarsus dissimilis* | 420 | - |
| 16 | 83 | Snail, *Aplexa hypnorum* | 83 | - |
| 15 | 29 | Leech, *Nephelopsis obscura* | 29 | - |
| 14 | 26 | Hydra, *Hydra* sp. | 26 | - |
| 13 | 17.3 | Channel catfish, *Ictalurus punctatus* | 17.3 | - |
| 12 | 15 | Cladoceran, *Simocephalus vetulus* | 15 | - |
| 11 | 13.38 | Rainbow trout, *Salmo gairdneri* | 13.38 | 33.29 |
| 10 | 13 | Bluegill, *Lepomis macrochirus* | 13 | - |
| 9 | 11.34 | Fathead minnow, *Pimephales promelas* | 11.34 | 13.66 |

Table 3. (continued)

| Rank[a] | Genus Mean Acute Value (µg/L) | Species | Species Mean Acute Value (µg/L)[b] | Species Mean Acute-Chronic Ratio[c] |
|---|---|---|---|---|
| 8 | 9.2 | Flagfish, *Jordanella floridae* | 9.2 | - |
| 7 | 8.490 | Mottled sculpin, *Cottus bairdi* | 8.490 | - |
| 6 | 8.163 | Speckled dace, *Rhinichthys osculus* | 8.163 | - |
| 5 | 5 | Amphipod, *Crangonyx pseudogracilis* | 5 | - |
| 4 | 4.5 | Amphipod, *Gammarus pseudolimnaeus* | 4.5 | - |
| 3 | 3.924 | Cladoceran, *Ceriodaphnia reticulata* | 3.924 | - |
| 2 | 2.2 | Mayfly, *Leptophlebia* sp. | 2.2 | - |
| 1 | 2.155 | Cladoceran, *Daphnia pulex* | 5.158 | - |
| | | Cladoceran, *Daphnia magna* | 0.9 | 0.4994[d] |

Table 3. (Continued)

| Rank[a] | Genus Mean Acute Value (µg/L) | Species | Species Mean Acute Value (µg/L)[b] | Species Mean Acute-Chronic Ratio[c] |
|---|---|---|---|---|
| 9 | 171.8 | Mysid, *Mysidopsis bahia* | 171.8 | 8.512 |
| 8 | > 100, < 200 | Squid, *Loligo opalescens* | > 100, < 200 | - |
| 7 | 110.1 | Atlantic silverside, *Menidia menidia* | 110.1 | - |
| 6 | 33.10 | Dungeness crab, *Cancer magister* | 33.10 | - |
| 5 | 33 | Bay scallop, *Argopectin irradians* | 33 | - |
| 4 | 22.02 | Copepod, *Acartia tonsa* | 36.46 | - |
| | | Copepod, *Acartia clausi* | 13.3 | - |
| 3 | 21 | Quahog, *Mercnaria mercenaria* | 21 | - |
| 2 | 18.08 | Summer flounder, *Paralichthys dentatus* | 18.08 | - |
| 1 | 14.18 | Pacific oyster, *Crassostrea gigas* | 14.21 | - |
| | | Eastern oyster, *Crassostrea virginica* | 14.15 | - |

Table 3. (continued)

| Rank[a] | Genus Mean Acute Value (µg/L) | Species | Species Mean Acute Value (µg/L)[b] | Species Mean Acute-Chronic Ratio[c] |
|---|---|---|---|---|
| | | **SALTWATER SPECIES** | | |
| 19 | 2,700 | Mummichog, *Fundulus heteroclitus* | 2,700 | - |
| 18 | 1,088 | Sheepshead minnow, *Cyprinodon variegatus* | 1,088 | - |
| 17 | > 838 | Sand shrimp, *Crangon* spp., (mostly *Crangon franciscorum*) | > 838 | - |
| 16 | > 800 | Cabezon, *Scorpaenichthys marmoratus* | > 800 | - |
| 15 | 800 | English sole, *Parophrys vetulus* | 800 | - |
| 14 | 546.6 | Fourspine stickleback *Apeltes quadracus* | 546.6 | - |
| 13 | 487.5 | Coho salmon, *Oncorhynchus kisutch* | 487.5 | - |
| 12 | 355.6 | Shiner perch, *Cymatogaster aggregata* | 355.6 | - |
| 11 | 196.3 | Winter flounder, *Pseudopleuronectes americanus* | 196.3 | - |
| 10 | 178.6 | Polychaete, *Neanthes arenaceodentata* | 178.6 | - |

Table 3. (continued)

[a] 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 data are available so that the Final Acute Value is not unnecessarily lowered.

[b] From Table 1.

[c] From Table 2.

[d] Value not used in calculation of the Final Acute-Chronic Ratio (see text).

<u>Fresh water</u>

Final Acute Value = 1.833 μg/L

Criterion Maximum Concentration = (1.833 μg/L) / 2 = 0.9165 μg/L

Final Acute-Chronic Ratio = 15.70 (see text)

Final Chronic Value = (1.833 μg/L) / 15.70 = 0.1168 μg/L

<u>Salt water</u>

Final Acute Value = 14.50 μg/L

Criterion Maximum Concentration = (14.50 μg/L) / 2 = 7.250 μg/L

Final Acute-Chronic Ratio = 15.70 (see text)

Final Chronic Value = (14.50 μg/L) / 15.70 = 0.9236 μg/L

Table 4. Toxicity of Silver to Aquatic Plants

| Species | Chemical | Hardness (mg/L as $CaCO_3$) | Duration (days) | Effect | Concentration (µg/L)[b] | Reference |
|---|---|---|---|---|---|---|
| | | | **FRESHWATER SPECIES** | | | |
| Green alga, *Selenastrum capricornutum* | Silver nitrate | - | 4 | EC50 | 2.6 | U.S. EPA 1978 |
| Waterweed, *Elodea* (*Anacharis*) *canadensis* | Silver nitrate | - | 28 | EC50 | 7,500 | Brown and Rattigan 1979 |
| Duckweed, *Lemna minor* | Silver nitrate | - | 28 | EC50 | 270 | Brown and Rattigan 1979 |
| | | | **SALTWATER SPECIES** | | | |
| Diatom, *Skeletonema costatum* | Silver nitrate | 30[b] | 4 | EC50 (chlorophyll *a*) | 170 | U.S. EPA 1978 |
| Diatom, *Skeletonema costatum* | Silver nitrate | 30[b] | 4 | EC50 (cell counts) | 130 | U.S. EPA 1978 |

[a] Concentration of silver, not the chemical.

[b] Salinity (g/kg), not hardness.

Table 5. Bioaccumulation of Silver by Aquatic Organisms

| Species | Chemical | Concentration in Water (μg/L)[a] | Duration (days) | Tissue | BCF or BAF[b] | Reference |
|---|---|---|---|---|---|---|
| **FRESHWATER SPECIES** | | | | | | |
| Largemouth bass, *Micropterus salmoides* | Silver nitrate | 1 | 120 | Muscle | 11 | Cearley 1971 |
| Largemouth bass, *Micropterus salmoides* | Silver nitrate | 10 | 120 | Muscle | 19 | Cearley 1971 |
| Bluegill, *Lepomis macrochirus* | Silver nitrate | 10 | 180 | Whole body | 15 | Cearley 1971 |
| Bluegill, *Lepomis macrochirus* | Silver nitrate | 100 | 180 | Whole body | 150 | Cearley 1971 |
| **SALTWATER SPECIES** | | | | | | |
| Blue mussel (juvenile to adult), *Mytilus edulis* | Silver nitrate | 1.5 | 630 | Soft parts | 5,100 | Calabrese et al. 1984 |
| Blue mussel (juvenile to adult), *Mytilus edulis* | Silver nitrate | 5.4 | 630 | Soft parts | 1,435 | Calabrese et al. 1984 |
| Blue mussel (juvenile to adult), *Mytilus edulis* | Silver nitrate | 10 | 630 | Soft parts | 1,056 | Calabrese et al. 1984 |
| Blue mussel (juvenile to adult), *Mytilus edulis* | Silver nitrate | 1.5 | 540 | Soft parts | 6,500 | Calabrese et al. 1984 |
| Blue mussel (juvenile to adult), *Mytilus edulis* | Silver nitrate | 5 4 | 540 | Soft parts | 2,203 | Calabrese et al. 1984 |

Table 5. (continued)

| Species | Chemical | Concentration in Water (μg/L)[a] | Duration (days) | Tissue | BCF or BAF[b] | Reference |
|---|---|---|---|---|---|---|
| Blue mussel (juvenile to adult), *Mytilus edulis* | Silver nitrate | 10 | 540 | Soft parts | 1,391 | Calabrese et al. 1984 |
| Blue mussel (juvenile to adult), *Mytilus edulis* | Silver nitrate | 10 | 365 | Soft parts | 1,533 | Calabrese et al. 1984 |

[a] Measured concentration of silver.

[b] Bioconcentration factors (BCFs) and bioaccumulation factors (BAFs) are based on measured concentrations of silver in water and in tissue.

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

| Species | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| | | | | **FRESHWATER SPECIES** | | |
| Mixed heterotrophic bacteria | Silver sulfate | - | 0.5 hr | < 1% survival | 1. | Albright et al. 1972 |
| Mixed heterotrophic bacteria | Silver sulfate | - | 0.5 hr | 53% reduction in glucose uptake | 0.1 | Albright et al. 1972 |
| Bacterium, *Nitrobacter* sp. and *Nitrosomonas* sp. | Silver nitrate | - | 4 hr | EC50 | 30 | Williamson and Nelson 1983 |
| Bacterium, *Nitrobacter* sp. and *Nitrosomonas* sp. | Silver nitrate | - | 4 hr | EC90 | 100 | Williamson and Nelson 1983 |
| Bacterium, *Pseudomonas putida* | Silver nitrate | - | 16 hr | Incipient inhibition | 7 | Bringmann and Kuhn 1977a,1980b |
| Green alga, *Chlorella vulgaris* | - | 4.5 | 14 days | Growth inhibition | 50 | Stokes et al. 1973; Hutchinson 1973; Hutchinson and Stokes 1975 |
| Green alga, *Haematococcus capensis* | - | - | 6 days | Reduced growth | 100 | Hutchinson 1973 |
| Blue-green alga, *Microcystis aeruginosa* | Silver nitrate | - | 8 days | Incipient inhibition | 0.7 | Bringmann and Kuhn 1978a,b |

Table 6. (continued)

| Species | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Blue-green alga, *Nostoc muscorum* | Silver chloride | - | 21 days | EC50 (survival) | 2.9 | Rai and Raizada 1985 |
| Green alga, *Scenedesmus acuminata* | - | - | 12 days | Reduced growth | 50 | Stokes et al. 1973; Hutchinson 1973 |
| Green alga, *Scenedesmus* sp. | Silver nitrate | 215 | 4 days | Incipient inhibition | 50 | Bringmann and Kuhn 1959b |
| Green alga, *Scenedesmus quadricauda* | Silver nitrate | - | 8 days | Incipient inhibition | 9.5 | Bringmann and Kuhn 1977a,1978a,b,1980b |
| Green alga, *Selenastrum capricornutum* | - | - | 14-21 days | EC50 | 6.39 | Turbak et al. 1986 |
| Macrophyte, *Ceratophyllum demersum* | Silver sulfide | - | 60 days | 70-80% defoliation | <10 | Pilie et al. 1975 |
| Protozoan, *Chilomonas paramaecium* | Silver nitrate | - | 48 hr | Incipient inhibition | 2.6 | Bringmann and Kuhn 1980a; Bringmann et al. 1980 |
| Protozoan, *Entosiphon sulcatum* | Silver nitrate | - | 72 hr | Incipient inhibition | 580 | Bringmann 1978; Bringmann and Kuhn 1980b |
| Protozoan, *Microregma heterostoma* | Silver nitrate | - | 28 hr | Incipient inhibition | 30 | Bringmann and Kuhn 1959a |

Table 6. (continued)

| Species | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Ciliate, *Uroneuma parduczi* | Silver nitrate | - | 20 hr | Incipient inhibition | 100 | Bringmann and Kuhn 1980c,1981 |
| Cladoceran, *Ceriodaphnia reticulata* | Silver nitrate | 240 | 7 days | RI50 | 0.8 | Elnabarawy et al. 1986 |
| Cladoceran, *Ceriodaphnia reticulata* | Silver nitrate | 240 | 7 days | Chronic value | 1.3[b] | Elnabarawy et al. 1986 |
| Cladoceran, *Daphnia magna* | Silver nitrate | - | 64 hr | Incipient inhibition | 3.24 | Anderson 1948 |
| Cladoceran (< 24 hr), *Daphnia magna* | Silver nitrate | 47 | 48 hr | EC50 (fed) | 9.5 | Chapman 1980 |
| Cladoceran (< 24 hr), *Daphnia magna* | Silver nitrate | 33 | 48 hr | EC50 (fed) | 12.5 | Nebeker et al. 1983 |
| Cladoceran, *Daphnia magna* | Silver nitrate | - | 48 hr | Incipient inhibition | 30 | Bringmann and Kuhn 1959a,b, 1960 |
| Cladoceran, *Daphnia magna* | Silver nitrate | 240 | 14 days | Chronic value | <0.56[b] | Elnabarawy et al. 1986 |
| Cladoceran, *Daphnia magna* | Silver nitrate | 60 | 21 days | LC50 | 2.9 | Nebeker 1982 |
| Cladoceran, *Daphnia magna* | Silver nitrate | 60 | 21 days | LC50 | 3.6 | Nebeker 1982 |
| Cladoceran, *Daphnia magna* | Silver nitrate | 60 | 21 days | LC50 | 3.9 | Nebeker 1982 |

Table 6. (continued)

| Species | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Cladoceran, *Daphnia pulex* | Silver nitrate | 240 | 14 days | RI50 | 1.2 | Elnabarawy et al. 1986 |
| Cladoceran, *Daphnia pulex* | Silver nitrate | 240 | 14 days | Chronic value | < 0.56[b] | Elnabarawy et al. 1986 |
| Mayfly (naiqd), *Ephemerella grandis* | Silver nitrate | 30-70 | Postmortem 1-14 days | BCF=17.4 | 750 | Nehring 1976 |
| Mayfly (naiad), *Ephemerella grandis* | Silver nitrate | 30-70 | Postmortem 1-14 days | BCF=18.4 | 400 | Nehring 1976 |
| Mayfly (naiad), *Ephemerella grandis* | Silver nitrate | | Postmortem 1-14 days | BCF=41.8 | 230 | Nehring 1976 |
| Mayfly (naiad), *Ephemerella grandis* | Silver nitrate | 30-70 | Postmortem 1-14 days | BCF=47.8 | 120 | Nehring 1976 |
| Mayfly (naiad), *Ephemerella grandis* | Silver nitrate | 30-70 | Postmortem 1-14 days | BCF=84.4 | 60 | Nehring 1976 |
| Mayfly (nymph), *Ephemeralla grandis* | Silver nitrate | 30-70 | 14 days | LC50 | < 1 | Nehring 1976 |
| Stonefly (naiad final instar), *Pteronarcys californica* | Silver nitrate | - | 15 days | LC50 | 8.8 | Nehring 1973,1976 |
| Stonefly (naiad), *Pteronarcys californica* | Silver nitrate | 30-70 | Postmortem 1-14 days | BCF=14.4 | 738 | Nehring 1976 |

Table 6. (continued)

| Species | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Stonefly (naiad), *Pteronarcys californica* | Silver nitrate | 30-70 | Postmortem 1-14 days | BCF=15.4 | 399 | Nehring 1976 |
| Stonefly (naiad), *Pteronarcys californica* | Silver nitrate | 30-70 | Postmortem 1-14 days | BCF=21.2 | 217 | Nehring 1976 |
| Stonefly (naiad), *Pteronarcys californica* | Silver nitrate | 30-70 | Postmortem 1-14 days | BCF=26 | 105 | Nehring 1976 |
| Stonefly (naiad), *Pteronarcys californica* | Silver nitrate | 30-70 | Postmortem 1-14 days | BCF=36.6 | 50 | Nehring 1976 |
| Rainbow trout (embryo, larva), *Salmo gairdneri* | Silver nitrate | 104 (92-110) | 27 days (4 days post hatch) | EC50 (Death and deformity) | 10 | Birge 1978; Birge et al. 1978,1980 |
| Rainbow trout (embryo, larva), *Salmo gairdneri* | Silver nitrate | 102 (92-110) | 27 days (4 days post hatch) | EC10 (Death and deformity) | 0.9 | Birge et al. 1980,1981 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | 35 hr | LT50 | 500 | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | 44 hr | LT50 | 400 | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | 35 hr | LT50 | 300 | Rombough 1985 |

Table 6. (continued)

| Species | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | 48 hr | LT50 | 200 | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | 61 hr | LT50 | 100 | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | > 168 hr | LT50 | 50 | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | > 168 hr | LT50 | 10 | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | 12 hr | LT50 | 500[c] | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | 12 hr | LT50 | 400[c] | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | 14 hr | LT50 | 300[c] | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | 12 hr | LT50 | 200[c] | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | 23 hr | LT50 | 100[c] | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | 58 hr | LT50 | 50[c] | Rombough 1985 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver chloride | 30 | > 168 hr | LT50 | 10[c] | Rombough 1985 |

Table 6. (continued)

| Species | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Concentration (μg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Rainbow trout (embryo, larva), *Salmo gairdneri* | Silver nitrate | - | 5 wks | LC50 | 0.69 | Davies et al. 1978 |
| Rainbow trout (embryo, larva), *Salmo gairdneri* | Silver nitrate | - | 22 wks | LC50 | 0.34 | Davies et al. 1978 |
| Rainbow trout (embryo), *Salmo gairdneri* | Silver nitrate | 28 | 6 days | Premature hatching | 2.2 | Davies et al. 1978 |
| Goldfish (embryo, larva), *Carassius auratus* | Silver nitrate | 195 | 7 days (4 days post hatch) | EC50 (Death and deformity) | 30 | Birge 1978 |
| Fathead minnow (37 mm, 0.5 g), *Pimephales promelas* | Silver nitrate | 29-38 | 24 hr | LC50 | 21 | EG & G Bionomics 1979 |
| Fathead minnow (37 mm, 0.5 g), *Pimephales promelas* | Silver nitrate | 29-38 | 48 hr | LC50 | 16 | EG & G Bionomics 1979 |
| Fathead minnow (37 mm, 0.5 g), *Pimephales promelas* | Silver nitrate | 29-38 | 72 hr | LC50 | 16 | EG & G Bionomics 1979 |
| Largemouth bass (embryo, larva), *Micropterus salmoides* | Silver nitrate | 93-105 | 8 days (4 days post hatch) | EC50 (Death and deformity) | 111 | Birge et al. 1978 |

Table 6. (continued)

| Species | Chemical | Hardness (mg/L as $CaCO_3$) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Narrow-mouthed toad (embryo, larva), _Gastrophryne carolinensis_ | Silver nitrate | 195 | 7 days (4 days post hatch) | EC50 (Death and deformity) | 10 | Birge 1978 |
| Marbled salamander (embryo, larva), _Ambystoma opacum_ | Silver nitrate | 93-105 | 7 days (4 days post hatch) | EC50 (Death and deformity) | 240 | Birge et al. 1978 |
| | | | **SALTWATER SPECIES** | | | |
| Green alga, _Dunaliella tertiolecta_ | Silver cyanide | - | 3 days | EC50 (cell counts) | 2,700 | Fisher et al. 1984 |
| Green alga, _Dunaliella tertiolecta_ | Silver cyanide | - | 12 hr | BCF = 13,000 | - | Fisher et al. 1984 |
| Golden-brown alga, _Isochrysis galbana_ | - | 10[d] | 2 days | Chlorophyll _a_ reduced about 65% at 20°C | 25 | Wilson and Freeberg 1980 |
| Golden-brown alga, _Isochrysis galbana_ | - | 12[d] | 2 days | Chlorophyll _a_ reduced about 65% at 16°C | 22 | Wilson and Freeberg 1980 |
| Golden-brown alga, _Isochrysis galbana_ | - | 12[d] | 2 days | Chlorophyll _a_ reduced about 65% at 28°C | 15 | Wilson and Freeberg 1980 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Golden-brown alga, *Isochrysis galbana* | - | 14 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 25 | Wilson and Freeberg 1980 |
| Golden-brown alga, *Isochrysis galbana* | - | 16 | 2 days | Chlorophyll *a* reduced about 65% at 16°C | 24 | Wilson and Freeberg 1980 |
| Golden-brown alga, *Isochrysis galbana* | - | 16 | 2 days | Chlorophyll *a* reduced about 65% at 28°C | 38 | Wilson and Freeberg 1980 |
| Golden-brown alga, *Isochrysis galbana* | - | 20 | 2 days | Chlorophyll *a* reduced about 65% at 16°C | 64 | Wilson and Freeberg 1980 |
| Golden-brown alga, *Isochrysis galbana* | - | 20 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 24 | Wilson and Freeberg 1980 |
| Golden-brown alga, *Isochrysis galbana* | - | 20 | 2 days | Chlorophyll *a* reduced about 65% at 28°C | 60 | Wilson and Freeberg 1980 |
| Golden-brown alga, *Isochrysis galbana* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 16°C | 24 | Wilson and Freeberg 1980 |
| Golden-brown alga, *Isochrysis galbana* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 26 | Wilson and Freeberg 1980 |
| Golden-brown alga, *Isochrysis galbana* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 28°C | 110 | Wilson and Freeberg 1980 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Golden-brown alga, *Isochrysis galbana* | - | 28 | 2 days | Reduction in chlorophyll *a*; (lowest value from 28 tests) | 20 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 3 | 2 days | Chlorophyll *a* reduced about 65% at 12°C | 14 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 3 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 84 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 3 | 2 days | Chlorophyll *a* reduced about 65% at 28°C | 13 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 5 | 2 days | Chlorophyll *a* reduced about 65% at 12°C | 30 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 5 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 70 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 5 | 2 days | Chlorophyll *a* reduced about 65% at 28°C | 16 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 7 | 2 days | Chlorophyll *a* reduced about 65% at 12°C | 23 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 7 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 68 | Wilson and Freeberg 1980 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Diatom, *Thalassiosira pseudonana* | - | 7 | 2 days | Chlorophyll *a* reduced about 65% at 28°C | 14 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 10 | 2 days | Chlorophyll *a* reduced about 65% at 12°C | 31 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 10 | 2 days | Chlorophyll *a* reduced about 65% at 16°C | 74 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 10 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 76 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 10 | 2 days | Chlorophyll *a* reduced about 65% at 24°C | 44 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 10 | 2 days | Chlorophyll *a* reduced about 65% at 28°C | 21 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 14 | 2 days | Chlorophyll *a* reduced about 65% at 12°C | 37 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 14 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 56 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 14 | 2 days | Chlorophyll *a* reduced about 65% at 28°C | 32 | Wilson and Freeberg 1980 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Diatom, *Thalassiosira pseudonana* | - | 21 | 2 days | Chlorophyll *a* reduced about 65% at 12°C | 23 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 21 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 68 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 21 | 2 days | Chlorophyll *a* reduced about 65% at 28°C | 40 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 12°C | 25 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 16°C | 31 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 42 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 24°C | 48 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 28°C | 52 | Wilson and Freeberg 1980 |
| Diatom, *Thalassiosira pseudonana* | - | 28 | 2 days | Reduction in chlorophyll *a*; (lowest value from 14 tests) | 40 | Wilson and Freeberg 1980 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Diatom, *Thalassiosira pseudonana* | Silver cyanide | - | 4 days | EC50 (cell counts) | 100 | Fisher et al. 1984 |
| Diatom, *Thalassiosira pseudonana* | Silver cyanide | - | 12 hr (equilibrium reached) | BCF = 34,000 | - | Fisher et al. 1984 |
| Dinoflagellate, *Glenodinium halli* | - | 28 | 2 days | Reduction in chlorophyll *a*; (lowest value from 6 tests) | 5 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 16°C | 7.5-8.0 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 18 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 24°C | 13 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 28°C | 13 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 30°C | 10 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 32°C | 2 | Wilson and Freeberg 1980 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Dinoflagellate, *Gymnodinium splendens* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 33°C | 10 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 14 | 2 days | Chlorophyll *a* reduced about 65% at 16°C | 7 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 14 | 2 days | Chlorophyll *a* reduced about 65% at 30°C | 11 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 14 | 2 days | Chlorophyll *a* reduced about 65% at 32°C | 2 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 14 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 1.3 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 16 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 6.5 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 20 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 8.5 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 24 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 6.0 | Wilson and Freeberg 1980 |
| Dinoflagellate, *Gymnodinium splendens* | - | 28 | 2 days | Chlorophyll *a* reduced about 65% at 20°C | 9.4 | Wilson and Freeberg 1980 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Dinoflagellate, *Gymnodinium splendens* | - | 28 | 2 days | Reduction in chlorophyll *a*; (lowest value from 14 tests) | 5 | Wilson and Freeberg 1980 |
| Red alga, *Champia parvula* | Silver nitrate | 30 | 25 days | Chronic limits for cystocarp formation (sexual fusion) | 1.2-1.9 | Steele and Thursby 1983 |
| Red alga (sporeling), *Plumaria elegans* | Silver nitrate | - | 18 hr immersion followed by 7 days in clean seawater | 98% mortality; 0% development | 1,000 | Boney et al. 1959 |
| Polychaete, *Neanthes arenaceodentata* | Silver nitrate | 30 | 28 days | LC50 | 158.7 (geometric mean of 5 values) | Pesch and Hoffman 1983 |
| Polychaete, *Neanthes arenaceodentata* | Silver nitrate | 30 | 28 days | EC50 (inability to burrow) | 151.7 (geometric mean of 5 values) | Pesch and Hoffman 1983 |
| Polychaete, *Neanthes arenaceodentata* | Silver nitrate | 30 | 96 hr | EC50 (inability to burrow) | 158.6 (geometric mean of 3 values) | Pesch and Hoffman 1983 |
| Polychaete (adult), *Neanthes virens* | Silver nitrate | 26 | 48 hr | Significant reduction in respiration | 800 | Pereira and Kanungo 1981 |
| Polychaete (adult), *Neanthes virens* | Silver nitrate | 26 | 24 hr | Significant reduction in respiration | 1,000 | Pereira and Kanungo 1981 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Polychaete (adult), *Neanthes virens* | Silver nitrate | 26 | 24 hr | Significant ionic imbalances in coelomic fluid | 1,000 | Pereira and Kanungo 1981 |
| Mud snail (adult), *Nassarius obsoletus* | Silver nitrate | 25 | 72 hr | Distressed behavior (inability to move) | 250 | MacInnes and Thurberg 1973 |
| Mud snail (adult), *Nassarius obsoletus* | Silver nitrate | 25 | 72 hr | Depressed respiration | 500 | MacInnes and Thurberg 1973 |
| Mud snail (adult), *Nassarius obsoletus* | Silver nitrate | 25 | 72 hr | Mortality | 20,000 | MacInnes and Thurberg 1973 |
| Blue mussel (adult), *Mytilus edulis* | Silver nitrate | 25 | 96 hr | Significant increase in respiration | 100 | Thurberg et al. 1974 |
| Blue mussel (adult), *Mytilus edulis* | Silver nitrate | 15 | 96 hr | Significant increase in respiration | 100 | Thurberg et al. 1974 |
| Blue mussel (embryo), *Mytilus edulis* | Silver nitrate | 30 | 72 hr | EC50 (development to veliger) | < 4.4 | Dinnel et al. 1983 |
| Blue mussel (juvenile), *Mytilus edulis* | Silver nitrate | 25 | 6 mo | No growth | 43.7 | Calabrese et al. 1984 |
| Blue mussel (adult), *Mytilus edulis* | Silver nitrate | 25 | 21 mo | Histological changes (deposition of colored particulates in basement membranes and connective tissues of various body organs) | 1.5 | Calabrese et al. 1984 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Bay scallop (juvenile), *Argopectin irradians* | Silver nitrate | 25 | 96 hr | Significant increase in respiration | 22 | Nelson et al. 1976 |
| Pacific oyster (gamete), *Crassostrea gigas* | Silver nitrate | 27 | 1 hr | EC50 (sperm cell fertilization success) | 28.8 | Dinnel et al. 1983 |
| Pacific oyster (embryo), *Crassostrea gigas* | Silver nitrate | 16.5 | 48 hr | EC50 (development) | 6.69 | Coglianese 1982 |
| Eastern oyster (larva), *Crassostrea virginica* | Silver nitrate | 24 | 12 days | LC50 | 25 | Calabrese et al. 1977a |
| Eastern oyster (larva), *Crassostrea virginica* | Silver nitrate | 24 | 12 days | 32.9% reduction in growth | 25 | Calabrese et al. 1977a |
| Eastern oyster (adult), *Crassostrea virginica* | Silver nitrate | 35 | 96 hr | No significant effect on respiration | 1,000 | Thurberg et al. 1974 |
| Eastern oyster (adult), *Crassostrea virginica* | Silver nitrate | 25 | 96 hr | Significant increase in respiration | 100 | Thurberg et al. 1974 |
| Eastern oyster (adult), *Crassostrea virginica* | Silver nitrate | 15 | 96 hr | Significant increase in respiration | 100 | Thurberg et al. 1974 |
| Surf clam (larva), *Spisula solidissima* | Silver nitrate | 26 | 2-15 days | Significant increase in respiration | 50 | Thurberg et al. 1975 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Surf clam (juvenile), *Spisula solidissima* | Silver nitrate | 26 | 96 hr | Significant increase in respiration | 10 | Thurberg et al. 1975 |
| Surf clam (adult), *Spisula solidissima* | Silver nitrate | 26 | 96 hr | Significant increase in respiration | 50 | Thurberg et al. 1975 |
| Surf clam (gamete), *Spisula solidissima* | Silver nitrate | 30 | 45 min | Significant abnormal larval development following prefertilization exposure of eggs and sperm | 6.4 | Eyster and Morse 1984 |
| Quahog (adult), *Mercenaria mercenaria* | Silver nitrate | 35 | 96 hr | No effect on respiration | 1,000 | Thurberg et al. 1974 |
| Quahog (adult), *Mercenaria mercenaria* | Silver nitrate | 25 | 96 hr | Significant effect on respiration | 100 | Thurberg et al. 1971 |
| Quahog (adult), *Mercenaria mercenaria* | Silver nitrate | 15 | 96 hr | Significant effect on respiration | 100 | Thurberg et al. 1974 |
| Quahog (larva), *Mercenaria mercenaria* | Silver nitrate | 24 | 8-10 days | LC50 | 32.4 | Calabrese et al. 1977a |
| Quahog (larva), *Mercenaria mercenaria* | Silver nitrate | 24 | 8-10 days | 33.8% reduction in growth | 32.4 | Calabrese et al. 1977a |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Soft-shell clam (adult), *Mya arenaria* | Silver nitrate | 35 | 96 hr | Significant increase in respiration | 100 | Thurberg et al. 1974 |
| Soft-shell clam (adult), *Mya arenaria* | Silver nitrate | 25 | 96 hr | Significant increase in respiration | 100 | Thurberg et al. 1974 |
| Soft-shell clam (adult), *Mya arenaria* | Silver nitrate | 15 | 96 hr | Significant increase in respiration | 100 | Thurberg et al. 1974 |
| Barnacle (adult), *Balanus balanoides* | Silver sulfate | - | 2 days | LC90 | 400 | Clarke 1947 |
| Barnacle (adult), *Balanus balanoides* | Silver sulfate | - | 5 days | LC90 | 200 | Clarke 1947 |
| American lobster (adult), *Homarus americanus* | Silver nitrate | - | 30 days | Heart transaminase activity depressed and induction of gonadal glycolytic enzymes | 6 | Calabrese et al. 1977b |
| Sea urchin (embryo), *Arbacia lixula* | Silver nitrate | - | 52 hr | Significant reduction in embryo development | 0.5 | Soyer 1963 |
| Sea urchin (gamete), *Strongylocentrotus droebachiensis* | Silver nitrate | 27.7-29.1 | 60 min | EC50 (sperm cell fertilization success) | 76 | Dinnel et al. 1982 |
| Sea urchin (gamete), *Strongylocentrotus droebachiensis* | Silver nitrate | 30 | 60 min | EC50 (sperm cell fertilization success) | 94.0 | Dinnel et al. 1983 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (μg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Sea urchin (gamete), *Strongylocentrotus droebachiensis* | Silver nitrate | 29 | 60 min | EC50 (sperm cell fertilization success) | 85.9 | Dinnel et al. 1983 |
| Sea urchin (gamete), *Strongylocentrotus droebachiensis* | Silver nitrate | 28 | 60 min | EC50 (sperm cell fertilization success) | 44.9 | Dinnel et al. 1983 |
| Sea urchin (gamete), *Strongylocentrotus droebachiensis* | Silver nitrate | 27 | 60 min | EC50 (sperm cell fertilization success) | 44.3 | Dinnel et al. 1983 |
| Sea urchin (gamete), *Strongylocentrotus droebachiensis* | Silver nitrate | 26 | 60 min | EC50 (sperm cell fertilization success) | 34.1 | Dinnel et al. 1983 |
| Sea urchin (gamete), *Strongylocentrotus droebachiensis* | Silver nitrate | 25 | 60 min | EC50 (sperm cell fertilization success) | 29.8 | Dinnel et al. 1983 |
| Sea urchin (gamete), *Strongylocentrotus droebachiensis* | Silver nitrate | 27 | 60 min | EC50 (sperm cell fertilization success) | 85.7 | Dinnel et al. 1983 |
| Sea urchin (gamete), *Strongylocentrotus droebachiensis* | Silver nitrate | 27 | 60 min | EC50 (sperm cell fertilization success) | 84.5 | Dinnel et al. 1983 |
| Sea urchin (embryo), *Strongylocentrotus droebachiensis* | Silver nitrate | 30 | 5 days | EC50 (development to pluteus) | 24.3 | Dinnel et al. 1983 |
| Sea urchin (gamete), *Strongylocentrotus franciscanus* | Silver nitrate | 27 | 60 min | EC50 (sperm cell fertilization success) | 112.2 | Dinnel et al. 1983 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Sea urchin (gamete), *Strongylocentrotus purpuratus* | Silver nitrate | 27 | 60 min | EC50 (sperm cell fertilization success) | 115.3 | Dinnel et al. 1983 |
| Sea urchin (gamete), *Strongylocentrotus purpuratus* | Silver nitrate | 27 | 60 min | EC50 (sperm cell fertilization success) | 89.5 | Dinnel et al. 1983 |
| Sea urchin (embryo), *Strongylocentrotus purpuratus* | Silver nitrate | 27 | 5 days | EC50 (development to pluteus) | 14.9 | Dinnel et al. 1983 |
| Sand dollar (gamete), *Dendraster excentricus* | Silver nitrate | 27-30 | 60 min | EC50 (sperm cell fertilization success) | 54.5 | Dinnel et al. 1983 |
| Sand dollar (gamete), *Dendraster excentricus* | Silver nitrate | - | 60 min | EC50 (sperm fertilization success) | 45 | Dinnel et al. 1982 |
| Coho salmon (gamete), *Oncorhynchus kisutch* | Silver nitrate | 27 | 60 min | EC50 (sperm cell fertilization success) | 11.4 | Dinnel et al. 1983 |
| Mummichog (adult), *Fundulus heteroclitus* | - | - | 96 hr | Inhibition of liver alkaline phosphatase activity | 40 | Jackim et al. 1970 |
| Mummichog (adult), *Fundulus heteroclitus* | Silver nitrate | - | 96 hr | Increase in liver enzyme activity | 20 | Jackim 1973 |
| Mummichog (adult), *Fundulus heteroclitus* | Silver chloride | 20 | 96 hr | Degeneration of lateral-line and olfactory structure | 50 | Gardner 1975 |
| Cunner (adult), *Tautogolabrus adspersus* | Silver nitrate | 24 | 96 hr | Significant decrease in respiration and liver-enzyme activity | 500 | Gould and MacInnes 1977 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Cunner (adult), *Tautogolabrus adspersus* | Silver acetate | 24 | 96 hr | Significant decrease in respiration and increase in liver-enzyme activity | 500 | Gould and MacInnes 1977 |
| Cunner (adult), *Tautogolabrus adspersus* | Silver nitrate | 24 | 96 hr | Significant decrease in respiration | 120 | Thurberg and Collier 1977 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | Silver nitrate | 10 | Throughout embryonic development | Significant reduction in hatch success | > 174 | Voyer et al. 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | Silver nitrate | 21 | Throughout embryonic development | Significant reduction in hatch success | > 167 | Voyer et al. 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | Silver nitrate | 32 | Throughout embryonic development | Significant reduction in hatch success | > 166 | Voyer et al. 1982 |
| Winter flounder (embryo), *Pseudopleuronectes americanus* | Silver nitrate | 27-32 | 18 days | Significant reduction in hatch success | 386 | Klein-MacPhee et al. 1984 |
| Winter flounder (larva), *Pseudopleuronectes americanus* | Silver nitrate | 27-32 | 18 days | Significant larval mortality | 92 | Klein-MacPhee et al. 1984 |

Table 6. (continued)

| Species | Chemical | Salinity (g/kg) | Duration | Effect | Concentration (µg/L)[a] | Reference |
|---|---|---|---|---|---|---|
| Winter flounder (larva), *Pseudopleuronectes americanus* | Silver nitrate | 27-32 | 18 days | Significant effect on growth | 180 | Klein-MacPhee et al. 1984 |
| Winter flounder (larva), *Pseudopleuronectes americanus* | Silver nitrate | 27-32 | 18 days | No effect on growth | 54 | Klein-MacPhee et al. 1984 |
| Winter flounder (adult), *Pseudopleuronectes americanus* | Silver nitrate | - | 60 days | No effect on respiration; depressed liver, transaminase activity | 10 | Calabrese et al. 1977b |

[a] Concentration of silver, not of chemical.

[b] Based upon nominal concentration.

[c] Zonae radiatae (egg capsule) removed.

[d] Salinity (g/kg), not hardness.

## REFERENCES


Albright, L.J. and E.M. Wilson. 1974. Sub-lethal effects of several metallic salts-organic compounds combinations 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 indigenous heterotrophic microflora of a natural water. Water Res. 6:1589-1596.

Amiard, J.C. 1978a. 110m silver contamination mechanisms in a marine benthic food chain. 3. Influence of the contamination mechanisms on the distribution of the radionuclide. Helgol. Wiss. Meeresunters. 31:444-456.

Amiard, J.C. 1978b. 110m silver contamination mechanisms in a marine benthic food chain. 4. Effects of contamination mechanisms on radionuclide elimination. J. Exp. Mar. Biol. Ecol. 34:215-225.

Amiard, J.C. 1979. 110m silver contamination mechanisms in a marine benthic food chain. I. Contamination of some marine organisms with water as the intermediary. Cah. Biol. Mar. 20:125-136.

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.

Barrows, M.E., S.R. Petrocelli, K.J. Macek and J.J. Carroll. 1980. Bioconcentration and elimination of selected water pollutants by bluegill sunfish (Lepomis macrochirus). In: Dynamics, exposure and hazard *assessment of* toxic chemicals. Hague, R. (Ed.). Ann Arbor Science, Ann Arbor, MI. pp. 379-392.

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., 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.). PB-298353. 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 developments. Vol. 1. Saxena, J. and F. Fisher (Eds.). Academic Press, New York, NY. pp. 59-115.

Boney, A.D., D.S. Corner and B.W.P. Sparrow. 1959. Effects of various poisons on the growth and viability of sporelings of the red alga Plumaria elegans (Bonnem.) Schm. Biochem. Pharmacol. 2:37-49.

Breteler, R.J., J.W. Williams and R.L. Buhl. 1982. Measurement of chronic toxicity using the opossum shrimp Mysidopsis bahia. Hydrobiologia 93:189-194.

Bringmann. G. 1978. Studies on the biological effects of water-borne pollutants in protozoans. I. Bacteriophagus flagellate (model organism: Entosiphon sulcatum Stein). Z. Wasser Abwasser Forsch. 11:210-215.

Bringmann, G. and R. Kuhn. 1959a. Water-toxicological investigations with protozoa as test organisms. Gesundh.-Ing. 80:239-242.

Bringmann, G. and R. Kuhn. 1959b. Comparative water toxicological investigations on bacteria, algae, and Daphnia. Gesundh.-Ing. 80:115-120.

Bringmann, G. and R. Kuhn. 1960. Results of water-toxicological tests of insecticides. Gesundh.-Ing. 81:243-244.

Bringmann, G. and R. Kuhn. 1977a. Limiting values for the damaging action of water pollutants to bacteria (Pseudomonas putida) and green algae (Scenedesmus quadricauda) in cell multiplication inhibition test. Z. Wasser Abwasser Forsch. 10:87-98.

Bringmann, G. and R. Kuhn. 1977b. The toxicity of waterborne contaminants towards Daphnia magna. Z. Wasser Abwasser Forsch. 10:161-166.

Bringmann, G. and R. Kuhn. 1978a. Limiting values for the noxious effects of water pollutant material to blue algae (Microcystis aeruginosa) and green algae (Scenedesmus quadricauda) in cell multiplication inhibition tests. Vom Wasser 50:45-60.

Bringmann, G. and R. Kuhn. 1978b. Testing of substances for their toxicity threshold: Model organisms Microcystis (Diplocystis) aeruginosa and Scenedesmus quadricauda. Mitt. Int. Ver. Theor. Angew. Limnol. 21:275-284.

Bringmann, G. and R. Kuhn. 1980a. Determination of the biological effect of water pollutants in protozoa. III. Saprozoic flagellates. Z. Wasser Abwasser Forsch. 13:170-173.

Bringmann, G. and R. Kuhn. 1980b. Comparison of the toxicity thresholds of water pollutants to bacteria, algae, and protozoa in the cell multiplication inhibition test. Water Res. 14:231-241.

Bringmann, G. and R. Kuhn. 1980c. Determination of the biological harmful effect of water substances for protozoa. II. Bacteriophagous ciliates. Z. Wasser Abwasser Forsch. 13:26-31.

Bringmann, G. and R. Kuhn. 1981. Comparison of the effects of harmful substances on flagellates as well as ciliates and on holozoic bacteriophagus and saprozoic protozoa. Gas-Wasserfach 122:308-313.

Brooke, L.T., D.J. Call, C.A. Lindberg, T.P. Markee, S.H. Poirier and D.J. McCauley. 1986. Acute toxicity of silver to selected freshwater invertebrates. Center for Lake Superior Environmental Studies, University of Wisconsin-Superior, Superior, WI. Report to Battelle Memorial Research Institute, Columbus, OH.

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

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.

Buccafusco, R.J., S.J. Ells and G.A. LeBlanc. 1981. Acute toxicity of priority pollutants to bluegill (Lepomis macrochirus). Bull. Environ. Contam. Toxicol. 26:446-452.

Buikema, A.L., Jr., J. Cairns, Jr. and G.W. Sullivan. 1973. Development and assessment of acute bioassay techniques for the littoral rotifer, (Philodina acuticornis). PB 290 937. National Technical Information Service, Springfield, VA.

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.

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. 1977a. Survival and growth of bivalve larvae under heavy-metal stress. Mar. Biol. (Berl.) 41:179-184.

Calabrese, A., F.P. Thurberg and E. Gould. 1977b. Effects of cadmium, mercury, and silver on marine animals. Mar. Fish. Rev. 39:5-11.

Calabrese, A., J.R. MacInnes, D.A. Nelson, R.A. Greig and P.P. Yevich. 1984. Effects of long-term exposure to silver or copper on growth, bioaccumulation and histopathology in the blue mussel Mytilus edulis. Mar. Environ. Res. 11:253-274.

Call, D.J., L.T. Brooke, N. Ahmad and J.E. Richter. 1983. Toxicity and metabolism studies with EPA priority pollutants and related chemicals in freshwater organisms. EPA-600/3-83-095 or PB83-263665. National Technical Information Service, Springfield, VA.

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. 17-1 to 17-11.

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

Cardin, J.A. 1986. Results of acute toxicity tests conducted with silver at ERL, Narragansett. (Memorandum to D. Hansen, U.S. EPA, Narragansett, RI.).

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. University Microfilms, Ann Arbor, MI. Order No. 72-9023.

Chambers, C.W. and C.M. Proctor. 1960. The bacteriological and chemical behavior of silver in low concentrations. Technical Report W60-4. U.S. Department of Health, Education and Welfare, Washington, DC.

Chapman, G.A. 1980. Memorandum to Q. Pickering (Newtown Fish Toxicology Station, July 14).

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.

Christensen, G.M. 1971. Effects of metal cations and other chemicals upon the in vitro activity of two enzymes in the blood plasma of the white sucker, Catostomus commersoni (Lacepede). Chem.-Biol. Interact. 4:351-361.

Christensen, G.M. and J.H. Tucker. 1976. Effects of selected water toxicants on the in vitro activity of fish carbonic anhydrase. Chem.-Biol. Interact. 13:181-192.

Chudd, J.M. 1983. Measurement of pAg in natural water samples. Environ. Toxicol. Chem. 2:315-323.

Clark, G.L. 1947. Poisoning and recovery in barnacles and mussels. Biol. Bull. 92:73-91.

Coglianese, M.P. 1982. The effects of salinity on copper and silver toxicity to embryos of the Pacific oyster. Arch. Environ. Contam. Toxicol. 11:297-303.

Coglianese, M.P. and M. Martin. 1981. Individual and interactive effects of environmental stress on the embryonic development of the Pacific oyster, Crassostrea gigas. Mar. Environ. Res. 5:13-27.

Coleman, R.L. and J.E. Cearley. 1974. Silver toxicity and accumulation in largemouth bass and bluegill. Bull. Environ. Contam. Toxicol. 12:53-61.

Dalmon, J. and M. Bayen. 1976. Interaction of silver ions with Chlorella pyrenoidosa nuclear DNA. Plant Sci. Lett. 7:381-390.

Davies, P.H. 1976. A method for determinating the long-term toxicity of insoluble metal compounds demonstrated by silver iodide in natural water. In: Toxicity to biota of metal forms in natural water. Andrew, R.W., P.V. Hodson and D.E. Konasawich (Eds.). International Joint Commission Research Advisory Board, Windsor, Ontario, Canada.

Davies, P.H. and J.P. Goettl, Jr. 1978. Evaluation of the potential impacts of silver and/or silver iodide on rainbow trout in laboratory and high mountain lake environments. In: Environmental impacts of artificial ice nucleating agents. Klein, D.A. (Ed.). Dowden, Hutchinson and Ross Inc., Stroudsburg, PA.

Davies, P.H., J.P. Goettl, Jr. and J.R. Winley. 1978. Toxicity of silver to rainbow trout (Salmo gairdneri). Water Res. 12:113-117.

Ding, S., F. Zhou, Z. Kong, L. Kong, B. Wang and L. Wang. 1982. Acute toxicity of silver to carp (Cyprinus carpio) and goldfish (Carassius auratus) and its accumulation and distribution in fish bodies. Huanjing Kexue 3:6-9.

Dinnel, P.A., Q.J. Stober, S.C. Crumley and R.E. Nakatani. 1982. Development of a sperm cell toxicity test for marine waters. In: Aquatic toxicology and hazard assessment: Fifth conference. Pearson, J.G., R.B. Foster and W.E. Bishop (Eds.). ASTM STP 766. American Society for Testing and Materials, Philadelphia, PA. pp. 82-98.

Dinnel, P.A., Q.J. Stober, 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. Final report to University of Washington Sea Grant Program, Grant R/TOX-1.

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

Doudoroff, P. and M. Katz. 1953. Critical review of literature on the toxicity of industrial wastes and their components to fish. 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 concentrations of molecular hydrocyanic acid. Trans. Am. Fish. Soc. 95:6-22.

EG & G, Bionomics. 1979. The acute toxicity of various silver compounds to the fathead minnow (Pimephales promelas). Report No. BW-79-12-576. Wareham, MA.

Eisler, R., M.M. Barry, R.L. Lapan, Jr., G. Teleek, E.W. Davey and A.E. Sopar. 1978. Metal survey of the marine clam Pitar morrhuana near a Rhode Island (USA) electroplating plant. Mar. Biol. (Berl.) 45:311-317.

Elnabarawy, M.T., A.N. Welter and R.R. Robideau. 1986. Relative sensitivity of three daphnid species to selected organic and inorganic chemicals. Environ. Toxicol. Chem. 5:393-398.

Engel, D.W., W.G. Sunda and B.A. Fowler. 1981. Factors affecting trace metal uptake and toxicity to estuarine organisms. I. Environmental parameters. In:

Biological monitoring of marine pollutants. Vernberg, F.J., A. Calabrese, F.P. Thurberg and W.B. Vernberg (Eds.). Academic Press, New York, NY. pp. 127-143.

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. Am. J. Bot. 72:209-216.

Eyster, L.S. and M.P. Morse. 1984. Development of the surf clam (Spisula solidissima) following exposure of gametes, embryos and larvae to silver. Arch. Environ. Contam. Toxicol. 13:641-646.

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

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

Fitzgerald, G.P. 1967. The algistatic properties of silver. Water Sew. Works 114:185-189.

Freeman, R.A. 1979. Ecological kinetics of silver in an alpine lake ecosystem. In: Aquatic toxicology. Marking, L.L. and R.A. Kimerle (Eds.). ASTM STP 667. American Society for Testing and Materials, Philadelphia, PA. pp. 342-358.

Ganther, H.E. 1980. Interactions of vitamin E and selenium with mercury and silver. Ann. N.Y. Acad. Sci. 355:212-226.

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

Goettl, J.P., Jr. and P.H. Davies. 1978. Water pollution studies. Job progress report. Colorado Division of Wildlife, Department of Natural Resources, Boulder, CO.

Goettl, J.P., Jr., J.R. Sinley and P.H. Davies. 1974. Laboratory studies. Water pollution studies. Colorado Fisheries Research Review. pp. 36-44.

Goettl, J.P., Jr., P.H. Davies and J.R. Sinley. 1976. Water pollution studies. In: Colorado fisheries research review 1972-1975. Cope, D.B. (Ed.). DOW-R-R-F72-75. Colorado Division of Wildlife, Boulder, CO.

Gould, E. and J.R. MacInnes. 1977. Short-term effects of two silver salts on tissue respiration and enzyme activity in the cunner (*Tautogolabrus adspersus*). Bull. Environ. Contam. Toxicol. 18:401-408.

Greig, R.A. 1979. Trace metal uptake by three species of molluscs. Bull. Environ. Contam. Toxicol. 22:643-647.

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

Hall, R.A., E.G. Zook and G.M. Meaburn. 1978. National Marine Fisheries Service survey of trace elements in the fishery resource. Technical Report NMFS SSRF-721. National Oceanic and Atmospheric Administration.

Hannan, P.J. and C. Patouillet. 1972. Effect of mercury on algal growth rates. Biotechnol. Bioeng. 14:93-101.

Hassall, K.A. 1962. A specific effect of copper on the respiration of Chlorella vulgaris. Nature 193:90.

Heitmuller, P.T., T.A. Hollister and P.R. Parrish. 1981. Acute toxicity of 54 industrial chemicals to sheepshead minnows (Cyprinodon variegatus). Bull. Environ. Contam. Toxicol. 27:596-604.

Hibiya, T. and M. Oguri. 1961. Gill absorption and tissue distribution of some radionuclides (Cr-51, Hg-203, Zn-65 and Ag-100 m, 110) in fish. Bull. Jpn. Soc. Sci. Fish. 27:996-1000.

Holcombe, G.W., G.L. Phipps and J.T. Fiandt. 1983. Toxicity of selected priority pollutants to various aquatic organisms. Ecotoxicol. Environ. Safety 7:400-409.

Holcombe, G.W., G.L. Phipps, A.H. Sulaiman and A.D. Hoffman. 1987. Simultaneous multiple species testing: Acute toxicity of 13 chemicals to 12 diverse freshwater families. Arch. Environ. Contam. Toxicol 16:697-710.

Hutchinson, T.C. 1973. Comparative studies on the toxicity of heavy metals to phytoplankton and their synergistic interactions. Water Pollut. Res. 8:68-90.

Hutchinson, T.C. and P.M. Stokes. 1975. Heavy metal toxicity and algal bioassays. In: Water quality parameters. Barabos, S. (Ed.). ASTM STP 573. American Society for Testing and Materials. Philadelphia, PA. pp. 320-343.

International Joint Commission. 1976. Water quality objectives subcommittee task force on scientific basis for water quality criteria. W. Q. B. Appendix A. Water Quality Board. Windsor, Ontario, Canada.

Ishizake, O., Y. Ito and S. Yamaoto. 1966. Determination of the toxicity of food additives by their effects on the life cycle of Chlorella. I. Cultures and method. Nagoya Shiritsu Daigaku Yakugakuba Kenkyu Nenpo 14:66-78; Chem. Abstr. 1968. 68:1965. Abstr. No. 20598h.

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

Jackim, E. 1974. Enzyme responses to metals in fish. In: Pollution and physiology of marine organisms. Vernberg, F.J. and W.B. Vernberg (Eds.). Academic Press, New York, NY. pp. 59-65.

Jackim, E., J.M. Hamlin and S. Sonis. 1970. Effects of metal poisoning on five liver enzymes in the killifish (Fundulus heteroclitus). J. Fish. Res. Board Can. 27:383-390.

Jenne, E.A., D.C. Giruin, J.W. Ball and J.M. Burchard. Manuscript. Inorganic speciation of silver in natural water - fresh to marine. In: Environmental impacts of nucleating agents used in weather modification programs. Klein, D.A. (Ed.). Dower, Hutchinson and Ross, Inc., Stroudsberg, PA.

Jones, J.R. 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, J.R. 1940. A further study of the relation between toxicity and solution pressure, with Polycelis nigra as test animal. J. Exp. Biol. 17:408-415.

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

Katz, B. 1979. Relationship of the physiology of aquatic organisms to the lethality of toxicants: A broad overview with emphasis on membrane permeability. In: Aquatic toxicity. Marking, L.L. and R.A. Kimerle (Eds.). ASTM STP 667. American Society for Testing and Materials, Philadelphia, PA. pp. 62-76.

Kay, S.H. 1984. Potential for biomagnification of contaminants within marine and freshwater food webs. Technical Report D-84-7 or AD-A150-747. National Technical Information Service, Springfield, VA.

Khangarot, B.S. and P.K. Ray. 1987a. Sensitivity of toad tadpoles, Bufo melanostrictus (Schneider), to heavy metals. Bull. Environ. Contam. Toxicol. 38:523-527.

Khangarot, B.S. and P.K. Ray. 1987b. Correlation between heavy metal acute toxicity values in Daphnia magna and fish. Bull. Environ. Contam. Toxicol. 38:722-726..

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.

Klein-MacPhee, G., J.A. Cardin and W.J. Berry. 1984. Effects of silver on eggs and larvae of the winter flounder. Trans. Am. Fish. Soc. 113:247-251.

LaPoint, T.W., S.M. Melancon and M.K. Morris. 1984. Relationships among observed metal concentrations, criteria, and benthic community structural responses in 15 streams. J. Water Pollut. Control Fed. 56:1030-1038.

Laroze, A. 1955. Effect of poisons on fish. Anais Fac. Farm. Porto 15:77-111.

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

LeBlanc, G.A. 1980. Acute toxicity of priority pollutants to water flea (Daphnia magna). Bull. Environ. Contam. Toxicol. 24:684-691.

LeBlanc, G.A., J.D. Maston, A.P. Paradice, B.F. Wilson, H.B. Lockhart, Jr. and K.A. Robillard. 1984. The influence of speciation on the toxicity of silver to fathead minnow (Pimephales promelas). Environ. Toxicol. Chem. 3:37-46.

Lemke, A.E. 1981. Interlaboratory comparison acute testing set. EPA 600/3-81-005 or PB81-160772. National Technical Information Service, Springfield, VA.

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.

Lima, A.R., C. Curtis, D.E. Hammermeister, D.J. Call and T.A. Felhaber. 1982. Acute toxicity of silver to selected fish and invertebrates. Bull. Environ. Contam. Toxicol. 29:184-189.

Lockhart, H.B., Jr. Manuscript. The environmental fate of silver discharged to the environment by the photographic industry. Health, Safety, and Human Factors Laboratory, Eastman Kodak Company, Rochester, NY.

Lopez-Avila, V., W.D. McKenzie, W.W. Sutton, R. Kaminsky, U. Spanagel, T.A. Olsson and J.H. Taylor. 1985. Application of chemical fractionation/aquatic bioassay procedure to hazardous waste site monitoring. EPA-600/4-85-059 or PB86-109493. National Technical Information Service, Springfield, VA.

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.

Luoma, S.N. and E.A. Jenne. 1975. The availability of sediment-bound cobalt, silver, and zinc to a deposit-feeding clam. In: Proceedings of biological implications of metals in the environment, 15th Life Sciences symposium, Hanford, WA, Sept. 29-Oct. 1, 1975.

Lussier, S.M. and J.A. Cardin. 1985. Results of acute toxicity tests conducted with silver at ERL, Narragansett. Memorandum to David 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.

Lytle, P.E. 1984. Fate and speciation of silver in publicly owned treatment works. Environ. Toxicol. Chem. 3:21-30.

MacInnes, J.R. and J. 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. pp. 195-202.

MacInnes, J.R. and F.P. Thurberg. 1973. Effects of metals on the behavior and oxygen consumption of the mud snail. Mar. Pollut. Bull. 4:185-186.

Malins, D.C., B.B. McCain, D.W. Brown, S.L. Chan, M.S. Myers, J.T. Landahl, P.G. Prohaska, A.J. Friedman, L.D. Rhodes, D.G. Burrows, W.D. Gronlund and H.O. Hodgins. 1984. Chemical pollutants in sediments and diseases of bottom-dwelling fish in Puget Sound, Washington. Environ. Sci. Technol. 18:705-713.

Martin, J.H. Manuscript. Bioaccumulation of heavy metals by littoral and pelagic marine organisms. U.S. EPA, Narragansett, RI.

Martin, J.H. and A.R. Flegal. 1975. High copper concentration in squid livers in association with elevated levels of silver, cadmium, and zinc. Mar. Biol. (Berl.) 30:51-55.

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.). Brookhaven National Laboratory, Brookhaven, NY. pp. 35-66.

Martin, M., G. Ichikawa, J. Goetzl, M. de los Reyes and M.D. Stephenson. 1984. Relationships between physiological stress and trace toxic substances in the bay mussel, Mytilus edulis, from San Francisco Bay, California. Mar. Environ. Res. 11:91-110.

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

McDermott, D.J., G.V. Alexander, D.R. Young, and A.J. Mearns. 1976. Metal contamination of flatfish around a large submarine outfall. J. Water Pollut. Control Fed. 48:1913-1918.

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.

McKenney, C.L. 1982. Interlaboratory comparison of chronic toxicity testing using the estuarine mysid (Mysidopsis bahia): A final report. U.S. EPA, Gulf Breeze, FL.

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

Mukai, H. 1977. Effects of chemical pretreatment on the germination of statoblasts of the freshwater bryozoan, Pectinatella gelatinosa. Biol. Zbl. 96:19-31.

Nebeker, A.V. 1982. Evaluation of a Daphnia magna renewal life-cycle test method with silver and endosulfan. Water Res. 16:739-744.

Nebeker, A.V., C.K. McAuliffe, R. Mshar and D.G. Stevens. 1983. Toxicity of silver to steelhead and rainbow trout, fathead minnows and Daphnia magna. Environ. Toxicol. Chem. 2:95-104.

Nehring. R.B. 1973. Heavy metal toxicity in two species of aquatic insects. Masters thesis. Colorado State University, Fort Collins, CO.

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

Nelson, D.A., A. Calabrese, R.A. Greig, P.P. Yevich and S. Chang. 1983. Long-term silver effects on the marine gastropod Crepidula fornicata. Mar. Ecol. Prog. Ser. 12:155-165.

Nelson, D.A., A. Calabrese, B.A. Nelson, J.R. MacInnes and D.R. Wenzloff. 1976. Biological effects of heavy metals on juvenile bay scallops, Argopecten irradians, in short-term exposures. Bull. Environ. Contam. Toxicol. 16:275-281.

Palmer, C.M. and T.E. Maloney. 1955. Preliminary screening for potential algicides. Ohio J. Sci. 55:1-8.

Parsons, T.R., C.A. Bawden and W.A. Heath. 1973. Preliminary survey of mercury and other metals contained in animals from the Fraser River mudflats. J. Fish. Res. Board Can. 30:1014-1016.

Pereira, J.J. and K. Kanungo. 1981. Effects of silver on respiration and on ion and water balance in Neanthes virens. In: Biological monitoring of marine pollutants. Vernberg, F.J., A. Calabrese, F.P. Thurberg and W.B. Vernberg (Eds.). Academic Press, New York, NY. pp. 107-125.

Pesch, C.E. and G.L. Hoffman. 1983. Interlaboratory comparison of a 28-day toxicity test with the polychaete Neanthes arenaceodentata. In: Aquatic toxicology and hazard assessment: Sixth symposium. Bishop, W.E., R.D. Cardwell and B.B. Heidolph (Eds.). ASTM STP 802. American Society for Testing and Materials, Philadelphia, PA. pp. 482-493.

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.

Pilie, R.J., R.E. Baier, R.C. Ziegler, R.P. Leonard, J.G. Michalovic, S.L. Pek and D.H. Bock. 1975. Methods to treat, control and monitor spilled hazardous materials. EPA-670/2-75-042. National Technical Information Service, Springfield, VA.

Rai, L.C. and M. Raizada. 1985. Effect of nickel and silver ions on survival, growth, carbon fixation and nitrogenase activity in Nostoc muscorum: Regulation of toxicity by EDTA and calcium. J. Gen. Appl. Microbiol. 31:329-337.

Reynolds, B.H. 1979. Trace metals monitoring at two ocean disposal sites. EPA-600/3-79-037. National Technical Information Service, Springfield, VA.

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.

Rombough, P.J. 1985. The influence of the zonae radieta on the toxicities of zinc, lead, mercury, copper and silver ions to embryos of steelhead trout Salmo gairdneri. Comp. Biochem. Physiol. 82C:115-117.

Schimmel, S.C. 1981. Results: Interlaboratory comparison--acute toxicity tests using estuarine animals. EPA-600/4-81-003. National Technical Information Service, Springfield, VA.

Shaw, W.H. and B. Grushkin. 1957. The toxicity of metal ions to aquatic organisms. Arch. Biochem. Biophys. 67:447-452.

Shaw, W.H. and B.R. Lowrance. 1956. Bioassay for the estimation of metal ions. Anal. Chem. 28:1164-1166.

Steel, R.L. and G.B. Thursby. 1983. A toxicity test using life stages of Champia parvula (Rhodophyta). In: Aquatic toxicology and hazard assessment: Sixth symposium. Bishop, W.E., R.D. Cardwell and B.B. Heidolph (Eds.). ASTM STP 802. American Society for Testing and Materials, Philadelphia, PA. pp. 73-89.

Soyer, J. 1963. Contribution to the study of the effects of mercury and silver on marine organisms. Vie et Milieu 14:1-36.

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.

Stokes, P.M., T.C. Hutchinson and K. Krauter. 1973. Heavy metal tolerance in algae isolated from polluted lakes near the Sudbury, Ontario smelters. Water Pollut. Res. 8:178-201.

Storebakken, T., E. Austreng and K. Steenberg. 1981. A method for determination of feed intake in salmonids using radioactive isotopes. Aquaculture 24:133-142.

Strong, C.R. and S.N. Luoma. 1981. Variations in the correlation of body size with concentrations of Cu and Ag in the bivalve Macoma balthica. Can. J. Fish. Aquat. Sci. 38:1059-1061.

Strumm, W. and J.J. Morgan. 1981. Aquatic chemistry. Wiley, New York, NY. pp. 176-177.

Tanaka, O. and C.F. Cleland. 1978. Influence of ferricyanide on flowering in Lemna. Plant Physiol. 61(Suppl.):52.

Telitchenko, M.M., G.V. Tsytsarin and Y.L. Shirokova. 1970. Trace elements and algal "bloom". Hydrobiol. J. (Engl. Transl. Gidrobiol. Zh.) 6(6):1-6.

Terhaar, C.J., W.S. Ewell, S.P. Dziuba and D.W. Fassett. 1972. Toxicity of photographic processing chemicals to fish. Photogr. Sci. Eng. 16:370-377.

Terhaar, C.J., W.S. Ewell, S.P. Dziuba, W.W. White and P.J. Murphy. 1977. A laboratory model for evaluating the behavior of heavy metals in an aquatic environment. Water Res. 11:101-110.

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.

Thurberg, F.P., W.D. Cable, M.A. Dawson, J.R. MacInnes and D.R. Wenzloof. 1975. Respiratory response of larval, juvenile and adult surf clams Spisula solidissima to silver. In: Respiration of marine organisms. Cech, J.J., Jr., D.W. Bridges and D.B. Horton (Eds.). TRIGOM Publishers, South Portland, ME.

Thurberg, F.P., A. Calabrese and M.A. Dawson. 1974. Effects of silver on oxygen consumption of bivalves at various salinities. In: Pollution and physiology of marine organisms. Vernberg, F.J. and W.B. Vernberg (Eds.). Academic Press, New York, NY. pp. 67-78.

Thurberg, F.P. and R.S. Collier. 1977. Respiratory response of cunners to silver. Mar. Pollut. Bull. 8:40-41.

Tong, S.C., W.H. Gutenmann, D.J. Lisk, G.E. Burdick and E.J. Harris. 1972. Trace metals in New York State fish. N.Y. Fish Game J. 19:123-131.

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.

U.S. EPA. 1976. Quality criteria for water. EPA-440/9-76-023 or PB-263943. National Technical Information Service, Springfield, VA.

U.S. EPA. 1978. In-depth studies on health and environmental impacts of selected water pollutants. (Table of data available from Charles E. Stephan, U.S. EPA, Duluth, MN.)

U.S. EPA. 1980a. Ambient water quality criteria for silver. EPA-440/5-80-071 or PB81-117822. National Technical Information Service, Springfield, VA.

U.S. EPA. 1980b. Water quality criteria documents. Federal Regist. 14:79318-79379. November 28.

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. Federal Regist. 48:51400-51413. November 8.

U.S. EPA. 1983c. Water quality standards 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." Federal Regist. 50:30793-30796. July 29.

U.S. EPA. 1985b. Water quality criteria. Federal Regist. 50:30784-30792. July 29.

U.S. EPA. 1985c. Technical support document for water quality-based toxics control. EPA-440/4-85-032 or PB86-150067. National Technical Information Service, Springfield, VA.

U.S. EPA. 1986. Chapter I - Stream design flow for steady-state modeling. In: Book VI - Design conditions. In: Technical guidance manual for performing waste load allocation. Office of Water, Washington, DC. August.

U.S. EPA. 1987. Permit writer's guide to water quality-based permitting for toxic pollutants. EPA-440/4-87-005. Office of Water, Washington, DC.

Van Coillie, R. and A. Rousseau. 1974. The mineral content of scales of Castostomus commersoni taken from two different environments: Results using electron microscopic analyses. J. Fish. Res. Board Can. 31:63-66.

Voyer, R.A., J.A. Cardin, J.F. Heltsch and G.L. Hoffman. 1982. Viability of embryos of the winter flounder Pseudopleuronectes americanus exposed to mixtures of cadmium and silver in combination with selected fixed salinities. Aquat. Toxicol. 2:223-233.

Watanabe, K. and A. Takimoto. 1977. Effects of some metabolic inhibitors on flowering of Lemna gibba G3, a long-day duckweed. Plant Cell Physiol. 18:1369-1372.

Whitton, B.A. 1970. Toxicity of heavy metals to freshwater algae: A review. Phykos 9:116-125.

Williamson, K.J. and P.O. Nelson. 1983. Bacterial bioassay for level 1 toxicity assessment. EPA-600/3-83-017 or PB83-182287. National Technical Information Service, Springfield, VA.

Wilson, W.B. and L.R. Freeberg. 1980. Toxicity of metals to marine phytoplankton cultures. EPA-600/3-870-025. National Technical Information Service, Springfield, VA.

Windom, H.L., K.T. Tenore and D.L. Rice. 1982. Metal accumulation by the polychaete Capitella capitata: Influence of metal content and nutritional quality detritus. Can. J. Fish. Aquat. Sci. 39:191-196.

Young, B.G. and D.J. Lisk. 1972. Effect of copper and silver ions on algae. J. Water Pollut. Control Fed. 44:1643-1647.

Zaroogian, G.E. Manuscript. Interlaboratory comparison--acute toxicity tests using the 48 hour oyster embryo-larval assay. U.S. EPA, Narragansett, R.I.