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8/19/8

# Revised Section B of Ambient Water Quality Criteria for Cadmium

## AQUATIC TOXICOLOGY*

### Introduction

In natural fresh waters cadmium sometimes occurs at concentrations of less than 0.01 ug/l, but in environments impacted by man, concentrations can be several micrograms per liter or greater. The impact of cadmium on aquatic organisms depends on a variety of possible chemical forms of cadmium (Callahan, et al. 1979), which may have different toxicities and bioconcentration factors. In most well oxygenated fresh waters that are low in total organic carbon, free divalent cadmium will be the predominant form. Precipitation by carbonate or hydroxide and formation of soluble complexes by chloride, sulfate, carbonate, and hydroxide should usually be of little importance. In saltwater systems with typical salinity, the number of important cadmium species is reduced to a few because cadmium chloride complexes probably predominate. In both fresh and salt water particulate matter and dissolved organic material may bind a substantial portion of the cadmium.

Most insoluble forms of most metals probably are not toxic, but some possibly can become toxic under natural conditions and precipitates of some metals apparently are toxic (Mount, 1966; Chapman, et al. Manuscript; Bradley and Sprague, Manuscript). Because of the variety of the forms of cadmium and

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*An understanding of the Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Life and Its Uses (Stephan, et al. 1983) is necessary in order to understand the following text, tables, and calculations.

lack of definitive information about their relative toxicities, no available analytical measurement is known to be ideal for expressing aquatic life criteria for cadmium, but active cadmium (operationally defined by acidifying the aqueous sample to pH = 4 with nitric acid and then measuring the concentration of cadmium that passes through a 0.45 μm membrane filter) is probably the best available measurement. Previous aquatic life criteria for cadmium (U.S. EPA, 1980) were specified in terms of total recoverable cadmium (U.S. EPA, 1979), but this measurement may be too rigorous in some situations. It is expected that measurement of active cadmium and total recoverable cadmium would have produced the same results in all tests used to derive criteria and would produce the same results on most samples from surface waters and effluents. Where the two measurements produce different results on samples of surface waters or effluents, measurement of active cadmium (as defined above) should be the more appropriate measurement.

Measurement of active cadmium is compatible with all of the data used to derive criteria because test results were not used if it was likely that they would have been different if they had been reported in terms of active cadmium. For example, results reported in terms of dissolved cadmium were not used if the concentration of precipitated cadmium was possibly significant. On samples of ambient water this method is intended to measure all forms of cadmium that are toxic to aquatic life or can be readily converted to toxic forms under natural conditions. In addition, this method is intended to exclude several forms, such as cadmium that is part of 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 method (and many others) will measure soluble, complexed forms of cadmium, such as the EDTA complex of cadmium, that probably have low toxicities to aquatic life, concentrations of these forms probably are negligible in ambient water. Measurement of active cadmium does not require immediate analysis in the field and does not require special effort or equipment. This is also the least rigorous of the measurements (a) which are compatible with the available toxicological data without using hypothetical extrapolations and (b) for which it is usually acceptable to assume that no harm will result from measured or calculated concentrations in ambient water that are below national criteria.

Active cadmium should also be a useful measurement for monitoring effluents, and dilution of effluent with receiving water before measurement should demonstrate whether the receiving water can decrease the concentration of active cadmium because of sorption. Measurement of both active cadmium and total recoverable cadmium in ambient water or effluent or both might be useful. For example, there is more cause for concern if total recoverable cadmium is above the appropriate criterion, even though active cadmium is below the criterion, than there is if both are below the criterion. If a national criterion is possibly unacceptable for a particular situation, a site-specific criterion (U.S. EPA, 1982) can be derived.

Unless other wise noted, all concentrations reported herein are expected to be essentially equivalent to active cadmium concentrations. All concentrations are expressed as cadmium, not as the chemical tested. The criteria presented herein supersede previous aquatic life water quality criteria for cadmium (U.S. EPA, 1976, 1980) because these new criteria were derived using improved procedures and additional information. The literature search for this document was conducted in October, 1981; some newer information was also used.

Acute Toxicity to Aquatic Animals

A reduction in toxicity associated with increased hardness is evident for several fish and invertebrate species. Carroll, et al. (1979) found that calcium, but not magnesium, reduced the acute toxicity of cadmium. In most natural waters, calcium and magnesium are both present, with calcium being somewhat more abundant. Giesy, et al. (1977) found that equilibrium associations of cadmium with dissolved organics substantially reduced its toxicity to daphnids, but had little effect on toxicity to fish. No consistent relationship of toxicity to organic particle size was demonstrated.

Among invertebrates, cladocerans were the most sensitive species and mayflies and stoneflies were the most resistant. However, insects and other invertebrates are more sensitive during molting which usually does not occur among most individuals in less than 96 hours. Salmonids uniformly appear to be the fish species most vulnerable to cadmium (Tables 1 and 6).

The available acute values for both striped bass and brook trout covered such a wide range that data for these species are not used in the calculation of the Final Acute Value. Drummond and Benoit (Manuscript) reported that stress greatly affected the sensitivity of brook trout to cadmium.

Different species exhibit different sensitivities to cadmium, and many other factors may affect the results of tests of the toxicity of cadmium to aquatic species. Criteria can quantitatively take into account such a factor, however, only if enough data are available to show that the factor similarly affects the results of tests with a variety of species. Hardness is often thought of as having a major effect on the toxicity of cadmium, although the observed effect may be due to one or more of a number of usually interrelated ions, such as hydroxide, carbonate, calcium, and magnesium. Hardness is used here as a surrogate for the ions which affect the results of toxicity tests on cadmium. An analysis of covariance (Dixon and Brown, 1979; Neter and Wasserman, 1974) was performed using the natural logarithm of the acute value as the dependent variable, species as the treatment or grouping variable, and natural logarithm of hardness as the covariate or independent variable. This analysis of covariance model was fit to the data in Table 1 for those species for which data are available over an adequate range of hardness, i.e., Philodina acuticornis, Daphnia magna, goldfish, fathead minnow, green sunfish and bluegill (see end of Table 1). Tests of the slopes for the individual species indicated that they were statistically different at P=0.03. The slope for Philodina acuticornis was slightly negative, the two hardnesses tested were both below 85 mg/l, and the result at the higher hardness fell between the results at the lower hardness. The other five were all between 0.90 and 1.56 and a test of these five slopes indicated that they were not statistically different at P=0.89; this large value of P shows a very small probability that the null hypothesis should have been rejected. The pooled slope of 1.16 was statistically significant from zero at P=0.0001. The pooled slope is close to the value of 1.0 that is expected on the basis that cadmium, calcium, magnesium and carbonate are all divalent; if hydroxide had a substantial effect, the slope would be greater than 1.0.

The pooled slope of 1.16 was then used with the data in Table 1 to calculate Species Mean Acute Values at a hardness of 50 mg/l (Table 1). Family Mean Acute Values were then calculated (Table 3) as geometric means of the available Species Mean Acute Values. The two salmonids were within a factor of 2 and the two cyprinids were within a factor of 6. The most sensitive family, Salmonidae, was 1,980 times more sensitive than the most resistant family, Bithyniidae. The freshwater Final Acute Value of 6.662 µg/l was calculated for a hardness of 50 mg/l from the Family Mean Acute Values using the procedure described in the Guidelines. Because the Species Mean Acute Value for rainbow trout is 3.945 µg/l at a hardness of 50 mg/l, the Final Acute Value is lowered to protect this important species (Table 3). Thus, the Criterion Maximum Concentration = $e^{(1.16[\ln(\text{hardness})]-3.841)}$.

The acute values for saltwater invertebrates range from 15.5 ug/l for a mysid to 46,600 for the adult fiddler crab. The acute values for adult saltwater polychaetes range from 7,500 ug/l for <u>Capitella capitata</u> to 12,500 ug/l for <u>Neanthes arenaceodentata</u> (Reish et al., 1976), but the larvae of <u>C. capitata</u> are thirty-five times more sensitive than the adults. Saltwater molluscs have acute values from 850 ug/l for the soft-shell clam (Eisler, 1971) to 35,000 ug/l for the mud snail (Eisler and Hennekey, 1977).

Frank and Robertson (1979) reported that the acute toxicity to juvenile blue crabs was related to salinity. The 96-hour acute toxicities were 320, 4,700, and 11,600 ug/l at salinities of 1, 15, and 35 g/kg, respectively. O'Hare (1973) investigated the effect of temperature and salinity on the toxicity of cadmium to the fiddler crab and did not find a significant effect of salinity. Acute toxicities at 20°C were 32,300, 46,600, and 37,000 at 10, 20, and 30 g/kg salinity. Increasing the temperature from 20 to 30°C increased toxicity at all salinities tested.

The saltwater fish species were generally more resistant to cadmium with acute values ranging from 577 µg/l for the larvae of Atlantic silversides to 114,000 ug/l for juvenile mummichog. In a study of the interaction of dissolved oxygen and salinity on the ~~acute~~ toxicity of cadmium to the mummichog, Voyer (1975) found similar toxicities at salinities of 10 and 20 g/kg but a doubling of the sensitivity at 30 g/kg. Resistance of mummichogs to acute cadmium poisoning was not influenced by reductions in dissolved oxygen levels to 4 mg/l.

Of the 26 families, the most sensitive, Mysidae, was 910 times more sensitive than the most resistant family, Cyprinodontidae. Acute values are available for more than one species in four families, and the range of values in a family is always less than a factor of 3.3. The saltwater Final Acute Value calculated from the Family Mean Acute Values in Table 3 is 75.44 ug/l.

## Chronic Toxicity to Aquatic Animals

Chronic toxicity tests have been conducted on cadmium with numerous freshwater animal species (Table 2). The range of available chronic toxicity values (0.15 to 50 ug/l) is less than the range of available acute toxicity values. *Daphnia magna* is the most sensitive species tested, and Bertram and Hart (1979) found chronic toxicity to *Daphnia pulex* at less than 1 ug/l (Table 6). A 200-hr LC10 value of 0.7 ug/l for rainbow trout was obtained by Chapman (1978) and probably would be close to the result of an early life-stage test because of the extent to which various life stages were investigated (Table 6). Other salmonids and many invertebrates are also quite sensitive, with effects having been observed at 5 ug/l or less (Table 6). These organisms include decomposers (Giesy, 1978), crayfish (Thorp, et al. 1979), copepods and annelids (Giesy, et al. 1979), midges (Anderson, et al. 1980) and mayflies (Spehar, et al. 1978).

All of the acute-chronic ratios for freshwater species are between 65 and 434, except for the value of 0.9021 obtained with chinook salmon (Table 2). The lowest ratio is surprising because all the other ratios are much higher and were obtained with a variety of species over a wide range of hardnesses and sensitivities. The lowest ratio is even more surprising because it is less than 1.0, indicating that acclimation must have occurred during the early life-stage test. Because the Final Acute Value is based on a species in the same family as the species with which the lowest acute-chronic ratio was obtained, it seems inappropriate to use the higher ratios to obtain the Final Chronic Value. To protect rainbow trout in those situations in which the concentration of cadmium is not constant enough to result in acclimation, the Final Chronic Value cannot be higher than the Criterion Maximum Concentration. Thus the Freshwater Final Chronic Value = $e^{(1.16[\ln(\text{hardness})]-3.84)}$.

Two chronic toxicity studies have been conducted with the saltwater invertebrate, *Mysidopsis bahia* (Table 2). Nimmo et al. (1977a) conducted a 23-day life-cycle test at 20-28 C and 15-23 g/kg salinity. Decreased survival occurred at 10.6 ug/l, whereas a 48-hr delay in brood formation, 24-hour delay in brood release, and a 57% decrease in the number of young per female resulted at 6.4 ug/l. No adverse effects were detected at 4.8 ug/l. The chronic toxicity limits, therefore, are 4.8 and 6.4 ug/l with a chronic value of 5.5 ug/l. The 96-hour LC50 was 15.5 ug/l resulting in an acute-chronic ratio of 2.8.

Another life-cycle study was conducted with cadmium and *Mysidopsis bahia* under different environmental conditions, including constant temperature (21 C) and salinity (30 g/kg). Complete mortality occurred after 28 days exposure at 25 ug/l. At 11.5 ug/l a series of morphological abberations occurred at the onset of sexual maturity. External genitalia in males were abberant, females failed to develop brood pouches and both sexes developed a carapace malformation that prohibited molting after the release of the initial brood. Although initial reproduction at this concentration was successful, successive broods could not be borne because molting resulted in death. No malformations or effects on initial or successive reproductive processes were noted in the controls or at 5.5 ug/l. The chronic limits for this study are 5.5 and 11.5 with a chronic value of 8.0 ug/l. The LC50 at 21 C and 30 g/kg salinity was 110 ug/l which results in an acute-chronic ratio of 14 from this study.

These two studies showed excellent agreement between the chronic values but considerable divergence between the acute values and acute-chronic ratios. Several studies have demonstrated an increase in acute toxicity of cadmium with decreasing salinity and increasing temperature (Table 6). The observed differences in acute toxicity to the mysids might be explained on this basis. Nimmo, et al. (1977a) conducted their acute test at 25 to 28 C and 10-17 g/kg salinity whereas the other test was performed at 21 C and 30 g/kg salinity.

Because the acute-chronic ratios with freshwater animals covered such a wide range, it would be inappropriate to use the geometric mean of all available acute-chronic ratios to calculate the saltwater Final Chronic Value. The saltwater species for which an acute-chronic ratio is available has a Species Mean Acute Value very close to the saltwater Final Acute Value and so it seems reasonable then to use this acute-chronic ratio. When the Final Acute Value of 75.44 ug/l is divided by the acute-chronic ratio of 6.218, a saltwater Final Chronic Value of 12.13 ug/l is obtained.

Toxicity to Aquatic Plants

Growth reduction was the major toxic effect observed with freshwater aquatic plants (Table 4), and several values are in the range of concentrations causing chronic effects in animals. The influence that plant growth media may have had on the toxicity studies is unknown, but is probably minor at least in the case of Conway (1978) who used a medium patterned after natural Lake Michigan water. Because the lowest toxicity values for fish and invertebrates species are lower than the values for plants, water quality criteria which protect freshwater aquatic animals should also protect aquatic plants.

Toxicity values are available for three species of saltwater diatoms and two species of macroalgae (Table 4). Concentrations causing fifty percent reductions in the growth rates of diatoms range from 60 ug/l for Ditylum brightwelli to 175 ug/l for Skeletonema costatum. The brown macroalga (kelp) was the least sensitive to cadmium with an EC50 of 860 µg/l. The most sensitive plant tested was the red alga, Champia parvula, with significant reductions in the growth of both the tetrasporophyte plant and female plant occurring below 14 ug/l. This species of plant is of comparable sensitivity to the chronic values for the most sensitive animal species tested.

## Bioaccumulation

Bioconcentration factors (BCF) for cadmium in fresh water (Table 5) ranged from 3 for brook trout muscle (Benoit, et al. 1976) to 12,400 in the whole body of mosquitofish (Giesy, et al. 1977). Usually, fish accumulate only small amounts of cadmium in muscle as compared to most other tissues and organs (Benoit, et al. 1976; Sangalang and Freeman, 1979). Also, cadmium residues in fish reach steady-state only after exposure periods greatly exceeding 28 days (Benoit, et al. 1976; Sangalang and Freeman, 1979; Giesy, et al. 1977). Daphnia magna, and presumably other invertebrates of about this size or smaller, often reach steady-state within a few days (Poldoski, 1979). Cadmium accumulated by fish from water is eliminated slowly (Benoit, et al. 1976, Kumada, et al. 1980), but Kumada, et al. (1980) found that cadmium accumulated from food is eliminated much more rapidly.

Mallard ducks are the only native wildlife species whose chronic sensitivity to cadmium has been studied. These birds can be expected to ingest many of the different freshwater plants and animals listed in Table 4. White and Finley (1978,a,b) found significant damage occurring at a cadmium concentration of 200 mg/kg in food for 90 days. Division of 200 mg/kg by the geometric mean BCF of 766 gives a Final Residue Value of 260 ug/l. This is a concentration which would cause damage to mallard ducks, but no additional data are available.

Among saltwater species, BCFs have been determined for cadmium with one species of alga, thirteen species of invertebrates and one species of fish (Table 5). Values range from 22 to 3,160 for whole body and from 5 to 2,040 for muscle. Kerfoot and Jacobs (1976) reported a BCF of 670 for the alga, Prasinocladus tricornutum. Theede et al. (1979) found that the colonial hydroid, Laomedea loveni, bioconcentrated cadmium 153 times within a 10-day exposure period. The highest BCF was reported for the polychaete Ophryotrocha diadema (Klockner, 1979). After sixty-four days exposure using the renewal technique, a BCF of 3,160 was attained. Tissue residues, however, had not reached steady-state.

BCFs for 5 species of bivalve molluscs range from 83 for the quahog clam (Kerfoot and Jacobs, 1976) to 2,600 for the eastern oyster (Zaroogian and Cheer, 1976). In addition, the range of reported BCFs is rather large for some individual species. BCFs for the oyster include 149 and 677 (Table 6) as well as 1,220 and 2,600 (Table 5). Similarly, two reported studies on the bay scallop report BCFs of 168 (Eisler, et al. 1972), and 2,040 (Pesch and Stewart, 1980) and three studies on the blue mussel report BCFs of 113, 306, and 710 (Tables 5 and 6). George and Coombs (1977) studied the importance of metal speciation on cadmium accumulation in the soft-tissues of Mytilus edulis. Cadmium complexed as Cd-EDTA, Cd-alginate, Cd-humate, and Cd-pectate (Table 6) was bioconcentrated at twice the rate of inorganic cadmium (Table 5). Because bivalve molluscs usually do not reach steady-state, comparisons between species may be difficult and the length of exposure may be the major determinant in the size of the BCF.

BCFs for six species of crustaceans range from 22 to 307 for whole body and from 5 to 25 for muscle (Table 6). Nimmo et al. (1977) reported whole body BCFs of 203 and 307 for two species of grass shrimp, Palaemontes pugio and Palaemonetes vulgaris. Vernberg et al. (1977) reported a factor of 140 for P. pugio at 25 C, whereas Pesch and Stewart (1980) reported a factor of only 42 for the same species exposed at 10 C indicating that temperature may be an important variable. The commercially important crustaceans, the pink shrimp and lobster, were not effective bioaccumulators of cadmium with factors of 57 for whole body and 25 for muscle, respectively. A single BCF of 48 is reported for saltwater fishes (Eisler, et al. 1972), which probably indicates that fish also do not bioconcentrate cadmium effectively.

Although a high degree of variability exists between the BCFs reported for saltwater organisms, shellfish can accumulate cadmium in tissues to concentrations potentially harmful to man. The emetic threshold of cadmium is 13-15 mg/kg for man (Anon., 1950). Zaroogian and Cheer (1976) reported finding cadmium in oyster tissue at 11 mg/kg after 280 days exposure to 5 ug/l. Kerfoot and Jacobs (1976) also demonstrated cadmium concentrations of 16 mg/kg in oyster tissue after a 40-day exposure to 30 ug/l.

Other Data

Cadmium-binding proteins were isolated from Amoeba proteus (Al-atia, 1978, 1980) and rainbow trout (Roberts, et al. 1979). The cumulative mortality resulting from exposure to cadmium for more than 96 hours is clearly evident from the studies of Reish, et al. (1976) on polychaetes; Eisler and Hennekey (1977) on bivalve molluscs, crabs, and starfish; Pesch and Stewart (1980) on scallops, shrimp, crabs; and on a mysid (Gentile, et al. 1982; Nimmo, et al. 1977a). Nimmo et al. (1977a) in studies with the mysid, Mysidopsis bahia, reported a 96-hr LC50 of 15.5 ug/l (Table 1) and a 17-day LC50 of 11 ug/l (Table 6) at 25-28 C and 15-23 g/kg salinity. In another series of studies on this mysid (Gentile, et al. 1982), the 96-hr LC50 was 105 ug/l (Table 1) and the 28-day LC50 was 16 ug/l (Table 6) at 20 C and 30 g/kg salinity. Comparison of these data leads to the hypothesis that short-term acute toxicity may be strongly influenced by environmental variables whereas long-term effects, even mortality, are not. This pattern was also reflected in the similarity of reproductive effects on this species (Table 2) tested under dissimilar environmental conditions.

Two studies of chronic exposure are illustrative of the effects of cadmium on growth and fecundity. Pesch and Stewart (1980) in a study of cadmium toxicity to the bay scallop, Argopecten irradians, reported a 96-hr LC50 of 1,480 ug/l and a 42-day LC50 of 530 ug/l. They also reported that 60 and 120 ug/l reduced growth 42 and 69 percent, respectively, which results in an EC50 of about 78 ug/l.

Considerable information exists concerning the effect of salinity and temperature on the acute toxicity of cadmium. Unfortunately the conditions and durations of exposure are so different that adjustment of acute toxicity data for salinity is not possible. Rosenberg and Costlow (1976) studied the synergistic effects of cadmium and salinity combined with constant and cycling temperatures on the larval development of two estuarine crab species. They reported reduction in survival and significant delay in development of the blue crab with decreasing salinity. Three times as much cadmium was required to produce an LC50 at 30 than at 10 g/kg salinity. Studies with the mud crab resulted in a similar cadmium-salinity response. In addition, the authors report that cycling temperatures may have a stimulating effect on survival of larvae compared to constant temperatures.

Theede, et al. (1979) investigated the effect of temperature and salinity on the acute toxicity of cadmium to the colonial hydroid, Laomedea loveni. At 17.5 C cadmium concentrations inducing irreversible retraction of half of the polyps ranged from 12.4 ug/l at 25 g/kg salinity to 3.0 ug/l at 10 g/kg salinity (Table 6). At 25 g/kg salinity the toxicity of cadmium decreased as temperature increased.

The effect of environmental factors on the acute toxicity of cadmium is also evident for the early life stages of saltwater vertebrates. Alderdice et al. (1979a,b,c,) reported that salinity influenced the effects of cadmium on the volume, capsule strength, and osmotic response of embryos of the Pacific herring. Voyer, et al. (1979) reported a significant linear relationship between salinity and cadmium toxicity to Atlantic silverside embryos. Previous studies on the embryos of the winter flounder indicated a quadratic salinity-cadmium relationship (Voyer, et al. 1977).

Several studies have reported on the chronic sublethal effects of cadmium on saltwater fishes (Table 6). Significant reduction in gill tissue respiratory rates and the alteration of liver enzyme activity have been reported for the cunner afer a 30-day exposure to 50 ug/l (MacInnes, et al. 1977). Dawson, et al. (1977) also reported a signficant decrease in gill-tissue respiration for striped bass at 0.5 ug/l above ambient after a 30-day, but not a 90-day, exposure. A similar study on the winter flounder (Calabrese, et al. 1975) demonstrated a significant alteration in gill tissue respiration rates measured in vitro after a 60-day exposure to 5 ug/l. The significance of these sublethal effects on growth and reproduction have yet to be evaluated.

Unused Data

Many data, such as those in Kobayashi (1971), D'Agostino and Finney (1974), Wasternhagen, et al. (1975, 1978), Westernhagen and Dethlefsen (1975), Ojaveer, et al. (1980), Negilski (1976), and Rainbow, et al. (1980), were not used because the species used are not resident in North America. Data in publications such as Ball (1967), Landner and Jernelov (1969), Ministry of Technology (1967, 1971), Tarzwell and Henderson (1960), Burnison, et al. (1975), Shcherban (1977), Fennikok, et al. (1978), Canton and Slooff (1979), Verma, et al. (1980) and Maas (1978) were not used because either the materials, methods, or results were insufficiently described. High control mortalities occurred in all except one test reported by Sauter, et al. (1976).

The acceptability of the dilution water used in some studies, e.g., Cearley and Coleman (1973, 1974) and Brkovic-Popovic and Popovic (1977a,b), was open to question because of its origin or content. Data from some algal studies (e.g., Muller and Payer, 1979, 1980; and Lue-Kim, et al. 1980) were not used because the medium contained EDTA. Some papers were omitted because of questionable treatment of test organisms, inappropriate test conditions or methodology or the data reported better in another source. Some of these included Eisler and Gardner, 1973; Moraitou-Apostolopoulou, et al 1979.

Mowdy, 1981; Hutcheson, 1975; Sunda, et al. 1978; Greig, 1979; and Bryan, 1971.

Data on bioconcentration by aquatic organisms were not used if the test was too short (Beattie and Pascoe, 1978; Yager and Harry, 1964; Garoday and Churchill, 1979; and Reichert, et al. 1979) or if the concentrations in water were not adequately measured (Freeman, 1978, 1980). The bioconcentration tests of Eisler (1974), Jennings and Rainbow (1979b), O'Hara (1973b), Phelps (1979), Sick and Baptist (1979) were not used because results were based on isotopic cadmium without adequate evaluation of non-isotopic cadmium. Data in Ray, et al. (1981), Greig and Wenzloff (1978), Boyden (1977), Noel-Lambot (1980), Kneip and Hazen (1979), Anderson, et al. (1978), Frazier (1979), and Hazen and Kneip (1980) were not used because the field exposure concentrations of cadmium were insufficiently characterized.

Mode of action studies (DeFilippis, 1981) and in vitro studies (Tucker and Matte, 1980) were not used. The data of Stern and Stern (1980) were not used because cadmium was only one of several metals in a mixture. Reviews by Chapman, et al. (1968), Thompson, et al. (1972), and Phillips and Russo (1978) only contain data that had been published elsewhere.

## Summary

Freshwater acute values for cadmium are available for 30 species and range from 2.9 μg/l for rainbow trout to 9,900 for mosquitofish. The antagonistic effect of hardness on acute toxicity has been demonstrated with six species. Chronic tests have been conducted on cadmium with eleven freshwater fish species and one invertebrate species with chronic values ranging from 0.15 μg/l for *Daphnia magna* to 50 μg/l for the bluegill.

Acute-chronic ratios are available for five species; four of the ratios are between 120 and 440, but the ratio for the sensitive chinook salmon is 0.9021, indicating substantial acclimation.

Freshwater aquatic plants are affected by cadmium at concentrations ranging from 2 to 7,400 ug/l. These values are in the same range as the acute toxicity values for fish and invertebrate species, and are considerably above the chronic values. Bioconcentration factors for cadmium reach 3,000 for some invertebrates, and may be as high as 12,000 for some fish species.

The saltwater acute values for cadmium and five species of fishes ranged from 577 ug/l for larval Atlantic silversides to 114,000 ug/l for juvenile mummichog. Acute values for twenty-six species of invertebrates ranged from 15.5 ug/l for a mysid to 46,600 ug/l for the fiddler crab. The acute toxicity of cadmium seems to increase as salinity decreases and as temperature inceases, although the magnitudes of the effects seem to be species specific. Two life-cycle tests on Mysidopsis bahia under different test conditions resulted in similar chronic values of 5.5 and 8.0 ug/l, but the acute-chronic ratios were 2.8 and 14, respectively. The acute values appear to reflect the effects of salinity and temperature, whereas the chronic values apparently do not. Plant studies with microalgae found growth inhibition at 160 ug/l.

Tissue residues were reported for one species of algae, ten species of invertebrates and one species of fish. Bioconcentration factors for fish and crustaceans were generally less than 400 whereas those for bivalve molluscs were above 1,000 in long exposures, with no indication that steady-state was reached. Cadmium mortality is cumulative for exposure periods beyond four days. Chronic cadmium exposure resulted in significant effects on the growth of bay scallops at 78 ug/l and on reproduction of a copepod at 44 ug/l.

National Criteria

Because the acute and chronic toxicities of cadmium to sensitive important freshwater species are about the same, to protect freshwater aquatic life and its uses, the concentration (in $\mu g/l$) of active cadmium (operationally defined as the cadmium that passes through a 0.45 $\mu m$ membrane filter after the sample is acidified to pH = 4 with nitric acid) should not exceed the numerical value given by $e^{(1.16[\ln(\text{hardness})]-3.841)}$. For example, at hardnesses of 50, 100, and 200 mg/l as $CaCO_3$ the maximum concentrations of active cadmium are 2.0, 4.5, and 10 $\mu g/l$. Data on the acute toxicity of cadmium to brook trout and striped bass cover a wide range, but if these species are as sensitive as some of the values indicate they might be, they will not be protected by this criterion.

To protect saltwater aquatic life and its uses, in each 30 consecutive days: (a) the average concentration of active cadmium should not exceed 12 $\mu g/l$; (b) the maximum concentration should not exceed 38 $\mu g/l$; and (c) the concentration may be between 12 and 38 $\mu g/l$ for up to 96 hours.

Table 1. Acute toxicity of cadmium to aquatic animals

| Species | Method* | Chemical | Hardness (mg/l as $CaCO_3$) | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|---|
| | | | FRESHWATER SPECIES | | | |
| Rotifer, *Philodina acuticornis* | R, U | Cadmium chloride | 25 | 500 | - | Buikema, et al. 1974 |
| Rotifer, *Philodina acuticornis* | R, U | Cadmium sulfate | 25 | 200 | - | Buikema, et al. 1974 |
| Rotifer, *Philodina acuticornis* | R, U | Cadmium sulfate | 81 | 300 | 440.7 | Buikema, et al. 1974 |
| Worm, *Nais* sp. | S, U | - | 50 | 1,700 | 1,700 | Rehwoldt, et al. 197[illegible] |
| Snail (adult), *Amnicola* sp. | S, U | - | 50 | 8,400 | 8,400 | Rehwoldt, et al. 197[illegible] |
| Snail (adult), *Physa gyrina* | S, M | - | 200 | 1,370 | - | Wier & Walter, 1976 |
| Snail (immature), *Physa gyrina* | S, M | - | 200 | 410 | 150.1 | Wier & Walter, 1976 |
| Cladoceran, *Ceriodaphnia reticulata* | S, U | - | 45 | 24**** | - | Mount & Norberg, Manuscript |
| Cladoceran, *Daphnia magna* | S, U | Cadmium chloride | 45 | 65***** | - | Biesinger & Christensen, 1972 |
| Cladoceran, *Daphnia magna* | FT, M | Cadmium chloride | 130 | 5.00 | - | Attar & Maly, 1982 |
| Cladoceran, *Daphnia magna* | S, M | Cadmium chloride | 51 | 9.9 | - | Chapman, Manuscript |
| Cladoceran, *Daphnia magna* | S, M | Cadmium chloride | 104 | 33 | - | Chapman, Manuscript |
| Cladoceran, *Daphnia magna* | S, M | Cadmium chloride | 105 | 34 | - | Chapman, Manuscript |
| Cladoceran, *Daphnia magna* | S, M | Cadmium chloride | 197 | 63 | - | Chapman, Manuscript |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/l as $CaCO_3$) | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|---|
| Cladoceran, *Daphnia magna* | S, M | Cadmium chloride | 209 | 49 | - | Chapman, Manuscript |
| Cladoceran, *Daphnia magna* | S, U | Cadmium nitrate | - | 30.18 (6) | - | Canton & Adema, 1978 |
| Cladoceran, *Daphnia magna* | S, U | - | 45 | 120**** | 8.540 | Mount & Norberg, Manuscript |
| Cladoceran, *Daphnia pulex* | S, U | Cadmium nitrate | - | 93.45 (2) | - | Canton & Adema, 1978 |
| Cladoceran, *Daphnia pulex* | S, U | - | 45 | 71**** | - | Mount & Norberg, Manuscript |
| Cladoceran, *Daphnia pulex* | S, U | Cadmium chloride | 57 | 47 | 40.37 | Bertram & Hart, 1979 |
| Cladoceran, *Simocephalus serrulatus* | S, M | Cadmium chloride | 10.0 | 35.0 | - | Giesy, et al. 1977 |
| Cladoceran, *Simocephalus serrulatus* | S, M | Cadmium chloride | 11.1 | 7.0 | - | Giesy, et al. 1977 |
| Cladoceran, *Simocephalus serrulatus* | S, M | Cadmium chloride | 11.1 | 3.5 | - | Giesy, et al. 1977 |
| Cladoceran, *Simocephalus serrulatus* | S, M | Cadmium chloride | 11.1 | 12.0 | - | Giesy, et al. 1977 |
| Cladoceran, *Simocephalus serrulatus* | S, M | Cadmium chloride | 11.1 | 16.5 | - | Giesy, et al. 1977 |
| Cladoceran, *Simocephalus serrulatus* | S, M | Cadmium chloride | 11.1 | 8.6 | 62.29 | Giesy, et al. 1977 |
| Cladoceran, *Simocephalus vetulus* | S, U | - | 45 | 24**** | - | Mount & Norberg, Manuscript |
| Scud, *Gammarus* sp. | S, U | - | 50 | 70 | 70.00 | Rehwoldt, et al. 1973 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/l as $CaCO_3$) | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|---|
| Mayfly, *Ephemerella grandis grandis* | FT, M | Cadmium chloride | - | 28,000 | - | Clubb, et al. 1975 |
| Mayfly, *Ephemerella grandis grandis* | S, U | Cadmium sulfate | 44 | 2,000 | 2,319 | Warnick & Bell, 1969 |
| Damselfly, (Unidentified) | S, U | - | 50 | 8,100 | 8,100 | Rehwoldt, et al. 1973 |
| Stonefly, *Pteronarcella badia* | FT, M | Cadmium chloride | - | 18,000 | - | Clubb, et al. 1975 |
| Caddisfly, (Unidentified) | S, U | - | 50 | 3,400 | 3,400 | Rehwoldt, et al. 1973 |
| Midge, *Chironomus* sp. | S, U | - | 50 | 1,200 | 1,200 | Rehwoldt, et al. 1973 |
| Bryozoan, *Pectinatella magnifica* | S, U | - | 190-220 | 700 | 136.2 | Pardue & Wood, 1980 |
| Bryozoan, *Lophopodella carteri* | S, U | - | 190-220 | 150 | 29.19 | Pardue & Wood, 1980 |
| Bryozoan, *Plumatella emarginata* | S, U | - | 190-220 | 1,090 | 212.1 | Pardue & Wood, 1980 |
| American eel, *Anguilla rostrata* | S, M | - | 55 | 820 | 734.2 | Rehwoldt, et al. 1972 |
| Coho salmon (parr), *Oncorhynchus kisutch* | FT, M | Cadmium chloride | 23 | 2.7 | - | Chapman, 1975 |
| Coho salmon (adult), *Oncorhynchus kisutch* | FT, M | Cadmium chloride | 23 | 17.5***** | 6.646 | Chapman, 1975 |
| Chinook salmon (alevin), *Oncorhynchus tshawytscha* | FT, M | Cadmium chloride | 23 | >26***** | - | Chapman, 1975, 1978 |
| Chinook salmon (swim-up), *Oncorhynchus tshawytscha* | FT, M | Cadmium chloride | 23 | 1.8 | - | Chapman, 1975, 1978 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/l as $CaCO_3$) | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|---|
| Chinook salmon (parr), *Oncorhynchus tshawytscha* | FT, M | Cadmium chloride | 23 | 3.5 | - | Chapman, 1975, 1978 |
| Chinook salmon (smolt), *Oncorhynchus tshawytscha* | FT, M | Cadmium chloride | 23 | >2.9***** | - | Chapman, 1975, 1978 |
| Chinook salmon (juvenile), *Oncorhynchus tshawytscha* | FT, M | Cadmium chloride | 25 | 1.41 | 4.936 | Chapman, 1982 |
| Rainbow trout (alevin), *Salmo gairdneri* | FT, M | Cadmium chloride | 23 | >27***** | - | Chapman, 1975, 1978 |
| Rainbow trout (swim-up), *Salmo gairdneri* | FT, M | Cadmium chloride | 23 | 1.3 | - | Chapman, 1975, 1978 |
| Rainbow trout (parr), *Salmo gairdneri* | FT, M | Cadmium chloride | 23 | 1.0 | - | Chapman, 1978 |
| Rainbow trout (smolt), *Salmo gairdneri* | FT, M | Cadmium chloride | 23 | 4.1<br>>2.9***** | | Chapman, 1975<br>Chapman, 1978 |
| Rainbow trout (2-mos), *Salmo gairdneri* | FT, M | Cadmium nitrate | -- | 6.6 | - | Hale, 1977 |
| Rainbow trout, *Salmo gairdneri* | FT, M | Cadmium sulfate | 31 | 1.75 | - | Davies, 1976 |
| Rainbow trout, *Salmo gairdneri* | S, U | - | - | 6 | - | Kumada, et al. 1973 |
| Rainbow trout, *Salmo gairdneri* | S, U | - | - | 7 | - | Kumada, et al. 1973 |
| Rainbow trout, *Salmo gairdneri* | S, U | Cadmium chloride | - | 6.0 | 3.945 | Kumada, et al. 1980 |
| Brook trout, *Salvelinus fontinalis* | FT, M | Cadmium chloride | 47.4 | 5,080 | - | Holcombe & Phipps, Manuscript |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/l as $CaCO_3$) | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|---|
| Brook trout, *Salvelinus fontinalis* | S, M | Cadmium sulfate | 42 | <1.5 | ****** | Carroll, et al. 1979 |
| Goldfish, *Carassius auratus* | S, U | Cadmium chloride | 20 | 2,340 | - | Pickering & Henderson, 1966 |
| Goldfish, *Carassius auratus* | S, M | Cadmium chloride | 20 | 2,130 | - | McCarty, et al. 1978 |
| Goldfish, *Carassius auratus* | S, M | Cadmium chloride | 140 | 46,800 | 8,397 | McCarty, et al. 1978 |
| Common carp, *Cyprinus carpio* | S, M | - | 55 | 240 | 214.9 | Rehwoldt, et al. 1972 |
| Fathead minnow, *Pimephales promelas* | S, U | Cadmium chloride | 20 | 1,050 | - | Pickering & Henderson, 1966 |
| Fathead minnow, *Pimephales promelas* | S, U | Cadmium chloride | 20 | 630 | - | Pickering & Henderson, 1966 |
| Fathead minnow, *Pimephales promelas* | S, U | Cadmium chloride | 360 | 72,600 | - | Pickering & Henderson, 1966 |
| Fathead minnow, *Pimephales promelas* | S, U | Cadmium chloride | 360 | 73,500 | - | Pickering & Henderson, 1966 |
| Fathead minnow, *Pimephales promelas* | FT, M | Cadmium sulfate | 201 | 11,200 | - | Pickering & Gast, 1972 |
| Fathead minnow, *Pimephales promelas* | FT, M | Cadmium sulfate | 201 | 12,000 | - | Pickering & Gast, 1972 |
| Fathead minnow, *Pimephales promelas* | FT, M | Cadmium sulfate | 201 | 6,400 | - | Pickering & Gast, 1972 |
| Fathead minnow, *Pimephales promelas* | FT, M | Cadmium sulfate | 201 | 2,000 | - | Pickering & Gast, 1972 |
| Fathead minnow, *Pimephales promelas* | FT, M | Cadmium sulfate | 201 | 4,500 | 2,082 | Pickering & Gast, 1972 |

2, 3

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/l as $CaCO_3$) | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|---|
| Fathead minnow (fry), *Pimephales promelas* | S, M | Cadmium chloride | 40 | 21.5******* | - | Spehar, 1982 |
| Fathead minnow (fry), *Pimephales promelas* | S, M | Cadmium chloride | 48 | 11.7******* | - | Spehar, 1982 |
| Fathead minnow (fry), *Pimephales promelas* | S, M | Cadmium chloride | 39 | 19.3******* | - | Spehar, 1982 |
| Fathead minnow (fry), *Pimephales promelas* | S, M | Cadmium chloride | 45 | 42.4******* | - | Spehar, 1982 |
| Fathead minnow (fry), *Pimephales promelas* | S, M | Cadmium chloride | 47 | 54.2******* | - | Spehar, 1982 |
| Fathead minnow (fry), *Pimephales promelas* | S, M | Cadmium chloride | 44 | 29.0******* | - | Spehar, 1982 |
| Northern squawfish, *Ptychocheilus oregonensis* | F, M | Cadmium chloride | 20-30 | 1,092 | - | Andros & Garton, 1980 |
| Northern squawfish, *Ptychocheilus oregonensis* | F, M | Cadmium chloride | 20-30 | 1,104 | 2,454 | Andros & Garton, 1980 |
| Banded killifish, *Fundulus diaphanus* | S, M | - | 55 | 110 | 98.49 | Rehwoldt, et al, 1972 |
| Flagfish, *Jordanella floridae* | FT, M | Cadmium chloride | 44 | 2,500 | 2,900 | Spehar, 1976a |
| Mosquitofish, *Gambusia affinis* | FT, M | Cadmium chloride | 10.0 | 1,300 | - | Giesy, et al. 1977 |
| Mosquitofish, *Gambusia affinis* | FT, M | Cadmium chloride | 10.0 | 1,500 | - | Giesy, et al. 1977 |
| Mosquitofish, *Gambusia affinis* | FT, M | Cadmium chloride | 10.0 | 2,600 | - | Giesy, et al. 1977 |
| Mosquitofish, *Gambusia affinis* | FT, M | Cadmium chloride | 11.1 | 900 | - | Giesy, et al. 1977 |

Table 1. (Continued)

| Species | Method* | Chemical | Hardness (mg/l as $CaCO_3$) | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|---|
| Mosquitofish, *Gambusia affinis* | FT, M | Cadmium chloride | 11.1 | 2,200 | 9,775 | Giesy, et al. 1977 |
| Guppy, *Poecilia reticulata* | S, U | Cadmium chloride | 20 | 1,270 | 3,676 | Pickering & Henderson, 1966 |
| Threespine stickleback, *Gasterosteus aculeatus* | S, U | Cadmium chloride | 115 | 6,500 | - | Pascoe & Cram, 1977 |
| Threespine stickleback, *Gasterosteus aculeatus* | R, M | Cadmium chloride | 103-111 | 23,000 | 4,852 | Pascoe & Mattey, 1977 |
| White perch, *Morone americana* | S, M | - | 55 | 8,400 | 7,521 | Rehwoldt, et al. 1972 |
| Striped bass, *Morone saxatilis* | S, M | - | 55 | 1,100 | - | Rehwoldt, et al. 1972 |
| Striped bass (larvae), *Morone saxatilis* | S, U | Cadmium chloride | 34.5 | 1 | - | Hughes, 1973 |
| Striped bass (fingerling), *Morone saxatilis* | S, U | Cadmium chloride | 34.5 | 2 | ****** | Hughes, 1973 |
| Green sunfish, *Lepomis cyanellus* | S, U | Cadmium chloride | 20 | 2,840 | - | Pickering & Henderson, 1966 |
| Green sunfish, *Lepomis cyanellus* | S, U | Cadmium chloride | 360 | 66,000 | - | Pickering & Henderson, 1966 |
| Green sunfish, *Lepomis cyanellus* | FT, M | Cadmium chloride | 335 | 20,500 | 4,987 | Jude, 1973 |
| Pumpkinseed, *Lepomis gibbosus* | S, M | - | 55 | 1,500 | 1,343 | Rehwoldt, et al. 1972 |
| Bluegill, *Lepomis macrochirus* | S, U | Cadmium chloride | 20 | 1,940 | - | Pickering & Henderson, 1966 |
| Bluegill, *Lepomis macrochirus* | FT, M | Cadmium chloride | 207 | 21,100 | 4,775 | Eaton, 1980 |

Table I. (Continued)

| Species | Method* | Chemical | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|
| | | SALTWATER SPECIES | | | |
| Polychaete worm (adult), *Neanthes arenaceodentata* | S, U | Cadmium chloride | 12,000 | - | Reish, et al. 1976 |
| Polychaete worm (juvenile), *Neanthes arenaceodentata* | S, U | Cadmium chloride | 12,500 | 12,200 | Reish, et al. 1976 |
| Polychaete worm, *Nereis virens* | S, U | Cadmium chloride | 9,300 | - | Eisler & Hennekey, 1977 |
| Polychaete worm, *Nereis virens* | S, U | Cadmium chloride | 11,000 | 10,100 | Eisler, 1971 |
| Polychaete worm (adult), *Capitella capitata* | S, U | Cadmium chloride | 7,500***** | - | Reish, et al. 1976 |
| Polychaete worm (larva), *Capitella capitata* | S, U | Cadmium chloride | 200 | 200 | Reish, et al. 1976 |
| Oyster drill, *Urosalpinx cinerea* | S, U | Cadmium chloride | 6,600 | 6,600 | Eisler, 1971 |
| Mud snail, *Nassarius obsoletus* | S, U | Cadmium chloride | 35,000 | - | Eisler & Hennekey, 1977 |
| Mud snail, *Nassarius obsoletus* | S, U | Cadmium chloride | 10,500 | 19,170 | Eisler, 1971 |
| Blue mussel, *Mytilus edulis* | S, U | Cadmium chloride | 25,000 | - | Eisler, 1971 |
| Blue mussel, *Mytilus edulis* | S, M | Cadmium chloride | 1,620 | - | Ahsanullah, 1976 |
| Blue mussel, *Mytilus edulis* | FT, M | Cadmium chloride | 3,600 | - | Ahsanullah, 1976 |
| Blue mussel, *Mytilus edulis* | FT, M | Cadmium chloride | 4,300 | 3,934 | Ahsanullah, 1976 |
| Bay scallop (juvenile), *Argopecten irradians* | S, U | Cadmium chloride | 1,480 | 1,480 | Nelson, et al. 1976 |

Table 1. (Continued)

| Species | Method* | Chemical | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|
| Eastern oyster (larva), *Crassostrea virginica* | S, U | Cadmium chloride | 3,800 | 3,800 | Calabrese, et al. 1973 |
| Soft-shell clam, *Mya arenaria* | S, U | Cadmium chloride | 2,500 | - | Eisler & Hennekey, 1977 |
| Soft-shell clam, *Mya arenaria* | S, U | Cadmium chloride | 2,200 | - | Eisler, 1971 |
| Soft-shell clam, *Mya arenaria* | S, U | Cadmium chloride | 850 | 1,672 | Eisler, 1977 |
| Copepod, *Pseudodiaptomus coronatus* | S, U | Cadmium chloride | 1,708 | 1,708 | Gentile, 1982 |
| Copepod, *Eurytemora affinis* | S, U | Cadmium chloride | 1,080 | 1,080 | Gentile, 1982 |
| Copepod, *Acartia clausi* | S, U | Cadmium chloride | 144 | 144 | Gentile, 1982 |
| Copepod, *Acartia tonsa* | S, U | Cadmium chloride | 90 | - | Sosnowski & Gentile, 1978 |
| Copepod, *Acartia tonsa* | S, U | Cadmium chloride | 122 | - | Sosnowski & Gentile, 1978 |
| Copepod, *Acartia tonsa* | S, U | Cadmium chloride | 220 | - | Sosnowski & Gentile, 1978 |
| Copepod, *Acartia tonsa* | S, U | Cadmium chloride | 337 | 168.9 | Sosnowski & Gentile, 1978 |
| Copepod, *Nitocra spinipes* | S, U | Cadmium chloride | 1,800 | 1,800 | Bengtsson, 1978 |

Table 1. (Continued)

| Species | Method* | Chemical | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|
| Mysid, *Mysidopsis bahia* | FT, M | Cadmium chloride | 15.5 | - | Nimmo, et al. 1977a |
| Mysid, *Mysidopsis bahia* | FT, M | Cadmium chloride | 110 | 41.29 | Gentile, et al. 1982 |
| Mysid, *Mysidopsis bigelowi* | FT, M | Cadmium chloride | 135 | 135 | Gentile, et al. 1982 |
| Amphipod (young), *Marinogammarus obtusatus* | S, M | Cadmium chloride | 3,500 | - | Wright & Frien, 1981 |
| Amphipod (adult), *Marinogammarus obtusatus* | S, M | Cadmium chloride | 13,000**** | 3,500 | Wright and Frien, 1981 |
| Amphipod (adult), *Ampelisca abdita* | FT, M | Cadmium chloride | 2,890 | 2,890 | Scott, 1982 |
| Pink shrimp, *Penaeus duorarum* | FT, M | Cadmium chloride | 3,500 | 3,500 | Nimmo, et al. 1977b |
| Grass shrimp, *Palaemonetes vulgaris* | S, U | Cadmium chloride | 420 | - | Eisler, 1971 |
| Grass shrimp, *Palaemonetes vulgaris* | FT, M | Cadmium chloride | 760 | 760 | Nimmo, et al. 1977b |
| Sand shrimp, *Crangon septemspinosa* | S, U | Cadmium chloride | 320 | 320 | Eisler, 1971 |
| American lobster (larva), *Homarus americanus* | S, U | Cadmium chloride | 78 | 78 | Johnson & Gentile, 1979 |
| Hermit crab, *Pagurus longicarpus* | S, U | Cadmium chloride | 320 | - | Eisler, 1971 |
| Hermit crab, *Pagurus longicarpus* | S, U | Cadmium chloride | 1,300 | 645 | Eisler & Hennekey, 1977 |
| Blue crab (juveniles), *Callinectes sapidus* | S, U | Cadmium chloride | 11,600 | - | Frank & Robertson, 1979 |

Table 1. (Continued)

| Species | Method* | Chemical | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|
| Blue crab (juveniles), Callinectes sapidus | S, U | Cadmium chloride | 4,700 | - | Frank & Robertson, 1979 |
| Blue crab (juveniles), Callinectes sapidus | S, U | Cadmium chloride | 320 | 2,594 | Frank & Robertson, 1979 |
| Green crab, Carcinus maenas | S, U | Cadmium chloride | 4,100 | 4,100 | Eisler, 1971 |
| Fiddler crab, Uca pugilator | S, U | Cadmium chloride | 46,600 | - | O'Hara, 1973 |
| Fiddler crab, Uca pugilator | S, U | Cadmium chloride | 37,000 | - | O'Hara, 1973 |
| Fiddler crab, Uca pugilator | S, U | Cadmium chloride | 32,300 | - | O'Hara, 1973 |
| Fiddler crab, Uca pugilator | S, U | Cadmium chloride | 23,300 | - | O'Hara, 1973 |
| Fiddler crab, Uca pugilator | S, U | Cadmium chloride | 10,400 | - | O'Hara, 1973 |
| Fiddler crab, Uca pugilator | S, U | Cadmium chloride | 6,800 | 21,190 | O'Hara, 1973 |
| Starfish, Asterias forbesii | S, U | Cadmium chloride | 7,100 | - | Eisler & Hennekey, 1977 |
| Starfish, Asterias forbesii | S, U | Cadmium chloride | 820 | 2,413 | Eisler, 1971 |
| Sheepshead minnow, Cyprinodon variegatus | S, U | Cadmium chloride | 50,000 | 50,000 | Eisler, 1971 |
| Mummichog (adult), Fundulus heteroclitus | S, U | Cadmium chloride | 49,000 | - | Eisler, 1971 |
| Mummichog (adult), Fundulus heteroclitus | S, U | Cadmium chloride | 22,000 | - | Eisler & Hennekey, 1977 |

Table 1. (Continued)

| Species | Method* | Chemical | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|
| Mummichog (juvenile), Fundulus heteroclitus | S, U | Cadmium chloride | 114,000 | - | Voyer, 1975 |
| Mummichog (juvenile), Fundulus heteroclitus | S, U | Cadmium chloride | 92,000 | - | Voyer, 1975 |
| Mummichog (juvenile), Fundulus heteroclitus | S, U | Cadmium chloride | 78,000 | - | Voyer, 1975 |
| Mummichog (juvenile), Fundulus heteroclitus | S, U | Cadmium chloride | 73,000 | - | Voyer, 1975 |
| Mummichog (juvenile), Fundulus heteroclitus | S, U | Cadmium chloride | 63,000 | - | Voyer, 1975 |
| Mummichog (juvenile), Fundulus heteroclitus | S, U | Cadmium chloride | 31,000 | - | Voyer, 1975 |
| Mummichog (juvenile), Fundulus heteroclitus | S, U | Cadmium chloride | 30,000 | - | Voyer, 1975 |
| Mummichog (juvenile), Fundulus heteroclitus | S, U | Cadmium chloride | 29,000 | 50,600 | Voyer, 1975 |
| Striped killifish (adult), Fundulus majalis | S, U | Cadmium chloride | 21,000 | 21,000 | Eisler, 1971 |
| Atlantic silverside (adult), Menidia menidia | S, U | Cadmium chloride | 2,032***** | - | Cardin, 1982 |
| Atlantic silverside (juvenile), Menidia menidia | S, U | Cadmium chloride | 28,532***** | - | Cardin, 1982 |
| Atlantic silverside (juvenile), Menidia menidia | S, U | Cadmium chloride | 13,652***** | - | Cardin, 1982 |
| Atlantic silverside (larva), Menidia menidia | S, U | Cadmium chloride | 1,054 | - | Cardin, 1982 |
| Atlantic silverside (larva), Menidia menidia | S, U | Cadmium chloride | 577 | 779.8 | Cardin, 1982 |

Table 1. (Continued)

| Species | Method* | Chemical | LC50 or EC50 (µg/l)** | Species Mean Acute Value (µg/l)*** | Reference |
|---|---|---|---|---|---|
| Winter flounder (larva), *Pseudopleuronectes americanus* | S, U | Cadmium chloride | 14,297 | - | Cardin, 1982 |
| Winter flounder (larva), *Pseudopleuronectes americanus* | S, U | Cadmium chloride | 602 | 2,934 | Cardin, 1982 |

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

** Results are expressed as cadmium, not as the chemical. Some values are averages from the number of tests in parentheses.

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

**** Not used in calculations because the food apparently reduced toxicity to *Daphnia magna* and probably also to the other species.

***** Not used in calculations.

****** No Species Mean Acute Value calculated for this species because of wide range of acute values.

******* Not used in calculations because for this species fry seem to be much more sensitive to cadmium than older fish.

Results of covariance analysis of freshwater acute toxicity vs. hardness:

(The data for rainbow trout were not included in the analysis because the range of hardness was too small.)

*Philodina acuticornis*: slope = -0.045, r = -0.07, n = 3

*Daphnia magna*: slope = 1.06, r = 0.55, n = 6

Goldfish: slope = 1.56, r = 1.00, n = 3

Fathead minnow: slope = 1.25, r = 0.83, n = 9

Green sunfish: slope = 0.90, r = 0.94, n = 3

Bluegill: slope = 1.02, r = 1.00, n = 2

Pooled slope = 1.16, P = <0.0001, degrees of freedom = 17

(Data for *Philodina acuticornis* not used in calculation of pooled slope; see text.)

## Table 2. Chronic toxicity of cadmium to aquatic animals

| Species | Test* | Chemical | Hardness (mg/l as $CaCO_3$) | Limits (µg/l)** | Chronic Value (µg/l/l)** | Reference |
|---|---|---|---|---|---|---|
| | | | FRESHWATER SPECIES | | | |
| Cladoceran, *Daphnia magna* | LC | Cadmium chloride | 45 | 0.17-0.7 | 0.3450 | Biesinger & Christensen, 1972 |
| Cladoceran, *Daphnia magna* | LC | Cadmium chloride | 53 | 0.08-0.29 | 0.1523 | Chapman, Manuscript |
| Cladoceran, *Daphnia magna* | LC | Cadmium chloride | 103 | 0.16-0.28 | 0.2117 | Chapman, Manuscript |
| Cladoceran, *Daphnia magna* | LC | Cadmium chloride | 209 | 0.21-0.91 | 0.4371 | Chapman, Manuscript |
| Coho salmon (Lake Superior), *Oncorhynchus kisutch* | ELS | Cadmium chloride | 44 | 1.3-3.4 | 2.102 | Eaton, et al. 1978 |
| Coho salmon (West Coast), *Oncorhynchus kisutch* | ELS | Cadmium chloride | 44 | 4.1-12.5 | 7.159 | Eaton, et al. 1978 |
| Chinook salmon, *Oncorhynchus tshawytscha* | ELS | Cadmium chloride | 25 | 1.3-1.88 | 1.563 | Chapman, 1975 |
| Brown trout, *Salmo trutta* | ELS | Cadmium chloride | 44 | 3.8-11.7 | 6.668 | Eaton, et al. 1978 |
| Brook trout, *Salvelinus fontinalis* | ELS | Cadmium chloride | 44 | 1.1-3.8 | 2.045 | Eaton, et al. 1978 |
| Brook trout, *Salvelinus fontinalis* | LC | Cadmium chloride | 44 | 1.7-3.4 | 2.404 | Benoit, et al. 1976 |
| Brook trout, *Salvelinus fontinalis* | ELS | Cadmium chloride | 37 | 1-3 | 1.732 | Sauter, et al. 1976 |
| Lake trout, *Salvelinus namaycush* | ELS | Cadmium chloride | 44 | 4.4-12.3 | 7.357 | Eaton, et al. 1978 |
| Northern pike, *Esox lucius* | ELS | Cadmium chloride | 44 | 4.2-12.9 | 7.361 | Eaton, et al. 1978 |

Table 2. (Continued)

| Species | Test* | Chemical | Hardness (mg/l as $CaCO_3$) | Limits (µg/l)** | Chronic Value (µg/l)** | Reference |
|---|---|---|---|---|---|---|
| Fathead minnow, *Pimephales promelas* | LC | Cadmium sulfate | 201 | 37-57 | 45.92 | Pickering & Gast, 1972 |
| White sucker, *Catostomus commersoni* | ELS | Cadmium chloride | 44 | 4.2-12.0 | 7.099 | Eaton, et al. 1978 |
| Flagfish, *Jordanella floridae* | LC | Cadmium chloride | 44 | 4.1-8.1 | 5.763 | Spehar, 1976a |
| Bluegill, *Lepomis macrochirus* | LC | Cadmium sulfate | 207 | 31-80 | 49.80 | Eaton, 1974 |
| Smallmouth bass, *Micropterus dolomieui* | ELS | Cadmium chloride | 44 | 4.3-12.7 | 7.390 | Eaton, et al. 1978 |
| | | SALTWATER SPECIES | | | | |
| Mysid, *Mysidopsis bahia* | LC | Cadmium chloride | - | 4.8-6.4 | 5.543 | Nimmo et al. 1977a |
| Mysid, *Mysidopsis bahia* | LC | Cadmium chloride | - | 5.5-11.5 | 7.953 | Gentile, et al. 1982 |

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

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

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* | 45 | 65 | 0.3450 | 191.3 |
| Cladoceran, *Daphnia magna* | 53 | 9.9 | 0.1523 | 65.00 |
| Cladoceran, *Daphnia magna* | 103 | 33 | 0.2117 | 155.9 |
| Cladoceran, *Daphnia magna* | 209 | 49 | 0.4371 | 112.1 |
| Chinook salmon, *Oncorhynchus tshawytscha* | 25 | 1.41 | 1.563 | 0.9021 |
| Fathead minnow, *Pimephales promelas* | 201 | 5, 970 | 45.92 | 130.0 |
| Flagfish, *Jordanella floridae* | 44 | 2,500 | 5.763 | 433.8 |
| Bluegill, *Lepomis macrochirus* | 207 | 21,100 | 49.80 | 423.7 |
| Mysid, *Mysidopsis bahia* | - | 15.5 | 5.543 | 2.796 |
| Mysid, *Mysidopsis bahia* | - | 110 | 7.943 | 13.83 |

Table 3. Summary of data in Tables 1 and 2 on acute and chronic toxicity of cadmium to aquatic animals

| Rank* | Family | Family Mean Acute Value (µg/l)** | Species | Species Mean Acute Value (µg/l)** | Species Mean Acute-Chronic Ratio |
|---|---|---|---|---|---|
| | | | FRESHWATER SPECIES | | |
| 21 | Bithyniidae | 8,400 | Snail, *Amnicola* sp. | 8,400 | - |
| 20 | - | 8,100 | Damselfly, (Unidentified) | 8,100 | - |
| 19 | Percichthyidae | 7,521 | White perch, *Morone americana* | 7,521 | - |
| 18 | Poeciliidae | 5,994 | Mosquitofish, *Gambusia affinis* | 9,775 | - |
| | | | Guppy, *Poecilia reticulata* | 3,676 | - |
| 17 | Gasterosteidae | 4,852 | Threespine stickleback, *Gasterosteus aculeatus* | 4,852 | - |
| 16 | - | 3,400 | Caddisfly, (Unidentified) | 3,400 | - |
| 15 | Centrarchidae | 3,174 | Green sunfish, *Lepomis cyanellus* | 4,987 | - |
| | | | Pumpkinseed, *Lepomis gibbosus* | 1,343 | - |
| | | | Bluegill, *Lepomis macrochirus* | 4,775 | 423.7 |
| 14 | Ephemerellidae | 2,319 | Mayfly, *Ephemerella grandis* | 2,319 | - |
| 13 | Cyprinidae | 1,743 | Goldfish, *Carassius auratus* | 8,397 | - |
| | | | Common carp, *Cyprinus carpio* | 214.9 | - |

Table 3. (Continued)

| Rank* | Family | Family Mean Acute Value (µg/l)** | Species | Species Mean Acute Value (µg/l)** | Species Mean Acute-Chronic Ratio |
|---|---|---|---|---|---|
| | | | Fathead minnow, *Pimephales promelas* | 2,082 | 130.0 |
| | | | Northern squawfish, *Ptychocheilus oregonensis* | 2,454 | - |
| 12 | Naididae | 1,700 | Worm, *Nais* sp. | 1,700 | - |
| 11 | Chironomidae | 1,200 | Midge, *Chironomus* sp. | 1,200 | - |
| 10 | Anguillidae | 734.2 | American eel, *Anguilla rostrata* | 734.2 | - |
| 9 | Cyprinodontidae | 534.4 | Banded killifish, *Fundulus diaphanus* | 98.49 | - |
| | | | Flagfish, *Jordanella floridae* | 2,900 | 433.8 |
| 8 | Philodinidae | 440.7 | Rotifer, *Philodina acuticornis* | 440.7 | - |
| 7 | Plumatellidae | 212.1 | Bryozoan, *Plumatella emarginata* | 212.1 | - |
| 6 | Physidae | 150.1 | Snail, *Physa gyrina* | 150.1 | - |
| 5 | Lophopodidae | 136.2 | Bryozoan, *Pectinatella magnifica* | 136.2 | - |
| 4 | Gammaridae | 70.00 | Scud, *Gammarus* sp. | 70.00 | - |
| 3 | Pectinalelcidae | 29.19 | Bryozoan, *Lophopodella carteri* | 29.19 | - |
| 2 | Daphnidae | 27.80 | Cladoceran, *Daphnia magna* | 8.540 | 121.4 |
| | | | Cladoceran, *Daphnia pulex* | 40.37 | - |

Table 3. (Continued)

| Rank* | Family | Family Mean Acute Value (µg/l)** | Species | Species Mean Acute Value (µg/l)** | Species Mean Acute-Chronic Ratio |
|---|---|---|---|---|---|
| | | | Cladoceran, *Simocephalus serrulatus* | 62.29 | - |
| 1 | Salmonidae | 5.058 | Coho salmon, *Oncorhynchus kisutch* | 6.646 | - |
| | | | Chinook salmon, *Oncorhynchus tshawytscha* | 4.936 | 0.7787 |
| | | | Rainbow trout, *Salmo gairdneri* | 3.945 | - |
| | | | SALTWATER SPECIES | | |
| 26 | Cyprinodontidae | 37,590 | Sheepshead minnow, *Cyprinodon variegatus* | 50,000 | - |
| | | | Mummichog, *Fundulus heteroclitus* | 50,600 | - |
| | | | Striped killifish, *Fundulus majalis* | 21,000 | - |
| 25 | Ocypodidae | 21,190 | Fiddler crab, *Uca pugilator* | 21,190 | - |
| 24 | Nassariidae | 19,170 | Mud snail, *Nassarius obsoletus* | 19,170 | - |
| 23 | Nereidae | 11,100 | Polychaete worm, *Neanthes arenaceodentata* | 12,200 | - |
| | | | Sand worm, *Nereis virens* | 10,100 | - |
| 22 | Muricidae | 6,600 | Oyster drill, *Urosalpinx cinerea* | 6,600 | - |
| 21 | Mytilidae | 3,934 | Blue mussel, *Mytilus edulis* | 3,934 | - |

Table 3. (Continued)

| Rank* | Family | Family Mean Acute Value (µg/l)** | Species | Species Mean Acute Value (µg/l)** | Species Mean Acute-Chronic Ratio |
|---|---|---|---|---|---|
| 20 | Ostreidae | 3,800 | Eastern oyster, *Crassostrea virginica* | 3,800 | - |
| 19 | Gammaridae | 3,500 | Amphipod, *Marinogammarus obtusatus* | 3,500 | - |
| 18 | Penaeidae | 3,500 | Pink shrimp, *Penaeus duorarum* | 3,500 | - |
| 17 | Portunidae | 3,261 | Blue crab, *Callinectes sapidus* | 2,594 | - |
| | | | Green crab, *Carcinus maenus* | 4,100 | - |
| 16 | Pleuronectidae | 2,934 | Winter flounder, *Pseudopleuronectes americanus* | 2,934 | - |
| 15 | Ampeliscidae | 2,890 | Amphipod, *Ampelisca abdita* | 2,890 | - |
| 14 | Asteriidae | 2,413 | Starfish, *Asterias forbesi* | 2,413 | - |
| 13 | Canthocamptidae | 1,800 | Copepod, *Nitocra spinipes* | 1,800 | - |
| 12 | Pseudodiaptomidae | 1,708 | Copepod, *Pseudodiaptomus cornatus* | 1,708 | - |
| 11 | Myidae | 1,672 | Soft-shell clam, *Mya arenaria* | 1,672 | - |
| 10 | Pectinidae | 1,480 | Bay scallop, *Argopecten irradians* | 1,480 | - |
| 9 | Temoridae | 1,080 | Copepod, *Eurytemora affinis* | 1,080 | - |
| 8 | Atherinidae | 779.8 | Atlantic silverside *Menidia menidia* | 779.8 | - |

Table 3. (Continued)

| Rank* | Family | Family Mean Acute Value (µg/l)** | Species | Species Mean Acute Value (µg/l)** | Species Mean Acute-Chronic Ratio |
|---|---|---|---|---|---|
| 7 | Palaemonidae | 760 | Grass shrimp, *Palaemonetes vulgaris* | 760 | - |
| 6 | Paguridae | 645 | Hermit crab *Pagurus longicarpus* | 645 | - |
| 5 | Crangonidae | 320 | Sand shrimp, *Crangon septemspinosa* | 320 | - |
| 4 | Capitellidae | 200 | Polychaete worm, *Capitella capitata* | 200 | - |
| 3 | Acartiidae | 156 | Copepod, *Acartia clausi* | 144 | - |
| | | | Copepod, *Acartia tonsa* | 168.9 | - |
| 2 | Homaridae | 78 | American lobster, *Homarus americanus* | 78 | - |
| 1 | Mysidae | 74.66 | Mysid, *Mysidopsis bahia* | 41.29 | 6.218 |
| | | | Mysid, *Mysidopsis bigelowi* | 135 | - |

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

**Freshwater Family Mean Acute Values and Species Mean Acute Values are for a hardness of 50 mg/l.

Fresh water

Final Acute Value = 6.662 µg/l (calculated for a hardness of 50 mg/l from Family Mean Acute Values)

Final Acute Value = 3.945 µg/l (to protect rainbow trout at a hardness of 50 mg/l)

Criterion Maximum Concentration = (3.945 µg/l) / 2 = 1.972 µg/l (for a hardness of 50 µg/l)

Table 3. (Continued)

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Final Chronic Value = 1.972 µg/l (for a hardness of 50 µg/l) (see text)

Pooled Slope = 1.16 (see Table 1)

ln (Criterion Maximum Intercept) = ln(1.972) - [slope x ln(50)]

= 0.697 - (1.16 x 3.912) = -3.841)

Criterion Maximum Concentration = $e^{(1.16\ [\ln(\text{hardness})]\ -3.841)}$

Final Chronic Value = $e^{(1.16\ [\ln(\text{hardness})]\ -3.841)}$ (see text)

<u>Salt</u> <u>water</u>

Final Acute Value = 75.44 µg/l

Criterion Maximum Concentration = (75.44 µg/l) / 2 = 37.72 µg/l

Final Acute-Chronic Ratio = 6.218 (see text)

Final Chronic Value = (75.44 µg/l) / 6.218 = 12.13

Table 4. Toxicity of cadmium to aquatic plants

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Effect | Result (µg/l)* | Reference |
|---|---|---|---|---|---|
| | | FRESHWATER SPECIES | | | |
| Diatom, *Asterionella formosa* | - | - | Factor of 10 growth rate decrease | 2 | Conway, 1978 |
| Diatom, *Scenedesmus quadracauda* | Cadmium chloride | - | Reduction in cell count | 6.1 | Klass, et al. 1974 |
| Alga, *Euglena gracilis* | Cadmium chloride | - | Morphological abnormalities | 5,000 | Nakano, et al. 1980 |
| Alga, *Euglena gracilis anabaena* | Cadmium nitrate | - | Cell division inhibition | 20,000 | Nakano, 1980 |
| Alga, *Ankistrodesmus braunii* | Cadmium nitrate | - | Growth inhibition | 112.4 | Laube, et al. 1980 |
| Blue alga, *Microcystis aeruginosa* | Cadmium nitrate | - | Incipient inhibition | 70 | Bringmann, 1975; Bringmann & Kuhn, 1976, 1978a,b |
| Green alga, *Scenedesmus quadricauda* | Cadmium nitrate | - | Incipient inhibition | 310 | Bringmann & Kuhn, 1977a, 1978a,b, 1979, 1980b |
| Green alga, *Chlorella pyrenoidosa* | - | - | Reduction in growth | 250 | Hart & Scaife, 1977 |
| Green alga, *Chlorella vulgaris* | - | - | Reduction in growth | 50 | Hutchinson & Stokes, 1975 |
| Green alga, *Chlorella vulgaris* | Cadmium chloride | - | 50% reduction in growth | 60 | Rosko & Rachlin, 1977 |
| Green alga, *Selenastrum capricornutum* | Cadmium chloride | - | Reduction in growth | 50 | Bartlett, et al. 1974 |
| Algae (mixed spp.) | Cadmium chloride | 11.1 | Significant reduction in population | 5 | Giesy, et al. 1979 |

Table 4. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Effect | Result (µg/l)* | Reference |
|---|---|---|---|---|---|
| Fern, *Salvina natans* | Cadmium nitrate | - | Reduction in number of fronds | 10 | Hutchinson & Czyrska, 1972 |
| Eurasian watermilfoil, *Myriophyllum spicatum* | - | - | 50% root weight inhibition | 7,400 | Stanley, 1974 |
| Duckweed, *Lemna valdiviana* | Cadmium nitrate | - | Reduction in number of fronds | 10 | Hutchinson & Cyrska, 1972 |
| | | SALTWATER SPECIES | | | |
| Kelp, *Laminana saccharina* | Cadmium chloride | - | 8-day EC50 (growth rate) | 860 | Markham, et al. 1980 |
| Diatom, *Ditylum brightwellii* | Cadmium chloride | - | 5-day EC50 (growth) | 60 | Canterford & Canterford, 1980 |
| Diatom, *Thalassiosira pseudonana* | Cadmium chloride | - | 96-hr EC50 (growth rate) | 160 | Gentile & Johnson, 1982 |
| Diatom, *Skeletonema costatum* | Cadmium chloride | | 96-hr EC50 (growth rate) | 175 | Gentile & Johnson, 1982 |
| Red alga, *Champia parvula* | Cadmium chloride | - | Reduced tetrasporophyte growth | <24.9 | Steele & Thursby, 1983 |
| Red alga, *Champia parvula* | Cadmium chloride | - | Reduced tetrasporangia production | >189 | Steele & Thursby, 1983 |
| Red alga, *Champia parvula* | Cadmium chloride | - | Reduced female growth | <11.4 | Steele & Thursby, 1983 |
| Red alga, *Champia parvula* | Cadmium chloride | - | Stopped sexual reproduction | <11.4 | Steele & Thursby, 1983 |

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

Table 5. Bioaccumulation of cadmium by aquatic organisms

| Species | Tissue | Chemical | Duration (days) | Bioconcentration Factor* | Reference |
|---|---|---|---|---|---|
| | | FRESHWATER SPECIES | | | |
| Aufwuchs (attached microscopic plants and animals | - | Cadmium chloride | 365 | 720 | Giesy, et al. 1979 |
| Aufwuchs (attached microscopic plants and animals | - | Cadmium chloride | 365 | 580 | Giesy, et al. 1979 |
| Duckweed, *Lemna valdiviana* | Whole plant | Cadmium nitrate | 21 | 603 | Hutchinson & Czyrska, 1972 |
| Fern, *Salvinia natans* | Whole plant | Cadmium nitrate | 21 | 960 | Hutchinson & Czyrska, 1972 |
| Snail, *Physa integra* | Whole body | Cadmium chloride | 28 | 1,750 | Spehar, 1981 |
| Cladoceran, *Daphnia magna* | Whole body | Cadmium sulfate | 2-4 | 320 | Poldoski, 1979 |
| Crayfish, *Orconectes propinquus* | Whole body | - | 8 | 184 | Gillespie, et al. 1977 |
| Mayfly, Ephemeroptera sp. | Whole body | Cadmium chloride | 365 | 1,630 | Giesy, et al. 1979 |
| Mayfly, Ephemeroptera sp. | Whole body | Cadmium chloride | 365 | 3,520 | Giesy, et al. 1979 |
| Dragonfly, *Pantala hymenea* | Whole body | Cadmium chloride | 365 | 736 | Giesy, et al. 1979 |
| Dragonfly, *Pantala hymenea* | Whole body | Cadmium chloride | 365 | 680 | Giesy, et al. 1979 |
| Damselfly, *Ischnura* sp. | Whole body | Cadmium chloride | 365 | 1,300 | Giesy, et al. 1979 |
| Dragonfly, *Ischnura* sp. | Whole body | Cadmium chloride | 365 | 928 | Giesy, et al. 1979 |

Table 5. (Continued)

| Species | Tissue | Chemical | Duration (days) | Bioconcentration Factor* | Reference |
|---|---|---|---|---|---|
| Stonefly, *Pteronarcys dorsata* | Whole body | Cadmium chloride | 373 | 28 | Spehar, 1981 |
| Beetle, Dytiscidae | Whole body | Cadmium chloride | 365 | 164 | Giesy, et al. 1979 |
| Beetle, Dytiscidae | Whole body | Cadmium chloride | 365 | 260 | Giesy, et al. 1979 |
| Caddisfly, *Hydropsyche betteni* | Whole body | Cadmium chloride | 28 | 4,190 | Spehar, 1981 |
| Caddisfly, *Hydropsyche* sp. | Whole body | Cadmium chloride | 6,017 | 2 to 8 | Dressing, 1980 |
| Biting midge, Ceratopoganidae | Whole body | Cadmium chlorde | 365 | 936 | Giesy, et al. 1979 |
| Biting midge, Ceratopoganidae | Whole body | Cadmium chloride | 365 | 662 | Giesy, et al. 1979 |
| Midge, Chironomidae | Whole body | Cadmium chloride | 365 | 2,200 | Giesy, et al. 1979 |
| Midge, Chironomidae | Whole body | Cadmium chloride | 365 | 1,830 | Giesy, et al. 1979 |
| Rainbow trout, *Salmo gairdneri* | Whole body | - | 140 | 540 | Kumada, et al. 1973 |
| Rainbow trout, *Salmo gairdneri* | Whole body | Cadmium chloride | 70 | 33 | Kumada et al. 1980 |
| Brook trout, *Salvelinus fontinalis* | Muscle | Cadmium chloride | 490 | 3 | Benoit, et al. 1976 |
| Brook trout, *Salvelinus fontinalis* | Muscle | Cadmium chloride | 84 | 151 | Benoit, et al. 1976 |
| Brook trout, *Salvelinus fontinalis* | Muscle | Cadmium chloride | 93 | 10 | Sangalang & Freeman, 1979 |

Table 5. (Continued)

| Species | Tissue | Chemical | Duration (days) | Bioconcentration Factor[a] | Reference |
|---|---|---|---|---|---|
| Mosquitofish, *Gambusia affinis* | Whole body (estimated steady state) | Cadmium chloride | 180 | 2,213 | Giesy, et al. 1979 |
| Mosquitofish, *Gambusia affinis* | Whole body (estimated steady state) | Cadmium chloride | 180 | 1,891 | Giesy, et al. 1979 |
| | | SALTWATER SPECIES | | | |
| Alga, *Prasinocladus tricornutum* | - | Cadmium iodide | 5 | 670 | Kerfoot & Jacobs, 1976 |
| Hydroid polyp, *Laomedea loveni* | Whole organism | Cadmium chloride | 10 | 153 | Theede, et al. 1979 |
| Polychaete worm, *Ophryotrocha diadema* | Whole body | Cadmium chloride | 64 | 3,160 | Klockner, 1979 |
| Blue mussel, *Mytilus edulis* | Soft parts | Cadmium chloride | 28 | 113 | George & Coombs, 1977 |
| Blue mussel, *Mytilus edulis* | Soft parts | Cadmium chloride | 35 | 306 | Phillips, 1976 |
| Bay scallop, *Argopecten irradians* | Muscle | Cadmium chloride | 42 | 2,040 | Pesch & Stewart, 1980 |
| Eastern oyster, *Crassostrea virginica* | Soft parts | Cadmium chloride | 280 | 2,600 | Zaroogian & Cheer, 1976 |
| Eastern oyster, *Crassostrea virginica* | Soft parts | Cadmium chloride | 280 | 1,830 | Zaroogian, 1979 |
| Eastern oyster, *Crassostrea virginica* | Soft parts | Cadmium nitrate | 98 | 1,220 | Schuster & Pringle, 1969 |
| Quahog clam, *Mercenaria mercenaria* | Soft parts | Cadmium nitrate | 40 | 83 | Kerfoot & Jacobs, 1976 |
| Soft-shell clam, *Mya arenaria* | Soft parts | Cadmium nitrate | 70 | 160 | Pringle, et al. 1968 |

Table 5. (Continued)

| Species | Tissue | Chemical | Duration (days) | Bioconcentration Factor* | Reference |
|---|---|---|---|---|---|
| Pink shrimp, *Penaeus durorarm* | Whole body | Cadmium chloride | 30 | 57 | Nimmo, et al. 1977b |
| Grass shrimp, *Paleomonetes pugio* | Whole body | Cadmium chloride | 42 | 22 | Pesch & Stewart, 1980 |
| Grass shrimp, *Palaemonetes pugio* | Whole body | Cadmium chloride | 28 | 203 | Nimmo, et al. 1977b |
| Grass shrimp, *Palaemonetes vulgaris* | Whole body | Cadmium chloride | 28 | 307 | Nimmo, et al. 1977b |
| Green crab, *Carcinus maenas* | Muscle | Cadmium chloride | 68 | 5 | Wright, 1977 |
| Green crab, *Carcinus maenas* | Muscle | Cadmium chloride | 40 | 7 | Jennings & Rainbow, 1979a |

* Results are based on cadmium, not the chemical.

**Maximum Permissible Tissue Concentration**

| Species | Effect | Concentration | Reference |
|---|---|---|---|
| Mallard, *Anas platyrhynchus* | Kidney tubule degeneration; significant testis weight reduction; evidence of inhibited spermatozoa production | 200 mg/kg in food for 90 days | White & Finley, 1978a,b; White, et al. 1978 |
| Man | Emetic threshold | 13-15 mg/kg | Anon., 1950 |

Table 5. (Continued)

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<u>Fresh water</u>

Geometric mean of all whole body and whole plant BCF values (weighted by species) = 757

Final Residue Value = 200 mg/kg ÷ 757 = 0.26 mg/kg = 260 μg/l

<u>Salt water</u>

Geometric mean BCF for long-term exposure of oyster = 3,080

Final Residue Value = 14 mg/kg ÷ 3,080 = 0.0045 mg/kg = 4.5 μg/l

Table 6. Other data on effects of cadmium on aquatic organisms

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (µg/l)* | Reference |
|---|---|---|---|---|---|---|
| | | FRESHWATER SPECIES | | | | |
| Mixed natural fungi and bacterial colonies on leaf litter | Cadmium chloride | 10.7 | 28 wks | Inhibition of leaf decomposition | 5 | Giesy, 1978 |
| Green alga, *Scenedesmus quadricauda* | Cadmium chloride | - | 96 hrs | Incipient inhibition (river water) | 100 | Bringmann & Kuhn, 1959a,b |
| Bacteria, *Escherichia coli* | Cadmium chloride | - | - | Incipient inhibition | 150 | Bringmann & Kuhn, 1959a |
| Bacteria, *Pseudomonas putida* | Cadmium chloride | - | 16 hrs | Incipient inhibition | 80 | Bringmann & Kuhn, 1976, 1977a, 1979, 1980b |
| Protozoan, *Entosiphon sulcatum* | Cadmium nitrate | - | 72 hrs | Incipient inhibiton | 11 | Bringmann, 1978, Bringmann & Kuhn, 1979, 1980b |
| Protozoan, *Microregma heterostoma* | Cadmium chloride | - | 28 hrs | Incipient inhibition | 100 | Bringmann & Kuhn, 1959b |
| Protozoan, *Chilomonas paramecium* | Cadmium nitrate | - | 48 hrs | Incipient inhibition | 160 | Bringmann, et al. 1980 |
| Protozoan, *Uronema parduezi* | Cadmium nitrate | - | 20 hrs | Incipient inhibition | 26 | Bringmann & Kuhn, 1980a |
| Mixed macroinvertebrates | Cadmium chloride | 11.1 | 52 wks | Reduction in mean total numbers and in numbers of taxa | 5 | Giesy, et al. 1979 |
| Annelid, *Pristina* sp. | Cadmium chloride | 11.1 | 52 wks | Population reduction | 5 | Giesy, et al. 1979 |
| Tubificid worm, *Tubifex tubifex* | Cadmium chloride | 224 | 48 hr | LC50 | 320,000 | Qureshi, et al. 1980 |
| Snail (embryo), *Amnicola* sp. | - | 50 | 96 hrs | LC50 | 3,800 | Rehwoldt, et al. 1973 |

Table 6. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (μg/l)* | Reference |
|---|---|---|---|---|---|---|
| Snail, *Physa integra* | Cadmium chloride | 44-58 | 28 days | LC50 | 10.4 | Spehar, et al. 1978 |
| Cladoceran, *Daphnia galeata mendotae* | Cadmium chloride | - | 22 wks | Reduced biomass | 4.0 | Marshall, 1978a |
| Cladoceran, *Daphnia galeata mendotae* | Cadmium chloride | - | 15 days | Reduced rate of increase | 5.0 | Marshall, 1978b |
| Cladoceran, *Daphnia magna* | Cadmium chloride | - | 48 hrs | EC50 (river water) | 100 | Bringmann & Kuhn, 1959a,b |
| Cladoceran, *Daphnia magna* | Cadmium nitrate | - | 24 hrs | LC50 | 600 | Bringmann & Kuhn, 1977b |
| Cladoceran (3-5 days), *Daphnia magna* | - | - | 72 hrs | LC50 (10 C)<br>(15 C)<br>(25 C)<br>(30 C) | 224<br>224<br>12<br>0.1 | Braginskiy & Shcherban, 1978 |
| Cladoceran (adult), *Daphnia magna* | - | - | 72 hrs | LC50 (10 C)<br>(15 C)<br>(25 C)<br>(30 C) | 479<br>187<br>10.2<br>2.4 | Braginskiy & Shcherban, 1978 |
| Cladoceran, *Daphnia pulex* | Cadmium chloride | 57 | 140 days | Reduced reproduction | 1 | Bertram & Hart, 1979 |
| Copepod, *Eucyclops agilis* | Cadmium chloride | 11.1 | 52 wks | Population reduction | 5 | Giesy, et al. 1979 |
| Copepod, *Acanthocyclops viridis* | - | - | 72 hrs | LC50 | 0.5 | Braginskiy & Shcherban, 1978 |
| Crayfish, *Cambarus latimanus* | Cadmium chloride | 11.1 | 5 mo | Significant mortality | 5 | Thorp, et al. 1979 |
| Mayfly, *Cloeon dipterum* | - | | 72 hrs | LC50 (10 C)<br>(15 C)<br>(20 C)<br>(30 C) | 70,600<br>28,600<br>6,990<br>930 | Braginskiy & Shcherban, 1978 |

Table 6. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (μg/l)* | Reference |
|---|---|---|---|---|---|---|
| Mayfly, *Ephemerella* sp. | Cadmium chloride | 44-48 | 28 days | LC50 | <3.0 | Spehar, et al. 1978 |
| Mayfly, *Hexagenia rigida* | Cadmium nitrate | 79.1 | 96 hrs | LC50 | ≥1,000 | Leonhard, et al. 1980 |
| Midge, *Tanytarsus dissimilis* | Cadmium chloride | 47 | 10 days | LC50 | 3.8 | Anderson, et al. 1980 |
| Coho salmon (juvenile), *Oncorhynchus kisutch* | Cadmium chloride | 22 | 217 hrs | LC50 | 2.0 | Chapman & Stevens, 1978 |
| Coho salmon (adult), *Oncorhynchus kisutch* | Cadmium chloride | 22 | 215 hrs | LC50 | 3.7 | Chapman & Stevens, 1978 |
| Chinook salmon (alevin), *Oncorhynchus tshawytscha* | Cadmium chloride | 23 | 200 hrs | LC10 | 18-26 | Chapman, 1978 |
| Chinook salmon (swim-up), *Oncorhynchus tshawytscha* | Cadmium chloride | 23 | 200 hrs | LC10 | 1.2 | Chapman, 1978 |
| Chinook salmon (parr), *Oncorhynchus tshawytscha* | Cadmium chloride | 23 | 200 hrs | LC10 | 1.3 | Chapman, 1978 |
| Chinook salmon (smolt), *Oncorhynchus tshawytscha* | Cadmium chloride | 23 | 200 hrs | LC10 | 1.5 | Chapman, 1978 |
| Rainbow trout, *Salmo gairdneri* | Cadmium stearate | - | 96 hrs | LC50 | 6.0 | Kumada, et al. 1980 |
| Rainbow trout, *Salmo gairdneri* | Cadmium acetate | - | 96 hrs | LC50 | 6.2 | Kumada, et al. 1980 |
| Rainbow trout, *Salmo gairdneri* | Cadmium chloride | 112 | 80 min | Significant avoidance | 52 | Black & Birge, 1980 |
| Rainbow trout, *Salmo gairdneri* | - | 112 | 18 mos | Reduced survival | 0.2 | Birge, et al. 1981 |

Table 6. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (µg/l)[a] | Reference |
|---|---|---|---|---|---|---|
| Rainbow trout (embryo, larva), Salmo gairdneri | Cadmium chloride | 104 | 28 days | EC50 (death and deformity) | 140 | Birge, 1978 |
| Rainbow trout, Salmo gairdneri | - | - | 240 hrs | LC50 | 7<br>5 | Kumada, et al. 1973 |
| Rainbow trout (adult), Salmo gairdneri | Cadmium chloride | 54 | 408 hrs | LC50 | 5.2 | Chapman & Stevens, 1978 |
| Rainbow trout (alevin), Salmo gairdneri | Cadmium chloride | 23 | 186 hrs | LC10 | >6 | Chapman, 1978 |
| Rainbow trout (swim-up), Salmo gairdneri | Cadmium chloride | 23 | 200 hrs | LC10 | 1.0 | Chapman, 1978 |
| Rainbow trout (parr), Salmo gairdneri | Cadmium chloride | 23 | 200 hrs | LC10 | 0.7 | Chapman, 1978 |
| Rainbow trout (smolt), Salmo gairdneri | Cadmium chloride | 23 | 200 hrs | LC10 | 0.8 | Chapman, 1978 |
| Rainbow trout, Salmo gairdneri | Cadmium sulfate | 326 | 96 hrs | LC20 | 20 | Davies, 1976 |
| Rainbow trout, Salmo gairdneri | Cadmium stearate | - | 10 wks | BCF=27<br>BCF=40 | - | Kumada, et al. 1980 |
| Rainbow trout, Salmo gairdneri | Cadmium acetate | - | 10 wks | BCF=63 | - | Kumada, et al. 1980 |
| Rainbow trout, Salmo gairdneri | Cadmium chloride | 125 | 10 days | LC50 (18 C)<br>(12 C)<br>(6 C) | 10-30<br>30<br>10-30 | Roch & Maly, 1979 |
| Rainbow trout, Salmo gairdneri | Cadmium sulfate | 210 | 234 days | Increased gill diffusion | 2 | Hughes, et al. 1979 |
| Brook trout, Salvelinus fontinalis | Cadmium chloride | 10 | 21 days | Testicular damage | 10 | Sangalang & O'Halloran, 1972, 1973 |

Table 6. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (µg/l)* | Reference |
|---|---|---|---|---|---|---|
| Goldfish (embryo, larva), Carassius auratus | Cadmium chloride | 195 | 7 days | EC50 (death and (deformity) | 170 | Birge, 1978 |
| Goldfish, Carasius auratus | - | - | 50 days | Reduced plasma sodium | 44.5 | McCarty & Houston, 1976 |
| Fathead minnow, Pimephales promelas | Cadmium chloride | 63 | 96 hrs | LC50 | 80.8 | Spehar, 1982 |
| Fathead minnow, Pimephales promelas | Cadmium chloride | 55 | 96 hrs | LC50 | 40.9 | Spehar, 1982 |
| Fathead minnow, Pimephales promelas | Cadmium chloride | 59 | 96 hrs | LC50 | 64.8 | Spehar, 1982 |
| Fathead minnow, Pimephales promelas | Cadmium chloride | 66 | 96 hrs | LC50 | 135 | Spehar, 1982 |
| Fathead minnow, Pimephales promelas | Cadmium chloride | 65 | 96 hrs | LC50 | 120 | Spehar, 1982 |
| Fathead minnow, Pimephales promelas | Cadmium chloride | 74 | 96 hrs | LC50 | 86.3 | Spehar, 1982 |
| Fathead minnow, Pimephales promelas | Cadmium chloride | 79 | 96 hrs | LC50 | 86.6 | Spehar, 1982 |
| Fathead minnow, Pimephales promelas | Cadmium chloride | 62 | 96 hrs | LC50 | 114 | Spehar, 1982 |
| Fathead minnow, Pimephales promelas | Cadmium chloride | 63 | 96 hrs | LC50 | 80.8 | Spehar, 1982 |
| Brown bullhead, Ictalurus nebulosus | Cadmium chloride | - | 2 hrs | Affected gills and kidney | 61,300 | Bilckens, 1978, Garofano, 1979 |
| Channel catfish, Ictalurus punctatus | Cadmium chloride | - | - | Increased albinism | 0.5 | Westerman & Birge, 1978 |

Table 6. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (µg/l)* | Reference |
|---|---|---|---|---|---|---|
| Channel catfish, *Ictalurus punctatus* | Cadmium chloride | - | - | BCF=4.0-6.7 | - | Birge, et [illegible] |
| Mosquitofish, *Gambusia affinis* | Cadmium chloride | - | 8 wks | BCF=6,100 at 0.02 µg/l & 1.13 ppm added to food | - | Williams & [illegible] |
| Mosquitofish, *Gambusia affinis* | Cadmium chloride | 29 | 8 wks | BCF=1,430 at 10 µg/l & 1.13 ppm added to food | - | Williams & [illegible] |
| Bluegill, *Lepomis macrochirus* | Cadmium chloride | 112 | 80 min | Significant avoidance | >41.1 | Black & B[illegible] |
| Largemouth bass, *Micropterus salmoides* | Cadmium chloride | 112 | 80 min | Significant avoidance | 8.83 | Black & [illegible] |
| Largemouth bass (embryo, larva) *Micropterus salmoides* | Cadmium chloride | 99 | 8 days | EC50 (death and deformity) | 1,640 | Birge, et [illegible] |
| Largemouth bass, *Micropterus salmoides* | - | - | 24 hrs | Affected opercular activity | 150 | Morgan, 19[illegible] |
| Narrow-mouthed toad (embryo, larva), *Gastrophyryne carolinensis* | Cadmium chloride | 195 | 7 days | EC50 (death and deformity) | 40 | Birge, 197[illegible] |
| Marbled salamander (embryo, larva), *Ambystoma opacum* | Cadmium chloride | 99 | 8 days | EC50 (death and deformity) | 150 | Birge, et [illegible] |
| SALTWATER SPECIES | | | | | | |
| Colonial hydroid, *Campanularia flexuosa* | - | - | - | Enzyme inhibition | 40-75 | Moore & S[illegible] |

Table 6. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (µg/l)* | Reference |
|---|---|---|---|---|---|---|
| Colonial hydroid, *Campanularia flexuosa* | - | - | 11 days | Growth rate | 110-280 | Stebbing, 1976 |
| Colonial hydroid, *Laomedea loveni* | Cadmium chloride | - | 7 days | EC50 (10 g/kg salinity) | 3 | Theede, et al. 1979 |
| Colonial hydroid, *Laomedea loveni* | Cadmium chloride | - | 7 days | EC50 (15 g/kg salinity) | 5.6 | Theede, et al. 1979 |
| Colonial hydroid, *Laomedea loveni* | Cadmium chloride | - | 7 days | EC50 (20 g/kg salinity) | 11 | Theede, et al. 1979 |
| Colonial hydroid, *Laomedea loveni* | Cadmium chloride | - | 7 days | EC50 (25 g/kg salinity) | 12.4 | Theede, et al. 1979 |
| Colonial hydroid, *Laomedea loveni* | Cadmium chloride | - | 7 days | EC50 (7.5 C)<br>(10 C)<br>(15 C)<br>(17.5 C) | 52<br>34<br>9<br>5.6 | Theede, et al. 1979 |
| Polychaete worm, *Neanthes arenaceodentata* | Cadmium chloride | - | 28 days | LC50 | 3,000 | Reish, et al. 1976 |
| Polychaete worm, *Capitella capitata* | Cadmium chloride | - | 28 days | LC50 | 630 | Reish, et al. 1976 |
| Polychaete worm, *Capitella capitata* | Cadmium chloride | - | 28 days | LC50 | 700 | Reish, et al. 1976 |
| Blue mussel, *Mytilus edulis* | Cadmium EDTA | - | 28 days | BCF=252 | - | George & Coambs, 1977 |
| Blue mussel, *Mytilus edulis* | Cadmium alginate | - | 28 days | BCF=252 | - | George & Coambs, 1977 |
| Blue mussel, *Mytilus edulis* | Cadmium humate | - | 28 days | BCF=252 | - | George & Coambs, 1977 |
| Blue mussel, *Mytilus edulis* | Cadmium poctate | - | 28 days | BCF=252 | - | George & Coambs, 1977 |

Table 6. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (µg/l)[a] | Reference |
|---|---|---|---|---|---|---|
| Blue mussel, *Mytilus edulis* | Cadmium chloride | - | 21 days | BCF=710 | - | Janssen & Scholz, 1979 |
| Bay scallop, *Argopecten irradians* | Cadmium chloride | - | 42 days | EC50 (growth reduction) | 78 | Pesch & Stewart, 1980 |
| Bay scallop, *Argopecten irradians* | Cadmium chloride | - | 21 days | BCF=168 | - | Eisler, et al. 1972 |
| Eastern oyster, *Crassostrea virginica* | Cadmium iodide | - | 40 days | BCF=677 | - | Kerfoot & Jacobs, 1976 |
| Eastern oyster, *Crassostrea virginica* | Cadmium chloride | - | 21 days | BCF=149 | - | Eisler, et al. 1972 |
| Soft-shell clam, *Mya arenaria* | Cadmium chloride | - | 7 days | LC50 | 150 | Eisler, 1977 |
| Soft-shell clam, *Mya arenaria* | Cadmium chloride | - | 7 days | LC50 | 700 | Eisler & Hennekey, 1977 |
| Mysid, *Mysidopsis bahia* | - | - | 17 days | LC50 (15-23 g/kg salinity) | 11 | Nimmo, et al. 1977a |
| Mysid, *Mysidopsis bahia* | Cadmium chloride | - | 16 days | LC50 (30 g/kg salinity) | 28 | Gentile, et al. 1982 |
| Mysid, *Mysidopsis bahia* | Cadmium chloride | - | 8 days | LC50 | 60 | Gentile, et al. 1982 |
| Mysid, *Mysidopsis bigelowi* | Cadmium chloride | - | 8 days | LC50 | 70 | Gentile, et al. 1982 |
| Mysid, *Mysidopsis bigelowi* | Cadmium chloride | - | 28 days | LC50 | 18 | Gentile, et al. 1982 |
| Isopod, *Idotea baltica* | Cadmium sulfate | - | 5 days | LC50 (3 g/kg salinity) | 10,000 | Jones, 1975 |
| Isopod, *Idotea baltica* | Cadmium sulfate | - | 3 days | LC50 (21 g/kg salinity) | 10,000 | Jones, 1975 |

Table 6. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (µg/l)* | Reference |
|---|---|---|---|---|---|---|
| Isopod, *Idotea baltica* | Cadmium sulfate | - | 1.5 days | LC50 (14 g/kg salinity) | 10,000 | Jones, 1975 |
| Pink shrimp, *Penaeus duorarum* | Cadmium chloride | - | 30 days | LC50 | 720 | Nimmo, et al. 1977b |
| Grass shrimp, *Palaemonetes pugio* | Cadmium chloride | - | 42 days | LC50 | 300 | Pesch & Stewart, 1980 |
| Grass shrimp, *Palaemonetes pugio* | Cadmium chloride | - | 21 days | LC25 (5 g/kg salinity) | 50 | Vernberg, et al. 1977 |
| Grass shrimp, *Palaemonetes pugio* | Cadmium chloride | - | 21 days | LC10 (10 g/kg salinity) | 50 | Vernberg, et al. 1977 |
| Grass shrimp, *Palaemonetes pugio* | Cadmium chloride | - | 21 days | LC5 (20 g/kg salinity) | 50 | Vernberg, et al. 1977 |
| Grass shrimp, *Palaemonetes pugio* | Cadmium chloride | - | 6 days | LC75 (10 g/kg salinity) | 300 | Middaugn & Floyd, 1978 |
| Grass shrimp, *Palaemonetes pugio* | Cadmium chloride | - | 6 days | LC50 (15 g/kg salinity) | 300 | Middaugh & Floyd, 1978 |
| Grass shrimp, *Palaemonetes pugio* | Cadmium chloride | - | 6 days | LC25 (30 g/kg salinity) | 300 | Middaugh & Floyd, 1978 |
| Grass shrimp, *Palaemonetes pugio* | Cadmium chloride | - | 21 days | BCF=140 | - | Vernberg, et al. 1977 |
| Grass shrimp, *Palaemonetes vulgaris* | Cadmium chloride | - | 29 days | LC50 | 120 | Nimmo, et al. 1977b |
| American lobster, *Homarus americanus* | Cadmium chloride | - | 21 days | BCF=25 | - | Eisler, et al. 1972 |
| American lobster, *Homarus americanus* | Cadmium chloride | - | 30 days | Increase in ATPase activity | 6 | Tucker, 1979 |
| Hermit crab, *Pagurus longicarpus* | Cadmium chloride | - | 7 days | 25% mortality | 270 | Eisler & Hennekoy, 1977 |

Table 6. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (µg/l)* | Reference |
|---|---|---|---|---|---|---|
| Hermit crab, *Pagurus longicarpus* | Cadmium chloride | - | 60 days | LC56 | 70 | Pesch & Stewart, 1980 |
| Rock crab, *Cancer irroratus* | Cadmium chloride | - | 96 hrs | Enzyme activity | 1,000 | Gould, et al. 1976 |
| Blue crab, *Callinectes sapidus* | Cadmium nitrate | - | 7 days | LC50 (10 g/kg salinity) | 50 | Rosenberg & Costlow, 1976 |
| Blue crab, *Callinectes sapidus* | Cadmium nitrate | - | 7 days | LC50 (30 g/kg salinity) | 150 | Rosenberg & Costlow, 1976 |
| Mud crab (larva), *Eurypanopeus depressus* | Cadmium chloride | - | 8 days | LC50 | 10 | Mirkes, et al. 1978 |
| Mud crab (larva), *Eurypanopeus depressus* | Cadmium chloride | - | 44 days | Delay in metamorphysis | 10 | Mirkes, et al. 1978 |
| Mud crab, *Rhithropanopeus harrisii* | Cadmium nitrate | - | 11 days | LC80 (10 g/kg salinity) | 50 | Rosenberg & Costlow, 1976 |
| Mud crab, *Rhithropanopeus harrisii* | Cadmium nitrate | - | 11 days | LC75 (20 g/kg salinity) | 50 | Rosenberg & Costlow, 1976 |
| Mud crab, *Rhithropanopeus harrisii* | Cadmium nitrate | - | 11 days | LC40 (30 g/kg salinity) | 50 | Rosenberg & Costlow, 1976 |
| Fiddler crab, *Uca pugilator* | - | - | 10 days | LC50 | 2,900 | O'Hara, 1973a |
| Fiddler crab, *Uca pugilator* | Cadmium chloride | - | - | Effect on respiration | 1.0 | Vernberg, et al. 1974 |
| Starfish, *Asterias forbesi* | Cadmium chloride | - | 7 days | 25% mortality | 270 | Eisler & Hennekey, 1977 |
| Herring (larva), *Clupea harengus* | Cadmium chloride | - | - | 100% embryonic survival | 5,000 | Westernhagen, et al. |
| Pacific herring (embryo), *Clupea harengus pallasi* | Cadmium chloride | - | <24 hrs | 17% reduction in volume | 10,000 | Alderdice, et al. 1979a |

Table 6. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (µg/l)* | Reference |
|---|---|---|---|---|---|---|
| Pacific herring (embryo), *Clupea harengus pallasi* | Cadmium chloride | - | 96 hrs | Decrease in capsule strength | 1,000 | Alderdice, et al. 1979b |
| Pacific herring (embryo), *Clupea harengus pallasi* | Cadmium chloride | - | 48 hrs | Reduced osmolality of perivitelline fluid | 1,000 | Alderdice, et al. 1979c |
| Mummichog (adult), *Fundulus heteroclitus* | Cadmium chloride | - | 48 hrs | LC50 (20 g/kg salinity) | 60,000 | Middaugh & Dean, 1977 |
| Mummichog (adult), *Fundulus heteroclitus* | Cadmium chloride | - | 48 hrs | LC50 (30 g/kg salinity) | 43,000 | Middaugh & Dean, 1977 |
| Mummichog, *Fundulus heteroclitus* | Cadmium chloride | - | 21 days | BCF=48 | - | Eisler, et al. 1972 |
| Mummichog (larva), *Fundulus heteroclitus* | Cadmium chloride | - | 48 hrs | LC50 (20 g/kg salinity) | 32,000 | Middaugh & Dean, 1977 |
| Mummichog (larva), *Fundulus heteroclitus* | Cadmium chloride | - | 48 hrs | LC50 (30 g/kg salinity) | 7,800 | Middaugh & Dean, 1977 |
| Atlantic silverside (adult), *Menidia menidia* | Cadmium chloride | - | 48 hrs | LC50 (20 g/kg salinity) | 13,000 | Middaugh & Dean, 1977 |
| Atlantic silverside (adult), *Menidia menidia* | Cadmium chloride | - | 48 hrs | LC50 (30 g/kg salinity) | 12,000 | Middaugh & Dean, 1977 |
| Atlantic silverside, *Menidia menidia* | Cadmium chloride | - | 19 days | LC50 (12 g/kg salinity) | <160 | Voyer, et al. 1979 |
| Atlantic silverside, *Menidia menidia* | Cadmium chloride | - | 19 days | LC50 (20 g/kg salinity) | 540 | Voyer, et al. 1979 |
| Atlantic silverside, *Menidia menidia* | Cadmium chloride | - | 19 days | LC50 (30 g/kg salinity) | >970 | Voyer, et al. 1979 |

Table 6. (Continued)

| Species | Chemical | Hardness (mg/l as $CaCO_3$) | Duration | Effect | Result (µg/l)* | Reference |
|---|---|---|---|---|---|---|
| Atlantic silverside (larva), *Menidia menidia* | Cadmium chloride | - | 48 hrs | LC50 (20 g/kg salinity) | 2,200 | Middaugh & Dean, 1977 |
| Atlantic silverside (larva), *Menidia menidia* | Cadmium chloride | - | 48 hrs | LC50 (30 g/kg salinity) | 1,600 | Middaugh & Dean, 1977 |
| Striped bass (juvenile), *Morone saxatilis* | Cadmium choride | - | 90 days | Significant decrease in enzyme activity | 5 | Dawson, et al. 1977 |
| Striped bass (juvenile), *Morone saxatilis* | Cadmium chloride | - | 30 days | Significant decrease in oxygen consumption | 0.5-5.0 | Dawson, et al. 1977 |
| Spot (larva), *Leiostomus xanthurus* | Cadmium chloride | - | 9 days | Incipient LC50 | 200 | Middaugh, et al. 1975 |
| Cunner (adult), *Tautogolabrus adspersus* | Cadmium chloride | - | 60 days | 37.5% mortality | 100 | MacInnes, et al. 1977 |
| Cunner (adult), *Tautogolabrus adspersus* | Cadmium chloride | - | 30 days | Depressed gill tissue oxygen consumption | 50 | MacInnes, et al. 1977 |
| Cunner (adult), *Tautogolabrus adspersus* | Cadmium chloride | - | 96 hrs | Decreased enzyme activity | 3,000 | Gould & Karolus, 1974 |
| Winter flounder, *Pseodopleuronectes americanus* | Cadmium chloride | - | 8 days | 50% viable hatch | 300 | Voyer, et al. 1977 |
| Winter flounder, *Pseodopleuronectes americanus* | Cadmium chloride | - | 60 days | Increased gill tissue respiration | 5 | Calabrese, et al. 1975 |

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

# REFERENCES


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

Al-atia, G.R. 1978. The uptake and toxicity of cadmium in Amoeba proteus. J. Protozool. 25: 5B.

Al-atia, G.R. 1980. Toxicity of cadmium to Amoeba proteus: a biochemical approach. J. Protozool. 27: 128.

Alderdice, D.F., et al. 1979a. Influence of salinity and cadmium on the volume of Pacific herring eggs. Helgolander wiss. Meeresunters. 32: 163.

Alderdice, D.F., et al. 1979b. Influence of salinity and cadmium on capsule strength in Pacific herring eggs. Helgolander wiss. Meeresunters. 32: 149.

Alderdice, D.F., et al. 1979c. Osmotic responses of eggs and larvae of the Pacific herring to salinity and cadmium. Helgolander wiss. Meeresunters. 32: 508.

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

Anderson, R.V. 1978. The distribution of Cd, Cu, Pb and Zn in the biota of two freshwater sites with different trace metal inputs. Holartic Ecology 1: 377.

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

Anonymous. 1950. Ohio River Valley Water Sanitation Commission, Subcommittee on Toxicities, Metal Finishing Industries Action Committee Rep. No. 3.

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

Ball, I.R. 1967. The toxicity of cadmium to rainbow trout (Salmo gairdnerii Richardson). Water Res. 1: 805.

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

Beattie, J.H. and D. Pascoe. 1978. Cadmium uptake by rainbow trout, Salmo gairdneri, eggs and alevins. J. Fish Biol. 13: 631.

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

Benoit, D.A., et al. 1976. Toxic effects of cadmium on three generations of brook trout (Salvelinus fontinalis). Trans. Am. Fish. Soc. 105: 550.

Bertram, P.E. and B.A. Hart. 1979. Longevity and reproduction of Daphnia pulex (deGeer) exposed to cadmium-contaminated food or water. Environ. Pollut. 19: 295.

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

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

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

Birge, W.J., et al. 1979. The effects of mercury on reproduction of fish and amphibians. In: J.O. Nriagu (ed.,), The Biochemistry of Mercury in the Environment. Elsevier/North-Holland, New York. p. 629.

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

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

Black, J.A. and W.J. Birge. 1980. An avoidance response bioassay for aquatic pollutants. PB 80-180490. National Technical Information Service, Springfield, Virginia.

Blickens, E.A.C. 1978. Cadmium induced histopathological changes in the gills of the brown bullhead Ictalurus nebulosus (Lesueur). Ph.D. Thesis. New York University.

Boyden, C.R. 1977. Effect of size upon metal content of shellfish. J. Marine Bio. Ass. 57: 675.

Bradley, R.W. and J.B. Sprague. Manuscript. The influence of pH, hardness, and alkalinity on the acute toxicity of zinc to rainbow trout. University of Guelph, Guelph, Ontario.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Bryan, G.W. 1971. The effects of heavy metals (other than mercury) on marine and estuarine organisms. Proc. Roy. Soc. London B. 177: 389.

Buikema, A.L., Jr., et al. 1974. Evaluation of Philodina acuticornis (Rotifera) as a bioassay organism for heavy metals. Water Resour. Bull. Am. Water Resour. Assoc. 10: 648.

Burnison, G., et al. 1975. Toxicity of cadmium to freshwater algae. Proc. Can. Fed. Biol. Soc. 18: 46.

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

Calabrese, A., et al. 1975. Sublethal Physiological Stress Induced by Cadmium and Mercury in the Winter Flounder, Pseudopleuronectes americanus. In: Sublethal Effects of Toxic Chemicals in Aquatic Animals. Elsevier, Amsterdam.

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

Canterford, G.S. and D.R. Canterford. 1980. Toxicity of heavy metals to the marine diatom Ditylum brightwellii (West) Grunow: correlation between toxicity and metal speciation. Mar. Biol. Ass. U.K. 60: 227.

Canton, J.H. and D.M.M. Adema. 1978. Reproducibility of short-term and reproduction toxicity experiments with Daphnia magna and comparison of the sensitivity of Daphnia magna with Daphnia pulex and Daphnia cucullata in short-term experiment. Hydrobiol. 59: 135.

Canton, J.H. and W. Slooff. 1979. A proposal to classify compounds and to establish water quality criteria based on laboratory data. Ecotoxicol. Environ. Safety. 3: 126.

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

Carroll, J.J., et al. 1979. Influences of hardness constituents on the acute toxicity of cadmium to brook trout (Salvelinus fontinalis). Bull. Environ. Contam. Toxicol. 22: 575.

Cearley, J.E. and R.L. Coleman. 1973. Cadmium toxicity and accumulation in southern naiad. Bull. Environ. Contam. Toxicol. 9: 100.

Cearley, J.E. and R.L. Coleman. 1974. Cadmium toxicity and bioconcentration in largemouth bass and bluegill. Bull. Environ. Contam. Toxicol. 11: 146.

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

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

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

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

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

Chapman, W.H., et al. 1968. Concentration factors of chemical elements in edible aquatic organisms. UCRL-50564. Lawrence Livermore Laboratory, Livermore, California.

Clubb, R.W., et al. 1975. Acute cadmium toxicity studies upon nine species of aquatic insects. Environ. Res. 9: 332.

Conway, H.L. 1978. Sorption of arsenic and cadmium and their effects on growth, micronutrient utilization, and photosynthetic pigment composition of Asterionella formosa. Jour. Fish. Res. Board Can. 35: 286.

D'Agostino, A. and C. Finney. 1974. The effect of copper and cadmium on the development of Tigriopus japonicus. In: F.J. Vernberg and W.B. Vernberg (eds.), Pollution and Physiology of Marine Organisms. Academic Press, New York. p. 445.

Davies, P.H. 1976. Use of dialysis tubing in defining the toxic fractions of heavy metals in natural waters. In: R.W. Andrew, et al. (eds.), Toxicity to Biota of Metal Forms in Natural Water. International Joint Commission. Windsor, Ontario. p. 110.

Dawson, M.A., et al. 1977. Physiological response of juvenile striped bass, Morone saxatilis, to low levels of cadmium and mercury. Chesapeake Sci. 18: 353.

DeFilippis, L.F., et al. 1981. The effects of sublethal concentrations of zinc, cadmium and mercury on Englena. II. Respiration, photosynthesis and photochemical activities. Arch. Microbiol. 128: 407.

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

Drummond, R.A. and D.A. Benoit. Manuscript. Toxicity of cadmium to fish: some observations on the influence of experimental procedures. U.S. EPA. Duluth, Minnesota.

Eaton, J.G. 1974. Chronic cadmium toxicity to the bluegill (Lepomis macrochirus Rafinesque). Trans. Am. Fish. Soc. 4: 729.

Eaton, J.G. 1980. Memorandum to C.E. Stephan. U.S. EPA. Duluth, Minnesota. August 5.

Eaton, J.G., et al. 1978. Metal toxicity to embryos and larvae of seven freshwater fish species--I. Cadmium. Bull. Environ. Contam. Toxicol. 19: 95.

Eisler, R. 1971. Cadmium poisoning in Fundulus heteroclitus (Pisces:Cyprinodontidae) and other marine organisms. Jour. Fish. Res. Board Can. 28: 1225.

Eisler, R. 1974. Radiocadmium exchange with seawater by Fundulus heteroclitus (L.) (Pisces: Cyprinodontidae). J. Fish Biol. 6: 601.

Eisler, R. 1977. Acute toxicities of selected heavy metals to the soft-shell calm, Mya arenaria. Bull. Environ. Contam. Toxicol. 17: 137.

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

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

Eisler, R., et al. 1972. Cadmium uptake by marine organisms. Jour. Fish. Res. Board Can. 29: 1367.

Faraday, W.E. and A.C. Churchill. 1979. Uptake of cadmium by the eelgrass Zostera marina. Marine Biol. 53: 293.

Fennikok, K.B., et al. 1978. Cadmium toxicity in planktonic organisms of a freshwater food web. Environ. Res. 15: 357.

Frank, P.M. and P.B. Robertson. 1979. The influence of salinity on toxicity of cadmium and chromium to the blue crab, Callinectes sapidus. Bull. Environ. Contam. Toxicol. 21: 74.

Frazier, J.M. 1979. Bioaccumulation of cadmium in marine organisms. Environ. Health Perspectives. 28: 75.

Freeman, B.J. 1978. Accumulation of cadmium, chromium, and lead by bluegill sunfish (Lepomis macrochirus Rafinesque) under temperature and oxygen stress. SRO-757-6. National Technical Information Service. Arlington, Virginia.

Freeman, B.J. 1980. Accumulation of cadmium, chromium, and lead by bluegill sunfish (Lepomis macrochirus Rafinesque) under temperature and oxygen stress. Thesis. University of Georgia. Athens, Georgia.

Garofano, J.S. 1979. The effects of cadmium on the peripheral blood and head kidney of the brown bullhead Ictalurus nebulosus (Lesueur). Thesis. New York University.

Gentile, S.M., et al. 1982. Chronic effects of cadmium on two species of mysid shrimp: Mysidopsis bahia and Mysidopsis bigelowi. Hydrobiologia 93: 195.

George, S.G. and T.L. Coombs. 1977. The effects of chelating agents on the uptake and accumulation of cadmium by Mytilus edulis. Mar. Biol. 39: 261.

Giesy, J.P., Jr. 1978. Cadmium inhibition of leaf decomposition in an aquatic microcosm. Chemosphere. 6: 467.

Giesy, J.P., Jr., et al. 1977. Effects of naturally occurring aquatic organic fractions on cadmium toxicity to Simocephalus serrulatus (Daphnidae) and Gambusia affinis (Poediliidae). Water Res. 11: 1013.

Giesy, J.P., Jr., et al. 1979. Fate and biological effects of cadmium introduced into channel microcosms. EPA-600/3-79-039. National Technical Information Service. Springfield, Virginia.

Gillespie, R., et al. 1977. Cadmium uptake by the crayfish, Orconectes propinquus propinquus (Girard). Environ. Res. 13: 364.

Gould, E. and J. Karolus. 1974. Physiological response of the cunner, Tautogolabrus adspersus, to cadmium. Observations on the biochemistry. NOAA Tech. Rep. SSRF-681, Part V.

Gould, E., et al. 1976. Heart transaminase in the rock crab, Cancer irroratus, exposed to cadmium salts. Bull. Environ. Contam. Toxicol. 15: 635.

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

Greig, R.A. and D.R. Wenzloff. 1978. Metal accumulation and depuration by the american oyster, Crassostrea virginica. Bull. Environ. Contam. Toxicl. 20: 499.

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

Hart, B.A. and B.D. Schaife. 1977. Toxicity and bioaccumulation of cadmium in Chlorella pyrenoidosa. Environ. Res. 14: 401.

Hazen, R.E. and T.J. Kneip. 1980. Biogeochemical cycling of cadmium in a marsh ecosystem. In: J.O. Nriagu (ed.), Cadmium in the Environment, Part I. Wiley, New York. p. 399.

Holcombe, G.W., et al. Manuscript. Toxicity of selected priority pollutants to various aquatic organisms. U.S. EPA. Duluth, Minnesota.

Hughes, G.M., et al. 1979. A morphometric study of effects of nickel, chromium and cadmium on the secondary lamellae of rainbow trout gills. Water Res. 13: 665.

Hughes, J.S. 1973. Acute toxicity of thirty chemicals to striped bass (Morone saxatilis). Pres. Western Assoc. State Game Fish Comm., Salt Lake City, Utah. July, 1973.

Hutcheson, M.S. 1975. The effects of temperature and salinity on cadmium uptake by the blue crab, Callinectes sapidus. Chesapeak Science. 15: 237.

Hutchinson, T.C. and H. Czyrska. 1972. Cadmium and Zinc Toxicity and Synergism to Floating Aquatic Plants. In: Water Pollution Research in Canada

1972. Proc. 7th Can. Symp. Water Pollut. Res. Inst. Environ. Sci. Eng. Publ. No. EI-3. p. 59.

Hutchinson, T.C. and P.M. Stokes. 1975. Heavy metal toxicity and algal bioassays. In: S. Barabos (ed.), Water Quality Parameters. ASTM STP 573. American Society for Testing and Materials. Philadelphia, Pennsylvania. p. 320.

Janssen, H.H. and N. Scholz. 1979. Uptake and cellular distribution of cadmium in *Mytilus edulis*. Mar. Biol. 55: 133.

Jennings, J.R. and P.S. Rainbow. 1979a. Studies on the uptake of cadmium by the crab *Carcinus maenas* in the laboratory. I. Accumulation from seawater and a food source. Mar. Biol. 50: 131.

Jennings, J.R. and P.S. Rainbow. 1979b. Accumulation of cadmium by *Dunaliella tertiolecta* Butcher. J. Plankton Res. 1: 67.

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

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

Jude, D.J. 1973. Sublethal effects of ammonia and cadmium on growth of green sunfish. Ph.D. Thesis. Dept. Fish. Wildl., Michigan State Univ.

Kerfoot, W.B. and S.A. Jacobs. 1976. Cadmium accural in combined waste-treatment aquaculture system. Environ. Sci. Technol. 10: 662.

Klass, E., et al. 1974. The effect of cadmium on population growth of the green alga Scenedesmus quadricauda. Bull. Environ. Contam. Toxicol. 12: 442.

Klockner, K. 1979. Uptake and accumulation of cadmium by Ophryotrocha diadema (Polychaeta). Mar. Ecol. Prog. Ser. 1: 71.

Kneip, T.J. and R.E. Hazen. 1979. Deposit and mobility of cadmium in marsh-cove ecosystem and the relation to cadmium concentration in biota. Environ. Health Perspectives 28: 67.

Kobayashi, N. 1971. Fertilized sea urchin eggs as an indicator material for marine pollution bioassay, preliminary experiments. Publ. Seto Mar. Biol. Lab. 18: 379.

Kumada, H., et al. 1973. Acute and chronic toxicity, uptake and retention of cadmium in freshwater organisms. Bull. Freshwater Fish. Res. Lab. 22: 157.

Kumada, H., et al. 1980. Accumulation and biological effects of cadmium in rainbow trout. Bull. Jap. Soc. Sci. Fish. 46: 97.

[illegible], [illegible]. and A. [illegible]. [illegible]. Cadmium in aquatic systems. Metals and Ecology Symposium. Stockholm, Sweden. p. 47.

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

Leonhard, S.L., et al. 1980. Evaluation of the acute toxicity of the heavy metal cadmium to nymphs of the burrowing mayfly, Hexagenia rigida. In: J.F. Flannagan and K.E. Marshall (eds.), Advances in Ephemeroptera Biology. Plenum Publishing Corp. p. 457.

Lue-Kim, H., et al. 1980. Cadmium toxicity on synchronous populations of Chlorella ellipsoides. Can. J. Biol. 58: 1780.

Maas, R.P. 1978. A field study of the relationship between heavy metal concentrations in stream water and selected benthic macroinvertebrate species. PB 297 284. National Technical Information Service, Springfield, Virginia.

MacInnes, J.R., et al. 1977. Long-term cadmium stress in the cunner Tautogolabrus adspersus. Fish. Bull. 75: 199.

Markham, J.W., et al. 1980. Effects of cadmium on Laminaria saccharina in culture. Mar. Ecol. Prog. Ser. 3: 31.

Marshall, J.S. 1978a. Population dynamics of Daphnia galeata mendotae as [illegible]ified by chronic cadmium stress. Jour. Fish. Res. Board Can. 35: 461.

Marshall, J.S. 1978b. Field verification of cadmium toxicity to laboratory Daphnia populations. Bull. Environ. Contam. Toxicol. 20: 387.

McCarty, L.S. and A.H. Houston. 1976. Effects of exposure to sublethal levels of cadmium upon water-electrolyte status in the goldfish (Carassius auratus). Jour. Fish. Biol. 9: 11.

McCarty, L.S., et al. 1978. Toxicity of cadmium to goldfish, Carassius auratus, in hard and soft water. Jour. Fish. Res. Board Can. 35: 35.

Middaugh, D.P. and J.M. Dean. 1977. Comparative sensitivity of eggs, larvae and adults of the estuarine teleosts, Fundulus heteroclitus and Menidia menidia to cadmium. Bull. Environ. Contam. Toxicol. 17: 645.

Middaugh, D.P. and G. Floyd. 1978. The effect of prehatch and posthatch exposure to cadmium on salinity tolerance of larval grass shrimp, Palaemonetes pugio. Estuaries 1: 123.

Middaugh, D.P., et al. 1975. The response of larval fish Leiostomus xanthurus to environmental stress following sublethal cadmium exposure. Contrib. Mar. Sci. 19.

Ministry of Technology. 1967. Effects of pollution on fish--Toxicity of zinc, phenol, cadmium, and nickel to trout eggs and alevins. Water Pollut. Res. London. p. 52.

Ministry of Technology. 1971. Effects of pollution on fish. Water Pollut. Res. London. p. 37.

Mirkes, D.Z., et al. 1978. Effects of cadmium and mercury on the behavioral responses and development of Eurypanopeus depressus larvae. Mar. Biol. 47: 143.

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

Moraitou-Apostolopoulou, M., et al. 1979. Effects of sublethal concentrations of cadmium pollution for two populations of Acartia clausi (Copepoda) living at two differently polluted areas. Bull. Environ. Contam. Toxicol. 23: 642.

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

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

Mount, D.I. and T.J. Norberg. Manuscript. A seven-day life-cycle cladoceran toxicity test. U.S. EPA. Duluth, Minnesota.

Mowdy, D.E. 1981. Elimination of laboratory-acquired cadmium by the oyster Crassostrea virginica in the natural environment. Bull. Environ. Contam. Toxicol. 26: 345.

Muller, K.W. and H.D. Payer. 1979. The influence of pH on the cadmium-repressed growth of the alga Coelostrum proboscideum. Physiol. Plant. 45: 415.

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

Nakano, Y., et al. 1980. Morphological observation on *Euglena gracilis* grown in zinc-sufficient media containing cadmium ions. Agric. Biol. Chem. 44: 2305.

Negilski, D.S. 1976. Acute toxicity of zinc, cadmium and chromium to the marine fishes, yellow-eye mullet (*Aldrichetta forsteri* C. and V.) and small mouth hardy head (*Atherinasoma microstoma* Whitley). Aust. Jour. Mar. Freshwater Res. 27: 137.

Nelson, D.A., et al. 1976. Biological effects of heavy metals on juvenile bay scallops, *Argopenten irradians*, in short-term exposures. Bull. Environ. Contam. Toxicol. 16: 275.

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

Nimmo, D.R., et al. 1977a. *Mysidopsis bahia*: An estuarine species suitable for life-cycle toxicity tests to determine the effects of a pollutant. *In*: F.L. Mayer and J.L. Hamelink (eds.), Aquatic Toxicology and Hazard Evaluation. ASTM STP 634. American Society for Testing and Materials. Philadelphia, Pennsylvania. p. 109.

Nimmo, D.R., et al. 1977b. Effects of Cadmium on the Shrimps *Panaeus duorarum*, *Palaemonetes pugio*, and *Palaemonetes vulgaris*. *In*: F.J. Vernberg, et al.

(eds.), Physiological Responses of Marine Biota to Pollutants. Academic Press, New York.

Noel-Lambot, F., et al. 1980. Cadmium, zinc, and copper accumulation in limpets (Patella vulgata) from the British channel and special reference to metallothioneins. Mar. Ecol. Prog. Ser. 2: 81.

O'Hara, J. 1973. The influence of temperature and salinity on the toxicity of cadmium to the fiddler crab, Uca pugilator. U.S. Dept. Commer. Fish. Bull. 71: 149.

O'Hara, J. 1973b. Cadmium uptake by fiddler crabs exposed to temperature and salinity stress. J. Fish. Res. Board Can. 30: 846.

Ojaveer, E., et al. 1980. On the effect of copper, cadmium and zinc on the embryonic development of Baltic spring spawning herring. Finnish Marine Research 247: 135.

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

Pascoe, D. and P. Cram. 1977. The effect of parasitism on the toxicity of cadmium to the three-spined stickleback, Gasterosteus aculeatus L. Jour. Fish. Biol. 10: 467.

Pascoe, D. and D.L. Mattey. 1977. Studies on the toxicity of cadmium to the three-spined stickleback, Gasterosteus aculeatus L. Jour. Fish. Biol. 11: 207.

Pesch, G.G. and N.E. Stewart. 1980. Cadmium toxicity to three species of estuarine invertebrates. Mar. Environ. Res. 3: 145.

Phelps, H.L. 1979. Cadmium sorption in estuarine mud-type sediment and the accumulation of cadmium in the soft-shell clam, Mya arenaria. Estuaries 2: 40.

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

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

Pickering, Q.H. and M.H. Gast. 1972. Acute and chronic toxicity of cadmium to the fathead minnow (Pimephales promelas) Jour. Fish. Res. Board Can. 29: 1099.

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

Poldoski, J.E. 1979. Cadmium bioaccumulation assays. Their relationship to various ionic equilibria in Lake Superior water. Environ. Sci. Technol. 13: 701.

Pringle, B.H., et al. 1968. Trace metal accumulation by estuarine mollusks. Jour. Sanit. Eng. Div. 94SA3: 455.

Qureshi, S.A., et al. 1980. Acute toxicity of four heavy metals to benthic fish food organisms from the river Khan, Ujjain. Intern. J. Environ. Studies 15: 59.

Rainbow, P.S., et al. 1980. Effects of chelating agents on the accumulation of cadmium by the barnacle Semibalanus balanoides, and the complexation of soluble Cd, Zn and Cu. Mar. Ecol. Prog. Ser. 2: 143.

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

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

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

Reichert, W.L., et al. 1979. Uptake and metabolism of lead and cadmium in coho salmon (Oncorhynchus kisutch). Comp. Biochem. Physiol. 63C: 229.

Reish, D.J., et al. 1976. The effect of heavy metals on laboratory populations of two polychaetes with comparisons to the water quality conditions and standards in Southern California marine waters. Water Res. 10: 299.

Reish, D.J., et al. 1978. Interlaboratory calibration experiments using the Polychaetous annelid Capitella capitata. Mar. Environ. Res. 1: 109.

Roberts, K.S. 1979. A high molecular-weight cadmium-binding fraction isolated from the liver cytosol of trout exposed to environmentally relevant concentrations of the metal. Trans. Biochem. Soc. London. 7: 650.

Roch, M. and E.J. Maly. 1979. Relationship of cadmium-induced hypocalcemia with mortality in rainbow trout (Salmo gairdneri) and the influence of temperature on toxicity. Jour. Fish. Res. Board Can. 36: 1297.

Rosenberg, R. and J.D. Costlow. 1976. Synergistic effects of cadmium and salinity combined with constant and cycling temperatures on the larval development of two estuarine crab species. Mar. Biol. 38: 291.

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

Sangalang, G.B. and H.C. Freeman. 1979. Tissue uptake of cadmium in brook trout during chronic sublethal exposure. Arch. Environ. Contam. Toxicol. 8: 77.

Sangalang, G.B. and M.J. O'Halloran. 1972. Cadmium-induced testicular injury and alterations of androgen synthesis in brook trout. Nature 240: 470.

Sangalang, G.B. and M.J. O'Halloran. 1973. Adverse effects of cadmium on brook trout testis and on in vitro testicular androgen synthesis. Biol. Reprod. 9: 394.

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

Schuster, C.N. and B.H. Pringle. 1969. Trace metal accumulation by the American oyster, Crassostrea virginica. 1968 Proc. Natl. Shellfish Assoc. 59: 91.

Scott, K.J. 1982. Memorandum to J.H. Gentile. U.S. EPA. Narragansett, Rhode Island.

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

Sick, L.V. and G. Baptist. 1979. Cadmium incorporation by the marine copepod Pseudodiaptomous coronatus. Limnol. Oceanogr. 24: 453.

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

Spehar, R.L. 1976a. Cadmium and zinc toxicity to flagfish, Jordanella floridae. Jour. Fish. Res. Board Can. 33: 1939.

Spehar, R.L. 1976b. Cadmium and zinc toxicity to Jordanella floridae. EPA-600/3-76-096. National Technical Information Service, Springfield, Virginia.

Spehar, R.L. 1982. Memorandum to J.G. Eaton. U.S. EPA, Duluth, Minnesota. February 24.

Spehár, R.L., et al. 1978. Toxicity and bioaccumulation of cadmium and lead in aquatic invertebrates. Environ. Pollut. 15: 195.

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

Stebbing, A.R.D. 1976. The effects of low metal levels on a colonial hydroid. Jour. Mar. Biol. Assoc. U.K. 56: 1977.

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

Stephan, C.E., et al. 1983. Guidelines for deriving numerical national water quality criteria for the protection of aquatic life and its uses. U.S. EPA. Duluth, Minnesota. July 5.

Stern, M.S. and D.H. Stern. 1980. Effects of fly ash heavy metals on Daphnia magna. PB 81-198327. National Technical Information Service, Springfield, Virginia.

Sunda, W.G., et al. 1978. Effect of chemical speciation on toxicity of cadmium to grass shrimp, Palaemonetes pugio: importance of free cadmium ion. Environ. Sci. Technol. 12: 409.

Theede, H., et al. 1979. Temperature and salinity effects on the acute toxicity of cadmium to Laomedea loveni (Hydrozoa). Mar. Ecol. Prog. Ser. 1: 13.

Thompson, S.E., et al. 1972. Concentration factors of the chemical elements in edible aquatic organisms. UCRL-50564. Rev. 1. Lawrence Livermore Laboratory, Livermore, California.

Thorp, J.H., et al. 1979. Effects of chronic cadmium exposure on crayfish survival, growth, and tolerance to elevated temperatures. Arch. Environ. Contam. Toxicol. 8: 449.

Tucker, R.K. 1979. Effects of in vivo cadmium exposure on ATPases in gill of the lobster, Homarus americanus. Bull. Environ. Contam. Toxicol. 23: 33.

Tucker, R.K. and A. Matte. 1980. In vitro effects of cadmium and lead on ATPases in the gill of the rock crab, Cancer irroratus. Bull. Environ. Contam. Toxicol. 24: 847.

U.S. EPA. 1976. Quality criteria for water. 055-001-01049-4. Government Printing Office. Washington, D.C.

U.S. EPA. 1979. Methods for chemical analysis of water and wastes. EPA-600/4-79-020. National Technical Information Service, Springfield, Virginia.

U.S. EPA. 1980. Ambient water quality criteria for cadmium. EPA-440/5-80-025. National Technical Information Service, Springfield, Virginia.

U.S. EPA. 1982. Water Quality Standards Regulation. Federal Register. 47: 49234. October 29.

Verma, S.R., et al. 1980. Short term toxicity tests with heavy metals for predicting safe concentrations. Tox. Let. 1: 113.

Vernberg, W.B., et al. 1974. Multiple Environmental Factor Effects on Physiology and Behavior of the Fiddler Crab, Uca pugilator. In: F.J. Vernberg and W.B. Vernberg (eds.), Pollution and Physiology of Marine Organisms. Academic Press, New York.

Vernberg, W.B., et al. 1977. Effects of sublethal concentrations of cadmium on adult Paleomonetes pugio under static and flow-through conditions. Bull. Environ. Contam. Toxicol. 17: 16.

Voyer, R.A. 1975. Effect of dissolved oxygen concentration on the acute toxicity of cadmium to the mummichog, Fundulua heteroclitus. Trans. Am. Fish. Soc. 104: 129.

Voyer, R.A., et al. 1977. Viability of embryos of the winter flounder Pseudopleuronectes americanus exposed to combinations of cadmium and salinity at selected temperatures. Mar. Biol. 44: 117.

Voyer, R.A., et al. 1979. Hatching success and larval mortality in an estuarine teleost, Menidia menidia (Linnaeus), exposed to cadmium in constant and fluctuating salinity regimes. Bull. Environ. Contam. Toxicol. 23: 475.

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

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

Westernhagen, H.V. and V. Dethlefsen. 1975. Combined effects of cadmium and salinity on development and survival of flounder eggs. J. Mar. Biol. Ass. U.K. 55: 945.

Westernhagen, H.V., et al. 1975. Combined affects of cadmium and salinity on development and survival of garpike eggs. Helgolander wiss Meeresunters. 27: 268.

Westernhagen, H.V., et al. 1978. Fate and effects of cadmium in an experimental marine ecosystem. Helgolander wiss Meeresunters. 31: 471.

Westernhagen, H.V., et al. 1979. Combined effects of cadmium, copper and lead on developing herring eggs and larvae. Helgolander wiss. Meeresunters. 32: 257.

White, D.H. and M.T. Finley. 1978a. Effects of Dietary Cadmium in Mallard Ducks. In: D.D. Hemphill (ed.), Trace Substances in Environmental Health-XII. University of Missouri, Columbia, Missouri.

White, D.H. and M.T. Finley. 1978b. Uptake and retention of dietary cadmium in mallard ducks. Environ. Res. 17: 53.

White, D.H., et al. 1978. Histopathologic effects of dietary cadmium on kidneys and testes of mallard ducks. J. Toxicol. Environ. Health. 4: 331.

Wier, C.F. and W.M. Walter. 1976. Toxicity of cadmium in the freshwater snail, Physa gyrina Say. Jour. Environ. Qual. 5: 359.

Williams, D.R. and J.P. Giesy, Jr. 1978. Relative importance of food and water sources to cadmium uptake by Gambusia affinis (Poeciliidae). Environ. Res. 16: 326.

Wright, D.A. 1977. The effect of salinity on cadmium uptake by the tissues of the shore crab, Carcinus maenas. Exp. Biol. 67: 137.

Wright, D.A. and J.W. Frain. 1981. Cadmium toxicity in Marinogammarus obtusatus: effect of external calcium. Environ. Res. 24: 338.

Yager, C.M. and H.W. Harry. 1964. The uptake of radioactive zinc, cadmium and copper by the freshwater snail, Taphius glabratus. Malacologia 1: 339.

Zaroogian, G.E. 1979. Studies on the depuration of cadmium and copper by the American oyster Crassostrea virginica. Bull. Environ. Contam. Toxicol. 23: 117.

Zaroogian, G.E. and S. Cheer. 1976. Cadmium accumulation by the American oyster, Crassostrea virginica. Nature 261: 408.