Environmental Protection Agency

Regulations and Standards
Criteria and Standards Division
Washington, DC 20460

January 1985

Water

EPA

Ambient Water Quality Criteria for

Arsenic - 1984

AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR

ARSENIC

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RESEARCH AND DEVELOPMENT
ENVIRONMENTAL RESEARCH LABORATORIES
DULUTH, MINNESOTA
NARRAGANSETT, RHODE ISLAND

DISCLAIMER

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

AVAILABILITY NOTICE

This document is available to the public through the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161.
NTIS ACCESSION NUMBER - PB85-227445.

FOREWORD

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

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

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

Edwin L. Johnson
Director
Office of Water Regulations and Standards

ACKNOWLEDGMENTS

Robert L. Spehar
(freshwater author)
Environmental Research Laboratory
Duluth, Minnesota

John H. Gentile
(saltwater author)
Environmental Research Laboratory
Narragansett, Rhode Island

Charles E. Stephan
(document coordinator)
Environmental Research Laboratory
Duluth, Minnesota

David J. Hansen
(saltwater coordinator)
Environmental Research Laboratory
Narragansett, Rhode Island

Clerical Support: Terry L. Highland

CONTENTS

TABLES

Introduction*

Arsenic is found in all living organisms, including those in aquatic systems. Little is known about the mechanisms of arsenic toxicity to aquatic organisms; however, arsenic readily forms stable bonds to sulfur and carbon in organic compounds. Like mercury, arsenic(III) reacts with sulfhydryl groups of proteins; enzyme inhibition by this mechanism may be the primary mode of toxicity. Arsenic(V) does not react with sulfhydryl groups as readily but may uncouple oxidative phosphorylation (Fowler, et al. 1977; Schiller, et al. 1977).

The chemistry of arsenic in water is complex, consisting of chemical, biochemical, and geochemical reactions which together control the concentration, oxidation state, and form of arsenic in water (Braman, 1983; Callahan, et al. 1979; Holm, et al. 1979; Scudlark and Johnson, 1982). Four arsenic species common in natural waters are inorganic arsenic(III) and arsenic(V), methanearsonic acid, and dimethylarsinic acid. In aerobic water, inorganic arsenic(III) is slowly oxidized to arsenic(V) at neutral pH, but the reaction proceeds measurably in several days in strongly alkaline or acidic solutions. Because the chemical and toxicological properties of the forms appear to be quite different and the toxicities of the forms have not been shown to be additive, the data for inorganic arsenic(III), inorganic arsenic(V), monosodium methanearsonate (MSMA), and other arsenic compounds will be treated separately. Methods have been developed for separately measuring these forms of arsenic in water (Fichlin, 1983; Grabinski, 1981; Irgolic, 1982).

---

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

Because of the variety of forms of inorganic arsenic(III) and inorganic arsenic(V) and lack of definitive information about their relative toxicities, no available analytical measurement is known to be ideal for expressing aquatic life criteria for arsenic. Previous aquatic life criteria for arsenic (U.S. EPA, 1980) were expressed in terms of total recoverable inorganic arsenic(III), but the total recoverable method cannot distinguish between inorganic arsenic(III) and arsenic(V). Acid-soluble arsenic(III) (operationally defined as the arsenic(III) that passes through a 0.45 μm membrane filter after the sample is acidified to pH = 1.5 to 2.0 with nitric acid) and acid-soluble arsenic(V) are probably the best measurements at the present for the following reasons:

1. These measurements are compatible with all available data concerning toxicity of arsenic to, and bioaccumulation of arsenic by, aquatic organisms. No test results were rejected just because it was likely that they would have been substantially different if they had been reported in terms of acid-soluble arsenic.
2. On samples of ambient water, measurement of acid-soluble arsenic(III) and arsenic(V) should measure all forms of arsenic that are toxic to aquatic life or can be readily converted to toxic forms under natural conditions. In addition, these measurements should not measure several forms, such as arsenic that is occluded in minerals, clays, and sand or is strongly sorbed to particulate matter, that are not toxic and are not likely to become toxic under natural conditions.
3. Although water quality criteria apply to ambient water, the measurements used to express criteria are likely to be used to measure arsenic in aqueous effluents. Measurements of acid-soluble arsenic(III) and

arsenic(V) should be applicable to effluents. If desired, dilution of effluent with receiving water before measurement of acid-soluble arsenic might be used to determine whether the receiving water can decrease the concentration of acid-soluble arsenic because of sorption. However, the relationship between what is in an effluent and what will result in the receiving water should take into account any conversion of one oxidation state of arsenic to the other.

4. The acid-soluble measurement should be useful for most metals, thus minimizing the number of samples and procedures that are necessary.
5. The acid-soluble measurement does not require filtration at the time of collection, as does the dissolved measurement.
6. For the measurement of total acid-soluble arsenic the only treatment required at the time of collection is preservation by acidification to pH = 1.5 to 2.0, similar to that required for the measurement of total recoverable arsenic. Durations of 10 minutes to 24 hours between acidification and filtration probably will not affect the measurement of total acid-soluble arsenic. However, acidification might not prevent conversion of inorganic arsenic(III) to arsenic(V) or vice versa. Therefore, measurement of acid-soluble arsenic(III) or acid-soluble arsenic(V) or both will probably require separation or measurement at the time of collection of the sample or special preservation to prevent conversion of one oxidation state of arsenic to the other.
7. The carbonate system has a much higher buffer capacity from pH = 1.5 to 2.0 than it does from pH = 4 to 9 (Weber and Stumm, 1963).
8. Differences in pH within the range of 1.5 to 2.0 probably will not affect the result substantially.

9. The acid-soluble measurement does not require a digestion step, as does the total recoverable measurement.
10. After acidification and filtration of the sample to isolate the acid-soluble arsenic, the analysis can be performed using either atomic absorption spectroscopy or ICP-emission spectroscopy for either total acid-soluble arsenic or total acid-soluble inorganic arsenic (U.S. EPA, 1983a). It might be possible to separately measure acid-soluble arsenic(III) and acid-soluble arsenic(V) using the methods described by Grabinski (1981) and Irgolic (1982).
11. It is not possible to separately measure total recoverable arsenic(III) and total recoverable arsenic(V).

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

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

Acute Toxicity to Aquatic Animals

Inglis and Davis (1972) found that hardness did not affect the toxicity of inorganic arsenic(III) to the bluegill. The fathead minnow was much less sensitive to arsenic trisulfide (Table 6) than to sodium arsenite (Table 1). Genus Mean Acute Values (Table 3) were calculated as geometric means of the sixteen available Species Mean Acute Values (Table 1). Acute values are available for two species in each of two genera and the range of Species Mean Acute Values within each genus is less than a factor of 3.3. Four crustacean genera are much more sensitive than the other tested invertebrate and fish genera. Both the most resistant genus, *Tanytarsus*, and the most sensitive genus, *Gammarus*, are invertebrates, but *Gammarus* is 110 times more sensitive than *Tanytarsus*. A freshwater Final Acute Value of 718.2 µg/L for inorganic arsenic(III) was calculated from the Genus Mean Acute Values (Table 3) using the calculation procedure described in the Guidelines.

Acute tests have been conducted on inorganic arsenic(V) with six species in five genera and the Species Mean Acute Values ranged from 850 µg/L for a cladoceran to 49,000 µg/L for the mosquitofish (Table 1). Inorganic arsenic(V) was slightly more toxic than arsenic(III) to rainbow trout, but arsenic(III) was nearly twice as toxic to the fathead minnow and *Daphnia magna*.

The acute sensitivities of eight species exposed to MSMA range from 1,921 μg/L for the bluegill to 1,403,000 μg/L for the channel catfish (Table 1). The fathead minnow was approximately 12 times more sensitive to MSMA than to sodium arsenate and the goldfish, fathead minnow, and bluegill were approximately 5 to 22 times more sensitive to MSMA than to sodium arsenite. Channel catfish and amphipods, however, were much less sensitive to MSMA than sodium arsenite.

Not enough acute values are available for calculation of freshwater Final Acute Values for inorganic arsenic(V) or MSMA.

Data are available on the acute toxicity of inorganic arsenic(III) to saltwater species in three fish and eight invertebrate genera (Tables 1 and 3). The fish species tested were the most resistant with a range of LC50s from 12,700 μg/L for the sheepshead minnow to 16,030 μg/L for the Atlantic silverside. Among the invertebrates, the lowest acute value, 232 μg/L, was obtained with zoeae of the Dungeness crab whereas the highest value, 10,120 μg/L, was from a test with the polychaete worm, Neanthes arenaceodentata. Interestingly, the acute value for the Pacific oyster is almost as low as that for the Dungeness crab, but that for the eastern oyster is almost as high as that for the polychaete worm. In addition, Alderdice and Brett (1957) obtained a 48-hr LC50 of 8,300 μg/L with arsenic trioxide to chum salmon (Table 6). Holland, et al. (1960) determined a 10-day LC54 of 3,787 μg/L for the pink salmon, whereas Curtis, et al. (1979) reported a 96-hr LC50 of 24,700 μg/L for arsenic trisulfide in tests with juvenile white shrimp (Table 6). Of the eleven Genus Mean Acute Values in Table 3, all eight for invertebrates are lower than the three for fish. The most sensitive genus, Cancer, is 69 times more sensitive than the most resistant, Menidia. The saltwater Final Acute Value for inorganic arsenic(III) is 137.1 μg/L, which is about one-half the lowest Species Mean Acute Value.

Data are available for inorganic arsenic(V) with two saltwater species. The toxicity of arsenic(V) to a mysid, Mysidopsis bahia, (LC50 = 2,319 μg/L) is similar to that of arsenic(III) (LC50 = 1,740 μg/L). Arsenic(V) is more toxic than arsenic(III) to the amphipod, Ampelisca abdita, whose Species Mean Acute Values are 4,610 μg/L for arsenic(V) and 8,227 μg/L for arsenic(III). Not enough data are available to calculate a saltwater Final Acute Value for inorganic arsenic(V).

Chronic Toxicity to Aquatic Animals

Three chronic tests have been conducted on inorganic arsenic(III) with freshwater species (Table 2). A life-cycle test with Daphnia magna (Call, et al. 1983; Lima, et al. 1984) resulted in a chronic value of 914.1 μg/L based on chronic limits of 633.0 and 1,320 μg/L. The 96-hr LC50 for this species in the same study was 4,340 μg/L, resulting in an acute-chronic ratio of 4.748. The chronic values for the fathead minnow and flagfish exposed to arsenic(III) were approximately the same. The 96-hr LC50 values for the two species were also similar and the acute-chronic ratios were 4.660 and 4.862, respectively.

Data on the chronic toxicity of arsenic to saltwater species are available for only one species, Mysidopsis bahia (Table 2). In a 35-day life-cycle test on arsenic(III), no adverse effects were statistically significant at 631 μg/L, whereas 1,270 μg/L affected reproduction and significantly reduced survival. These results provide a chronic value of 895.2 μg/L and an acute-chronic ratio of 1.944.

The four acute-chronic ratios available for inorganic arsenic(III) are 4.748, 4.660, 4.862, and 1.944 and the geometric mean of 3.803 is the Final Acute-Chronic Ratio. Division of the freshwater and saltwater Final Acute Values by this ratio results in freshwater and saltwater Final Chronic Values of 188.9 and 36.05 µg/L, respectively (Table 3).

An early life-stage test with the fathead minnow (DeFoe, 1982) exposed to arsenic(V) resulted in chronic limits of 530 and 1,500 µg/L and a chronic value of 891.6 µg/L. The 96-hr LC50 for this species in the same study was 25,600 µg/L producing an acute-chronic ratio of 28.71 (Table 2). A life-cycle test with <u>Daphnia magna</u> (Biesinger and Christensen, 1972) (Table 6) exposed to arsenic(V) was not used in the calculation of a chronic value because the test concentrations were not measured as specified in the Guidelines. However, the chronic limits in this test were 520 and 1,400 µg/L and the comparable acute value was 7,400 µg/L, resulting in an estimated acute-chronic ratio of 8.7.

The fathead minnow was approximately 3 times more sensitive on a chronic basis to arsenic(V) than to arsenic(III), but <u>Daphnia magna</u> appeared to be equally sensitive to both forms of inorganic arsenic. No chronic tests have been conducted on MSMA or any other organic arsenic compound.

<u>Toxicity to Aquatic Plants</u>

Adverse effects were observed at concentrations of arsenic(III) ranging from 2,320 µg/L for three species of algae and one submerged plant to over 59,000 µg/L for the alga, <u>Selenastrum capricornutum</u> (Table 4). Except for <u>S. capricornutum</u>, values reported for aquatic plants exposed to arsenic(III) are comparable to the acute values for some of the more sensitive invertebrate species (Table 1) and to the chronic values reported for the fathead minnow and flagfish (Table 2).

Concentrations of inorganic arsenic(V) that caused adverse effects on six species of freshwater algae ranged from 48 to 202,000 µg/L (Table 4). A 14-day EC50 value of 48 µg/L obtained for the most sensitive alga, Scenedesmus obliquus, was 18 times lower than the lowest acute value and approximately 19 times lower than the only chronic value available for inorganic arsenic(V). Data on the sensitivity of S. capricornutum to both oxidation states of inorganic arsenic cover a wide range and appear to depend on the kind of toxicity test used (Richter, 1982).

Data on the toxicity of arsenic(III) to saltwater plants are available for four species of microalgae and two species of macroalgae (Table 4). Growth of the saltwater diatoms, Skeletonema costatum and Thalassiosira aestivalis, was affected at 20 µg/L and 22 µg/L, respectively, and photosynthesis of S. costatum was reduced at 19 µg/L. These values are less than the Final Chronic Value for arsenic(III) but the ecological implications of reduced growth on these species is uncertain. Boney, et al. (1959) showed that arsenic(III) inhibited the development of sporelings of the red macroalga, Plumana elegans, at 577 µg/L. In addition, formation of mature cystocarps by another red macroalgae, Champia parvula, was prevented at 95 µg/L and growth of female plants was reduced at 145 µg/L.

Data on the toxicity of arsenic(V) to saltwater plants are available for four species of microalgae and one species of macroalgae (Table 4). Based upon these data, there is no significant difference between the toxicity of arsenic(III) and arsenic(V) to the plant species tested. Thursby and Steele (1984) found that phosphate decreased the toxicity of arsenic(V) to Champia parvula, but did not affect the toxicity of arsenic(III).

Bioaccumulation

Bioconcentration tests have been conducted on arsenic(III), arsenic(V), and a number of organic arsenic compounds with a variety of freshwater fish and invertebrates (Table 5). The highest bioconcentration factor (BCF) was 17, which was obtained for inorganic arsenic(III) with a snail (Spehar, et al. 1980). An early life-stage test on arsenic(V) with the fathead minnow (DeFoe, 1982) showed that the BCF decreased with increased exposure concentrations in the water. BCFs were slightly lower (down to 1.2) in exposure concentrations that caused significant adverse effects than in those that did not (Table 5).

A study by Oladimeji, et al. (1982) showed that the pretreatment of rainbow trout to arsenic(III) enhanced the elimination of a subsequent dose of arsenic. Additional results indicated that fish retained less arsenic after 4 weeks of exposure than after 2 weeks.

In the one acceptable bioconcentration test on arsenic with a saltwater species, a BCF of 350 was obtained with the oyster, Crassostrea virginica, after 112 days of exposure (Zaroogian and Hoffman, 1982). In a test that only lasted 4 days, Nelson, et al. (1976) obtained a BCF of 15 with the bay scallop (Table 6).

No Final Residue Value could be determined because no maximum permissible tissue concentration is available for arsenic.

Other Data

Comparison of data for fish in Tables 1 and 6 indicates that in almost all cases, arsenic toxicity increased with increased duration of exposure. One value for the bluegill (Hughes and Davis, 1967) was an exception resulting in a low 48-hr LC50 of 290 µg/L. A special pelletized form of sodium arsenite was used, which may have accounted for the low LC50. The invertebrate data were too variable to indicate a trend in toxicity in regard to duration of exposure.

Spehar, et al. (1980) compared the toxicities of different forms of arsenic in the same water. In 28-day tests, inorganic arsenic(III) was more toxic to the amphipod, Gammarus pseudolimnaeus, than inorganic arsenic(V), sodium dimethyl arsenate, or disodium methyl arsenate. Survival of stoneflies, snails, and rainbow trout was not adversely affected by any of the compounds at the concentrations tested.

Two studies on the effects of environmental factors on the toxicity of arsenic to freshwater organisms have been reported. Sorenson (1976c) showed that increased water temperature decreased the median lethal time of green sunfish during exposure to two concentrations of arsenic(V) (Table 6). Lima, et al. (1984) found that the toxicity of inorganic arsenic(III) to Daphnia magna was decreased by about a factor of 3 when food was added in 48-hr tests compared to exposures in which food was not added. Additional exposures showed that arsenic(III) did not affect additional unfed animals from 48 to 96 hours, indicating that the lack of food in these tests was not too stressful. Arsenic(III) increased albinism in channel catfish (Westerman and Birge, 1978).

Exposures of embryos and larvae of rainbow trout and goldfish to inorganic arsenic(III) resulted in values that were several times lower than those for older juvenile stages of these species (Tables 1 and 6), and these values were lower than the chronic values in Table 2. The lowest value obtained in any test on arsenic, however, was 40 µg/L from a 7-day exposure of embryos and larvae of the toad, Gastrophryne carolinensis, to inorganic arsenic(III) (Birge, 1978). This value is about a factor of 4.5 lower than the freshwater Final Chronic Value for inorganic arsenic(III).

Bryan (1976) exposed the saltwater polychaete worm, Nereis diversicolor, to arsenic(III) and estimated the 192-hr LC50 to be greater than 14,500 μg/L (Table 6). Arsenic(III) caused other effects, such as depressed oxygen consumption rate and behavioral changes, in mud snails exposed to concentrations greater than 2,000 ug/L for 72 hours (MacInnes and Thurberg, 1973).

Unused Data

Some data on the effects of arsenic on aquatic organisms were not used because the studies were conducted with species that are not resident in North America. Data were not used if arsenic was a component of a mixture (Thomas, et al. 1980; Wong, et al. 1982). Reviews by Chapman, et al. (1968), Eisler (1981), Eisler, et al. (1979), Kaiser (1980), Phillips and Russo (1978), Taylor (1981), Thompson, et al. (1972), and U.S. EPA (1975, 1976b) only contain data that had been published elsewhere.

Data in Dabrowski (1976), Paladino (1976), and Paladino and Spotila (1978) and one value in Mount and Norberg (1984) were not used because control survival was too low. Studies by Eipper (1959), Grindley (1946), Irgolic, et al. (1977), and Spotila and Paladino (1979) were not used because insufficient detail was reported about such items as use of controls and control survival or because methodology problems occurred during the tests which made the results questionable. Bringmann and Kuhn (1982) cultured Daphnia magna in one water but conducted tests in another water. Tests by Comparetto, et al. (1982), Jones (1940, 1941), Schaefer and Pipes (1973), Stary and Kratzer (1982), and Weir and Hine (1970) were not included because the medium or dilution water was unacceptable.

Papers by Baker, et al. (1983), Belding (1927), Brunskill, et al. (1980), Budd and Craig (1981), Christensen (1971), Christensen and Tucker (1976), Christensen and Zielski (1980), Conway (1978), Devi Prasad and Chowdary (1981), Hiltibran (1967), Jennett, et al. (1982), Lawrence (1958), Maeda, et al. (1983), McLarty (1960), Morris, et al. (1984), Nissen and Benson (1982), Oladimeji, et al. (1979, 1982, 1984b), Ontario Water Resources Commission (1959), Penrose (1975), Planas and Lamarche (1983), Surber (1943), and Westerman and Birge (1978) were not used because the species names were not given, the concentrations causing effects or the effect endpoints were not clearly reported or defined, or no test effects were given. Johnson (1978) was not used because the fish were not acclimated to the test water for a sufficient amount of time after collection from the field. A study by Passino and Kramer (1980) on the effects of arsenic on Lake Superior cisco fry was not used because fry were obtained from eggs and sperm of two different species.

Several papers dealing with the accumulation of arsenic in aquatic organisms, including those by Brooks, et al. (1982), Bryan, et al. (1983), Copeland, et al. (1973), Dupree (1960), Ellis (1937), Ellis, et al. (1941), Foley, et al. (1978), Gibbs, et al. (1983), Harden (1976), Hunter, et al. (1981), La Touche and Mix (1982), Maher (1983), Martin, et al. (1984), May and McKinney (1981), Mehrle, et al. (1982), Pennington, et al. (1982), Reay (1972), Sandhu (1977), Sohacki (1968), Sorenson, et al. (1979, 1980), Stary, et al. (1982), Tsui and McCart (1981), Wagemann, et al. (1978), Whyte and Englar (1983), and Wiebe, et al. (1931), were not used because the tests were conducted in distilled water, were not long enough, or were not flow-through, or because the concentration of arsenic in the test solution during the test varied unacceptably or was unknown. BCFs calculated by Anderson, et al. (1979), Isensee, et al. (1973), Klumpp and Peterson (1981), Schuth, et al. (1974), and Woolson, et al. (1976) were not used because they were calculated from microcosm or model ecosystem studies in which water concentrations decreased with time or were obtained after short exposures before steady-state was reached.

Summary

The chemistry of arsenic in water is complex and the form present in solution is dependent on such environmental conditions as Eh, pH, organic content, suspended solids, and sediment. The relative toxicities of the various forms of arsenic apparently vary from species to species. For inorganic arsenic(III) acute values for sixteen freshwater animal species ranged from 812 µg/L for a cladoceran to 97,000 µg/L for a midge, but the three acute-chronic ratios only ranged from 4.660 to 4.862. The five acute values for inorganic arsenic(V) covered about the same range, but the single acute-chronic ratio was 28.71. The six acute values for MSMA ranged from 3,243 to 1,403,000 µg/L. The freshwater residue data indicated that arsenic is not bioconcentrated to a high degree but that lower forms of aquatic life may accumulate higher arsenic residues than fish. The low bioconcentration factor and short half-life of arsenic in fish tissue suggest that residues should not be a problem to predators of aquatic life.

The available data indicate that freshwater plants differ a great deal as to their sensitivity to arsenic(III) and arsenic(V). In comparable tests, the alga, Selenastrum capricornutum, was 45 times more sensitive to arsenic(V) than to arsenic(III), although other data present conflicting information on the sensitivity of this alga to arsenic(V). Many plant values for inorganic arsenic(III) were in the same range as the available chronic values for freshwater animals; several plant values for arsenic(V) were lower than the one available chronic value.

The other toxicological data revealed a wide range of toxicity based on tests with a variety of freshwater species and endpoints. Tests with early life stages appeared to be the most sensitive indicator of arsenic toxicity. Values obtained from this type of test with inorganic arsenic(III) were lower than chronic values contained in Table 2. For example, an effect concentration of 40 μg/L was obtained in a test on inorganic arsenic(III) with embryos and larvae of a toad.

Twelve species of saltwater animals have acute values for inorganic arsenic(III) from 232 to 16,030 μg/L and the single acute-chronic ratio is 1.945. The only values available for inorganic arsenic(V) are for two invertebrates and are between 2,000 and 3,000 μg/L. Arsenic(III) and arsenic(V) are equally toxic to various species of saltwater algae, but the sensitivities of the species range from 19 μg/L to more than 1,000 μg/L. In a test with an oyster, a BCF of 350 was obtained for inorganic arsenic(III).

National Criteria

The procedures described in the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" indicate that, except possibly where a locally important species is very sensitive, freshwater aquatic organisms and their uses should not be affected unacceptably if the four-day average concentration of arsenic(III) does not exceed 190 μg/L more than once every three years on the average and if the one-hour average concentration does not exceed 360 μg/L more than once every three years on the average.

The procedures described in the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" indicate that, except possibly where a locally important species is very sensitive, saltwater aquatic organisms and their uses should not be affected unacceptably if the four-day average concentration of arsenic(III) does not exceed 36 μg/L more than once every three years on the average and if the one-hour average concentration does not exceed 69 μg/L more than once every three years on the average. This criterion might be too high wherever Skeletonema costatum or Thalassiosira aestivalis are ecologically important.

Not enough data are available to allow derivation of numerical national water quality criteria for freshwater aquatic life for inorganic arsenic(V) or any organic arsenic compound. Inorganic arsenic(V) is acutely toxic to freshwater aquatic animals at concentrations as low as 850 μg/L and an acute-chronic ratio of 28 was obtained with the fathead minnow. Arsenic(V) affected freshwater aquatic plants at concentrations as low as 48 μg/L. Monosodium methanearsenate (MSMA) is acutely toxic to aquatic animals at concentrations as low as 1,900 μg/L, but no data are available concerning chronic toxicity to animals or toxicity to plants.

Very few data are available concerning the toxicity of any form of arsenic other than inorganic arsenic(III) to saltwater aquatic life. The available data do show that inorganic arsenic(V) is acutely toxic to saltwater animals at concentrations as low as 2,319 μg/L and affected some saltwater plants at 13 to 56 μg/L. No data are available concerning the chronic toxicity of any form of arsenic other than inorganic arsenic(III) to saltwater aquatic life.

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

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

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

Table 1. Acute Toxicity of Arsenic to Aquatic Animals

Species	Method*	Chemical	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)**	Reference
		FRESHWATER SPECIES			
		Inorganic Arsenic(III)			
Snail, *Aplexa hypnorum*	S, M	Arsenic trioxide	24,500	24,500	Holcombe, et al. 1983
Cladoceran, *Ceriodaphnia reticulata*	S, U	-	1,800	1,800	Mount & Norberg, 1984
Cladoceran, *Daphnia magna*	S, U	Sodium arsenite	5,278	-	Anderson, 1946
Cladoceran, *Daphnia magna*	S, U	-	3,800	-	Mount & Norberg, 1984
Cladoceran, *Daphnia magna*	S, M	Sodium arsenite	4,340	4,432	Call, et al. 1983; Lima, et al. 1984
Cladoceran, *Daphnia pulex*	S, U	Sodium arsenite	1,044	-	Sanders & Cope, 1966
Cladoceran, *Daphnia pulex*	S, U	Sodium arsenite	1,740	1,348	Johnson & Finley, 1980
Cladoceran, *Simocephalus serrulatus*	S, U	Sodium arsenite	812	812	Sanders & Cope, 1966
Cladoceran, *Simocephalus vetulus*	S, U	-	1,700	1,700	Mount & Norberg, 1984
Amphipod, *Gammarus pseudolimnaeus*	FT, M	Sodium arsenite	874	874	Call, et al. 1983; Lima, et al. 1984
Stonefly, *Pteronarcys californica*	S, U	Sodium arsenite	22,040	22,040	Sanders & Cope, 1968; Johnson & Finley, 1980
Midge, *Tanytarsus dissimilis*	S, M	Arsenic trioxide	97,000	97,000	Holcombe, et al. 1983
Rainbow trout, *Salmo gairdneri*	S, U	Sodium arsenite	13,340	13,340	Johnson & Finley, 1980

Table 1. (Continued)

Species	Method*	Chemical	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)**	Reference
Brook trout, *Salvelinus fontinalis*	FT, M	Sodium arsenite	14,960	14,960	Cardwell, et al. 1976
Goldfish (juvenile), *Carassius auratus*	FT, M	Sodium arsenite	26,040	26,040	Cardwell, et al. 1976
Fathead minnow, (juvenile) *Pimephales promelas*	FT, M	Sodium arsenite	15,660	-	Cardwell, et al. 1976
Fathead minnow (juvenile), *Pimephales promelas*	FT, M	Sodium arsenite	14,100	14,860	Call, et al. 1983; Lima, et al. 1984
Channel catfish (fingerling), *Ictalurus punctatus*	S, U	Sodium arsenite	15,022	-	Clemens & Sneed, 1959
Channel catfish (juvenile), *Ictalurus punctatus*	FT, M	Sodium arsenite	18,096	18,100	Cardwell, et al. 1976
Flagfish (fry), *Jordanella floridae*	FT, M	Sodium arsenite	28,130	-	Cardwell, et al. 1976
Flagfish (juvenile), *Jordanella floridae*	FT, M	Sodium arsenite	14,400	20,130	Call, et al. 1983; Lima, et al. 1984
Bluegill, *Lepomis macrochirus*	S, U	Sodium arsenite	15,370	-	Inglis & Davis, 1972
Bluegill, *Lepomis macrochirus*	S, U	Sodium arsenite	16,240	-	Inglis & Davis, 1972
Bluegill, *Lepomis macrochirus*	S, U	Sodium arsenite	15,486	-	Inglis & Davis, 1972
Bluegill, *Lepomis macrochirus*	S, U	Sodium arsenite	17,400	-	Johnson & Finley, 1980
Bluegill (juvenile), *Lepomis macrochirus*	FT, M	Sodium arsenite	41,760	41,760	Cardwell, et al. 1976

Table 1. (Continued)

Species	Method*	Chemical	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)**	Reference
		Inorganic Arsenic(V)			
Cladoceran, *Daphnia magna*	S, U	Sodium arsenate	<8,100***	-	Anderson, 1946
Cladoceran, *Daphnia magna*	S, U	Sodium arsenate	7,400	7,400	Biesinger & Christensen, 1972
Cladoceran, *Daphnia pulex*	S, M	Sodium arsenate	3,600	-	Jurewicz & Bulkema, 1980
Cladoceran, *Daphnia pulex*	S, M	Sodium arsenate	49,600	****	Passino & Novak, 1984
Cladoceran, *Bosmina longirostris*	S, M	Sodium arsenate	850	850	Passino & Novak, 1984
Rainbow trout (2 mos), *Salmo gairdneri*	FT, M	Sodium arsenate*****	10,800	10,800	Hale, 1977
Fathead minnow (juvenile), *Pimephales promelas*	FT, M	Sodium arsenate	25,600	25,600	DeFoe, 1982
Mosquitofish, *Gambusia affinis*	S, M	Sodium arsenate	49,000	49,000	Jurewicz & Bulkema, 1980
		Monosodium Methanearsonate (MSMA)			
Amphipod, *Gammarus fasciatus*	S, U	Monosodium methanearsonate	>16,010	>16,010	Johnson & Finley, 1980
Crayfish, *Procambarus* sp.	S, U	Monosodium methanearsonate	506,000	506,000	Anderson, et al. 1975
Cutthroat trout, *Salmo clarki*	S, U	Monosodium methanearsonate	>16,010	>16,010	Johnson & Finley, 1980
Goldfish, *Carassius auratus*	S, U	Monosodium methanearsonate	4,978	4,978	Johnson & Finley, 1980

Table 1. (Continued)

Species	Method*	Chemical	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)**	Reference
Fathead minnow, *Pimephales promelas*	S, U	Monosodium methanearsonate	2,129	2,129	Johnson & Finley, 1980
Channel catfish, *Ictalurus punctatus*	S, U	Monosodium methanearsonate	1,403,000	1,403,000	Anderson, et al. 1975
Bluegill, *Lepomis macrochirus*	S, U	Monosodium methanearsonate	1,921	1,921	Johnson & Finley, 1980
Smallmouth bass (fingerling), *Micropterus dolomieui*	S, U	Monosodium methanearsonate	414,000	414,000	Anderson, et al. 1975
		SALTWATER SPECIES			
		Inorganic Arsenic(III)			
Polychaete worm, *Neanthes arenaceodentata*	FT, M	Sodium arsenite	10,120	10,120	Scott and Pesch, 1981
Blue mussel (embryo), *Mytilus edulis*	S, U	Sodium arsenite	>3,000	>3,000	Martin, et al. 1981
Bay scallop (juvenile), *Argopecten irradians*	R, U	Sodium arsenite	3,490	3,490	Nelson, et al. 1976
Pacific oyster (embryo), *Crassostrea gigas*	S, U	Sodium arsenite	326	326	Martin, et al. 1981
Eastern oyster (larvae), *Crassostrea virginica*	S, U	Sodium arsenite	7,500	7,500	Calabrese, et al. 1973
Copepod, *Acartia clausi*	S, U	Sodium arsenite	508	508	Gentile, 1981
Mysid, *Mysidopsis bahia*	FT, M	Sodium arsenite	1,740	1,740	Lussier, et al. Manuscript
Amphipod, *Ampelisca abdita*	FT, M	Sodium arsenite	8,000	-	Scott, et al. Manuscript

Table 1. (Continued)

Species	Method*	Chemical	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)**	Reference
Amphipod, *Ampelisca abdita*	FT, M	Sodium arsenite	8,460	8,227	Scott, et al. Manuscript
Dungeness crab (zoea), *Cancer magister*	S, U	Sodium arsenite	232	232	Martin, et al. 1981
Sheepshead minnow, *Cyprinodon variegatus*	FT, M	Sodium arsenite	12,700	12,700	Cardin, 1982
Atlantic silverside, *Menidia menidia*	S, U	Sodium arsenite	16,033	16,033	Cardin, 1982
Fourspine stickleback, *Apeltes quadracus*	S, U	Sodium arsenite	14,953	14,953	Cardin, 1982
		Inorganic Arsenic(V)			
Mysid, *Mysidopsis bahia*	FT, M	Sodium arsenate	2,319	2,319	Gentile, 1981
Amphipod, *Ampelisca abdita*	FT, M	Sodium arsenate	5,110	-	Scott, et al. Manuscript
Amphipod, *Ampelisca abdita*	FT, M	Sodium arsenate	4,160	4,611	Scott, et al. Manuscript

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

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

*** Not used in calculations.

**** No Species Mean Acute Value calculated because acute values are too divergent for this species.

*****Hale confirmed that compound tested was Na_2HAsO_4, not $NaAsO_2$.

Table 2. Chronic Toxicity of Arsenic to Aquatic Animals

Species	Test*	Chemical	Limits (µg/L)**	Chronic Value (µg/L)**	Reference
		FRESHWATER SPECIES			
		Inorganic Arsenic(III)			
Cladoceran, *Daphnia magna*	LC	Sodium arsenite	633.0-1,320	914.1	Call, et al. 1983; Lima, et al. 1984
Fathead minnow, *Pimephales promelas*	ELS	Sodium arsenite	2,130-4,300	3,026	Call, et al. 1983; Lima, et al. 1984
Flagfish, *Jordanella floridae*	ELS	Sodium arsenite	2,130-4,120	2,962	Call, et al. 1983; Lima, et al. 1984
		Inorganic Arsenic(V)			
Fathead minnow, *Pimephales promelas*	ELS	Sodium arsenate	530-1,500	891.6	DeFoe, 1982
		SALTWATER SPECIES			
		Inorganic Arsenic(III)			
Mysid, *Mysidopsis bahia*	LC	Sodium arsenite	631-1,270	895.2	Lussier, et al. Manuscript

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

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

Acute-Chronic Ratio

Species	Acute Value (µg/L)	Chronic Value (µg/L)	Ratio
	Inorganic Arsenic(III)		
Cladoceran, *Daphnia magna*	4,340	914.1	4.748

Table 2. (Continued)

Acute-Chronic Ratio

Species	Acute Value (µg/L)	Chronic Value (µg/L)	Ratio
Fathead minnow, *Pimephales promelas*	14,100	3,026	4.660
Flagfish, *Jordanella floridae*	14,400	2,962	4.862
Mysid, *Mysidopsis bahia*	1,740	895.2	1.944
Inorganic Arsenic(V)			
Fathead minnow, *Pimephales promelas*	25,600	891.6	28.71

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

Rank*	Genus Mean Acute Value (µg/L)	Species	Species Mean Acute Value (µg/L)	Species Mean Acute-Chronic Ratio
		FRESHWATER SPECIES		
		Inorganic Arsenic(III)		
14	97,000	Midge, *Tanytarsus dissimilis*	97,000	-
13	41,760	Bluegill, *Lepomis macrochirus*	41,760	-
12	26,040	Goldfish, *Carassius auratus*	26,040	-
11	24,500	Snail, *Aplexa hypnorum*	24,500	-
10	22,040	Stonefly, *Pteronarcys californica*	22,040	-
9	20,130	Flagfish, *Jordanella floridae*	20,130	4.862
8	18,100	Channel catfish, *Ictalurus punctatus*	18,100	-
7	14,960	Brook trout, *Salvelinus fontinalis*	14,960	-
6	14,860	Fathead minnow, *Pimephales promelas*	14,860	4.660
5	13,340	Rainbow trout, *Salmo gairdneri*	13,340	-
4	2,444	Cladoceran, *Daphnia magna*	4,432	4.748
		Cladoceran, *Daphnia pulex*	1,348	-
3	1,800	Cladoceran, *Ceriodaphnia reticulata*	1,800	-

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)	Species	Species Mean Acute Value (µg/L)	Species Mean Acute-Chronic Ratio
2	1,175	Cladoceran, *Simocephalus serrulatus*	812	-
		Cladoceran, *Simocephalus vetulus*	1,700	-
1	874	Amphipod, *Gammarus pseudolimnaeus*	874	-
		SALTWATER SPECIES		
		Inorganic Arsenic(III)		
11	16,030	Atlantic silverside, *Menidia menidia*	16,033	-
10	14,950	Fourspine stickleback, *Apeltes quadracus*	14,953	-
9	12,700	Sheepshead minnow, *Cyprinodon variegatus*	12,700	-
8	10,120	Polychaete worm, *Neanthes arenaceodentata*	10,120	-
7	8,227	Amphipod, *Ampelisca abdita*	8,227	-
6	3,490	Bay scallop, *Argopecten irradians*	3,490	-
5	>3,000	Blue mussel, *Mytilus edulis*	>3,000	-
4	1,740	Mysid, *Mysidopsis bahia*	1,740	1.944

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)	Species	Species Mean Acute Value (µg/L)	Species Mean Acute-Chronic Ratio
3	1,564	Pacific oyster, *Crassostrea gigas*	326	-
		Eastern oyster, *Crassostrea virginica*	7,500	-
2	508	Copepod, *Acartia clausi*	508	-
1	232	Dungeness crab, *Cancer magister*	232	-

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

Inorganic Arsenic(III)

Fresh water

Final Acute Value = 718.2 µg/L

Criterion Maximum Concentration = (718.2 µg/L) / 2 = 359.1 µg/L

Final Acute-Chronic Ratio = 3.803 (see text)

Final Chronic Value = (718.2 µg/L) / 3.803 = 188.9 µg/L

Salt water

Final Acute Value = 137.1 µg/L

Criterion Maximum Concentration = (137.1 µg/L) / 2 = 68.55 µg/L

Final Acute-Chronic Ratio = 3.803 (see text)

Final Chronic Value = (137.1 µg/L) / 3.803 = 36.05 µg/L

Table 4. Toxicity of Arsenic to Aquatic Plants

Species	Chemical	Effect	Result (µg/L)*	Reference
		FRESHWATER SPECIES		
		Inorganic Arsenic(III)		
Alga, *Cladophora* sp.	Sodium arsenite	100% kill in 2 wks	2,320	Cowell, 1965
Alga, *Spirogyra* sp.	Sodium arsenite	100% kill in 2 wks	2,320	Cowell, 1965
Alga, *Zygnema* sp.	Sodium arsenite	100% kill in 2 wks	2,320	Cowell, 1965
Alga, *Selenastrum capricornutum*	Sodium arsenite	50% inhibition of growth in 4 days	31,200	Richter, 1982
Alga, *Selenastrum capricornutum*	Sodium arsenite	**	>59,200	Richter, 1982
Submerged plant, *Potamogeton* sp.	Sodium arsenite	95% kill in 1 mo	2,320	Cowell, 1965
		Inorganic Arsenic(V)		
Alga, *Ankistrodesmus falcatus*	Sodium arsenate	14-day EC50	256	Vocke, et al. 1980
Alga, *Scenedesmus obliquus*	Sodium arsenate	14-day EC50	48	Vocke, et al. 1980
Alga, *Chlamydomonas reinhardii*	Sodium arsenate	50% growth inhibition	202,000	Jurewicz & Buikema, 1980
Alga, *Chlamydomonas reinhardii*	Sodium arsenate	Decreased growth	2,620	Planas & Healey, 1978
Alga, *Selenastrum capricornutum*	Sodium arsenate	50% inhibition of growth in 4 days	690	Richter, 1982
Alga, *Selenastrum capricornutum*	Sodium arsenate	**	>3,000	Richter, 1982

Table 4. (Continued)

Species	Chemical	Effect	Result (µg/L)*	Reference
Alga, *Selenastrum capricornutum*	Sodium arsenate	14-day EC50	30,761	Vocke, et al. 1980
Alga, *Melosira granulata*	Sodium arsenate	Decreased growth	75	Planas & Healey, 1978
Alga, *Ochromonas vallesiaca*	Sodium arsenate	Decreased growth	75	Planas & Healey, 1978
Blue alga, *Microcystis aeruginosa*	Sodium arsenate	Incipient inhibition	11,000	Bringmann, 1975; Bringmann & Kuhn, 1976, 1978a,b
Green alga, *Scenedesmus quadricauda*	Sodium arsenate	Incipient inhibition	4,700	Bringmann & Kuhn, 1977a, 1978a,b, 1979, 1980b
Eurasian watermilfoil, *Myriophyllum spicatum*	-	32-day EC50 (root weight)	2,030	Stanley, 1974
		SALTWATER SPECIES		
		Inorganic Arsenic(III)		
Alga, *Skeletonema costatum*	Sodium arsenite	Growth inhibition	20	Sanders, 1979
Alga, *Skeletonema costatum*	Sodium arsenite	50% decrease C-14 uptake	19	Sanders, 1979
Alga, *Thalassiosira aestivalis*	Sodium arsenite	Reduced chlorophyll a	22	Hollibaugh, et al. 1980
Red alga, *Champia parvula*	Sodium arsenite	Prevented maturation of cystocarps	95	Thursby & Steele, 1984
Red alga, *Champia parvula*	Sodium arsenite	Reduced female growth	145	Thursby & Steele, 1984
Red alga, *Plumaria elegans*	Sodium arsenite	Arrested development of sporelings	577	Boney, et al. 1959

Table 4. (Continued)

Species	Chemical	Effect	Result (µg/L)*	Reference
Alga, *Tetraselmis chui*	Sodium arsenite	No growth inhibition	1,000	Bottino, et al. 1978
Alga, *Hymenomonas carterae*	Sodium arsenite	No growth inhibition	10,000	Bottino, et al. 1978
		Inorganic Arsenic(V)		
Alga, *Skeletonema costatum*	Sodium arsenate	Growth inhibition	13	Sanders, 1979
Alga, *Skeletonema costatum*	Sodium arsenate	50% decrease C-14 uptake	>25	Sanders, 1979
Alga, *Thalassiosira aestivalis*	Sodium arsenate	Reduced chlorophyll a	75	Hollibaugh, et al. 1980
Alga, *Tetraselmis chui*	Sodium arsenate	No growth inhibition	1,000	Bottino, et al. 1978
Alga, *Hymenomonas carterae*	Sodium arsenate	No growth inhibition	150,000	Bottino, et al. 1978
Red alga, *Champia parvula*	Sodium arsenate	Reduced female growth	56	Thursby & Steele, 1984

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

**Highest concentration that would not have killed a significant number of cells in five days.

Table 5. Bioaccumulation of Arsenic by Aquatic Organisms

Species	Tissue	Chemical	Duration (days)	Bioconcentration Factor*	Reference
		FRESHWATER SPECIES			
		Inorganic Arsenic(III)			
Snail, *Stagnicola emarginata*	Whole body	Arsenic trioxide	28	3	Spehar, et al. 1980
Snail, *Helisoma campanulatum*	Whole body	Arsenic trioxide	28	17	Spehar, et al. 1980
Cladoceran, *Daphnia magna*	Whole body	Arsenic trioxide	21	10	Spehar, et al. 1980
Stonefly, *Pteronarcys dorsata*	Whole body	Arsenic trioxide	28	9	Spehar, et al. 1980
Rainbow trout, *Salmo gairdneri*	Whole body	Arsenic trioxide	28	0	Spehar, et al. 1980
Bluegill, *Lepomis macrochirus*	Whole body	Arsenic trioxide	28	4	Barrows, et al. 1980
		Inorganic Arsenic(V)			
Snail, *Stagnicola emarginata*	Whole body	Arsenic pentoxide	28	3	Spehar, et al. 1980
Snail, *Helisoma campanulatum*	Whole body	Arsenic pentoxide	28	6	Spehar, et al. 1980
Cladoceran, *Daphnia magna*	Whole body	Arsenic pentoxide	21	4	Spehar, et al. 1980
Amphipod, *Gammarus pseudolimnaeus*	Whole body	Arsenic pentoxide	28	0	Spehar, et al. 1980
Stonefly, *Pteronarcys dorsata*	Whole body	Arsenic pentoxide	28	7	Spehar, et al. 1980
Rainbow trout, *Salmo gairdneri*	Whole body	Arsenic pentoxide	28	0	Spehar, et al. 1980
Fathead minnow, *Pimephales promelas*	Whole body	Arsenic pentoxide	30	3	DeFoe, 1982

Table 5. (Continued)

Species	Tissue	Chemical	Duration (days)	Bioconcentration Factor*	Reference
		Organic Arsenic Compounds			
Herb, *Hydrophila lacustris*	Whole body	Monosodium methanearsonate	42	2	Anderson, et al. 1980
Water hyacinth, *Eichhornia crassipes*	Whole body	Monosodium methanearsonate	42	2	Anderson, et al. 1980
Alligator weed, *Alternanthera philoxeroides*	Whole body	Monosodium methanearsonate	42	3	Anderson, et al. 1980
Duckweed, *Lemna minor*	Whole body	Monosodium methanearsonate	42	5	Anderson, et al. 1980
Snail, *Stagnicola emarginata*	Whole body	Disodium methyl arsenate	28	3	Spehar, et al. 1980
Snail, *Stagnicola emarginata*	Whole body	Sodium dimethyl arsenate	28	2	Spehar, et al. 1980
Snail, *Helisoma campanulatum*	Whole body	Disodium methyl arsenate	28	4	Spehar, et al. 1980
Snail, *Helisoma campanulatum*	Whole body	Sodium dimethyl arsenate	28	5	Spehar, et al. 1980
Cladoceran, *Daphnia magna*	Whole body	Disodium methyl arsenate	21	4	Spehar, et al. 1980
Cladoceran, *Daphnia magna*	Whole body	Sodium dimethyl arsenate	21	4	Spehar, et al. 1980
Amphipod, *Gammarus pseudolimnaeus*	Whole body	Disodium methyl arsenate	28	0	Spehar, et al. 1980
Amphipod, *Gammarus pseudolimnaeus*	Whole body	Sodium dimethyl arsenate	28	0	Spehar, et al. 1980
Stonefly, *Pteronarcys dorsata*	Whole body	Disodium methyl arsenate	28	9	Spehar, et al. 1980
Stonefly, *Pteronarcys dorsata*	Whole body	Sodium dimethyl arsenate	28	7	Spehar, et al. 1980

Table 5. (Continued)

Species	Tissue	Chemical	Duration (days)	Bioconcentration Factor*	Reference
Rainbow trout, *Salmo gairdneri*	Whole body	Disodium methyl arsenate	28	0	Spehar, et al. 1980
Rainbow trout, *Salmo gairdneri*	Whole body	Sodium dimethyl arsenate	28	0	Spehar, et al. 1980
		SALTWATER SPECIES			
		Inorganic Arsenic(III)			
Eastern oyster, *Crassostrea virginica*	Soft parts	Sodium arsenite	112	350	Zaroogian & Hoffman, 1982

*Results are based on arsenic, not the chemical.

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

Species	Chemical	Duration	Effect	Result (µg/L)*	Reference
			FRESHWATER SPECIES		
			Inorganic Arsenic(III)		
Green alga, *Scenedesmus quadricauda*	Sodium arsenite	96 hr	Incipient inhibition	35,000-46,000**	Bringmann & Kuhn, 1959a,b
Bacteria, *Escherichia coli*	Sodium arsenite	-	Incipient inhibition	290,000	Bringmann & Kuhn, 1959a
Protozoan, *Microregma heterostoma*	Sodium arsenite	28 hrs	Incipient inhibition	5,000	Bringmann & Kuhn, 1959b
Rotifer, (unidentified)	Sodium arsenite	1 wk	Significant population reduction	2,320	Cowell, 1965
Rotifer, (unidentified)	Sodium arsenite	16 wks	Reduced population (monthly treatments)	690***	Gilderhus, 1966
Cladoceran, *Daphnia magna*	Sodium arsenite	26 hrs	EC50 (immobilization)	3,770	Crosby & Tucker, 1966
Cladoceran, *Daphnia magna*	Sodium arsenite	48 hrs	EC50	1,500	Call, et al. 1983; Lima, et al. 1984
Cladoceran, *Daphnia magna*	Sodium arsenite	48 hrs	EC50 (fed)	4,630	Call, et al. 1983; Lima, et al. 1984
Cladoceran, *Daphnia magna*	Sodium arsenite	48 hrs	EC50	4,600**	Bringmann & Kuhn, 1959a,b
Cladoceran, (unidentified)	Sodium arsenite	1 wk	Significant population reduction	2,320	Cowell, 1965
Cladoceran, (unidentified)	Sodium arsenite	16 wks	Reduced population (one treatment)	690	Gilderhus, 1966
Copepod (adult), (unidentified)	Sodium arsenite	16 wks	Reduced population (weekly treatments)	690****	Gilderhus, 1966
Copepod, (unidentified)	Sodium arsenite	1 wk	Significant population reduction	2,320	Cowell, 1965

Table 6. (Continued)

Species	Chemical	Duration	Effect	Result (µg/L)*	Reference
Amphipod, <u>Gammarus pseudolimnaeus</u>	Arsenic trioxide	7 days	80% mortality	961	Spehar, et al. 1980
Amphipod, <u>Hyalella knickerbockeri</u>	Arsenic trioxide	5 days	70% mortality	4,469	Surber & Meehean, 1931
Mayfly, <u>Callibaetis</u> sp.	Arsenic trioxide	5 days	94% mortality	4,469	Surber & Meehean, 1931
Mayfly (nymph), <u>Caenis diminuta</u>	Arsenic trioxide	5 days	25% mortality	2,234	Surber & Meehean, 1931
Mayfly (nymph), <u>Caenis diminuta</u>	Arsenic trioxide	5 days	62% mortality	5,958	Surber & Meehean, 1931
Coho salmon, <u>Oncorhynchus kisutch</u>	Arsenic trioxide	5 mo	Physiological alterations	300	Nichols, 1981; Nichols, et al. 1984
Rainbow trout (embryo, larva), <u>Salmo gairdneri</u>	Sodium arsenite	28 days	EC50 (death and deformity)	550	Birge, et al. 1980; Birge, et al. 1981
Rainbow trout (embryo, larva), <u>Salmo gairdneri</u>	Sodium arsenite	28 days	EC10	134	Birge, et al. 1980; Birge, et al. 1981
Rainbow trout, <u>Salmo gairdneri</u>	Arsenic trioxide	144 hrs	LC50	13,300	Dixon & Sprague, 1981
Rainbow trout (juvenile), <u>Salmo gairdneri</u>	Arsenic trioxide	21 days	Decrease in fat weight gain	1,000	Speyer, 1974; Speyer & Leduc, 1975
Rainbow trout, <u>Salmo gairdneri</u>	Sodium arsenite	4 wks	Decrease in hematocrit	10,000 *****	Oladimeji, et al. 1984a
Rainbow trout, <u>Salmo gairdneri</u>	Sodium arsenite	2 wks	Decrease in weight gain	30,000 *****	Oladimeji, et al. 1984a
Brook trout, <u>Salvelinus fontinalis</u>	Sodium arsenite	262 hrs	LC50	10,440	Cardwell, et al. 1976
Goldfish (juvenile), <u>Carassius auratus</u>	Sodium arsenite	336 hrs	LC50	18,618	Cardwell, et al. 1976

Table 6. (Continued)

Species	Chemical	Duration	Effect	Result (µg/L)*	Reference
Goldfish (embryo, larva), *Carassius auratus*	Sodium arsenite	7 days	EC50 (death and deformity)	490	Birge, 1978
Spottail shiner, *Notropis hudsonius*	Sodium arsenite	72 hrs	LC50	27,000	Boschetti & McLoughlin, 1957
Fathead minnow (juvenile), *Pimephales promelas*	Sodium arsenite	336 hrs	LC50	10,556	Cardwell, et al. 1976
Fathead minnow (adult), *Pimephales promelas*	Sodium arsenite	-	50% reduction in AChE *in vitro*	2,400	Olson & Christensen, 1980
Fathead minnow, *Pimephales promelas*	Arsenic trisulfide	96 hrs	LC50	82,400	Curtis, et al. 1979; Curtis & Ward, 1981
Bluegill (juvenile), *Lepomis macrochirus*	Sodium arsenite	16 wks	Reduced survival (one treatment)	690	Gilderhus, 1966
Bluegill (adult), *Lepomis macrochirus*	Sodium arsenite	16 wks	Histopathological alterations (weekly treatments)	690****	Gilderhus, 1966
Bluegill (juvenile), *Lepomis macrochirus*	Sodium arsenite	336 hrs	LC50	18,328	Cardwell, et al. 1976
Bluegill (fingerling), *Lepomis macrochirus*	Sodium arsenite (pelletized)	48 hrs	LC50	290	Hughes & Davis, 1967
Largemouth bass (embryo, larva), *Micropterus salmoides*	Sodium arsenite	8 days	EC50 (death and deformity)	42,100	Birge, et al. 1978
Narrow-mouthed toad (embryo, larva), *Gastrophryne carolinensis*	Sodium arsenite	7 days	EC50 (death and deformity)	40	Birge, 1978
Marbled salamander (embryo, larva), *Ambystoma opacum*	Sodium arsenite	8 days	EC50 (death and deformity)	4,450	Birge, et al. 1978

Table 6. (Continued).

Species	Chemical	Duration	Effect	Result (µg/L)*	Reference
		Inorganic Arsenic(V)			
Bacteria, *Proteus sp.*	Sodium arsenate	48 hrs	BCF = 0.22-0.24	-	Shariatpanahi, et al. 1982
Bacteria, *Escherichia coli*	Sodium arsenate	48 hrs	BCF = 0.30	-	Shariatpanahi, et al. 1982
Bacteria, *Flavobacterium sp.*	Sodium arsenate	48 hrs	BCF = 0.21-0.25	-	Shariatpanahi, et al. 1982
Bacteria, *Corynebacterium sp.*	Sodium arsenate	48 hrs	BCF = 0.25-0.30	-	Shariatpanahi, et al. 1982
Bacteria, *Pseudomonas sp.*	Sodium arsenate	48 hrs	BCF = 0.30-0.34	-	Shariatpanahi, et al. 1982
Bacteria, *Pseudomonas putida*	Sodium arsenate	16 hrs	Incipient inhibition	10,000	Bringmann & Kuhn, 1976, 1977a, 1979, 1980b
Protozoan, *Entosiphon sulcatum*	Sodium arsenate	72 hrs	Incipient inhibition	4,800 8,900	Bringmann, 1978; Bringmann & Kuhn, 1979, 1980b, 1981
Protozoan, *Chilomonas paramecium*	Sodium arsenate	48 hrs	Incipient inhibition	45,000	Bringmann, et al. 1980, 1981
Protozoan, *Uronema parduezi*	Sodium arsenate	20 hrs	Incipient inhibition	144,000 45,000	Bringmann & Kuhn, 1980a, 1981
Cladoceran, *Daphnia magna*	Sodium arsenate	24 hrs	LC50	17,000	Bringmann & Kuhn, 1977b
Cladoceran, *Daphnia magna*	Sodium arsenate	16 hrs	EC50 (immobilization)	12,500	Anderson, 1944
Cladoceran, *Daphnia magna*	Sodium arsenate	3 wks	LC50	2,850	Biesinger & Christensen, 1972
Cladoceran, *Daphnia magna*	Sodium arsenate	3 wks	Reproductive impairment	520	Biesinger & Christensen, 1972
Fathead minnow (adult), *Pimephales promelas*	Sodium arsenate	-	50% reduction in AChE *in vitro*	262,500	Olson & Christensen, 1980

Table 6. (Continued)

Species	Chemical	Duration	Effect	Result (µg/L)*	Reference
Channel catfish, *Ictalurus punctatus*	Lead arsenate	96 hrs	LC50	>22,000	Johnson & Finley, 1980
Channel catfish, *Ictalurus punctatus*	Sodium arsenate	6 mos	Ultrastructural changes in liver	15,000	Sorenson & Smith, 1981
Green sunfish (juvenile), *Lepomis cyanellus*	Sodium arsenate	39 hrs	LT50	40,000	Sorenson, 1976a
Green sunfish, *Lepomis cyanellus*	Sodium arsenate	2 wks	Ultrastructural changes in liver	31,700	Sorenson, 1976b
Green sunfish, *Lepomis cyanellus*	Sodium arsenate	678 hrs	LT50 (10 C)	60,000	Sorenson, 1976c
Green sunfish, *Lepomis cyanellus*	Sodium arsenate	210 hrs	LT50 (20 C)	60,000	Sorenson, 1976c
Green sunfish, *Lepomis cyanellus*	Sodium arsenate	124 hrs	LT50 (30 C)	60,000	Sorenson, 1976c
Green sunfish, *Lepomis cyanellus*	Sodium arsenate	527 hrs	LT50 (20 C)	30,000	Sorenson, 1976c
Green sunfish, *Lepomis cyanellus*	Sodium arsenate	209 hrs	LT50 (30 C)	30,000	Sorenson, 1976c
Green sunfish, *Lepomis cyanellus*	Sodium arsenate	2 wks	Arsenic inclusion in liver nucleus	60,000	Sorenson, et al. 1982
		SALTWATER SPECIES			
		Inorganic Arsenic(III)			
Polychaete worm, *Nereis diversicolor*	Sodium arsenite	192 hrs	LC50	>14,500	Bryan, 1976
Mud snail, *Nassarius obsoletus*	Sodium arsenite	72 hrs	O_2 consumption rate depressed and abnormal behavior	>2,000	MacInnes & Thurberg 1973

Table 6. (Continued)

Species	Chemical	Duration	Effect	Result (µg/L)*	Reference
Bay scallop (juvenile), *Argopecten irradians*	Sodium arsenite	4 days	BCF=15	-	Nelson, et al. 1976
White shrimp (juvenile), *Penaeus setiferus*	Arsenic trisulfide	96 hrs	LC50	24,700	Curtis, et al. 1979
Pink salmon, *Oncorhynchus gorbuscha*	Arsenic trioxide	96 hrs	LC100	12,307	Holland, et al. 1960
Pink salmon, *Oncorhynchus gorbuscha*	Arsenic trioxide	7 days	LC100	7,195	Holland, et al. 1960
Pink salmon, *Oncorhynchus gorbuscha*	Arsenic trioxide	10 days	LC54	3,787	Holland, et al. 1960
Chum salmon, *Oncorhynchus keta*	Arsenic trioxide	48 hrs	LC50	8,330	Alderdice & Brett, 1957
		Inorganic Arsenic(V)			
Natural phytoplankton populations	Sodium arsenate	4 days	Reduced biomass	75	Hollibaugh, et al. 1980

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

** In river water.

*** Measured concentration after 16 weeks was 2,280 µg/L.

**** Measured concentration after 16 weeks was 9,040 µg/L.

*****Concentration in ng/g in diet.

REFERENCES

Alderdice, D.F. and J.R. Brett. 1957. Toxicity of sodium arsenite to young chum salmon. Issue No. 108. Progress Report of the Pacific Coast Stations of the Fisheries Research Board of Canada. p. 27.

Anderson, A.C., et al. 1975. The acute toxicity of MSMA to black bass (Micropterus dolomieu), crayfish (Procambarus sp.), and channel catfish (Ictalurus lacustris). Bull. Environ. Contam. Toxicol. 14: 330.

Anderson, A.C., et al. 1979. Fate of the herbicide MSMA in microcosms. In: D.D. Hemphill (ed.), Trace Substances in Environmental Health-XIII. University of Missouri, Columbia, Missouri. p. 274.

Anderson, A.C., et al. 1980. Screening of four vascular plants for uptake of monosodium methanearsonate (MSMA). Sci. Total Environ. 16: 95.

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

Anderson, B.G. 1946. The toxicity thresholds of various sodium salts determined by the use of Daphnia magna. Sew. Works Jour. 18: 82.

Baker, M.D., et al. 1983. Methylation of arsenic by freshwater green algae. Can. Jour. Fish. Aquat. Sci. 40: 1254.

Barrows, M.E., et al. 1980. *Bioconcentration* and elimination of selected water pollutants by bluegill sunfish (Lepomis macrochirus). In: R. Hague (ed.), Dynamics, Exposure and Hazard Assessment of Toxic Chemicals. Ann Arbor Science Publishers, Ann Arbor, Michigan. p. 379.

Belding, D.L. 1927. Toxicity experiments with fish in reference to trade waste pollution. Trans. Am. Fish. Soc. 57: 100.

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

Birge, W.J., et al. 1980. Aquatic toxicity tests on inorganic elements occurring in oil shale. In: C. Gale (ed.), Oil Shale Symposium: Sampling, Analysis and Quality Assurance. PB80-221435. 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. Vol. I. Current Developments. Academic Press, New York. p. 59.

Boney, A.D., et al. 1959. The effects of various poisons on the growth and vitality of sporelings of the red alga Plumaria elegans (Bonnem.). Biochem. Pharmacol. 2: 37.

Boschetti, M.M. and T.F. McLoughlin. 1957. Toxicity of sodium arsenite to minnows. Sanitalk 5: 14.

Bottino, N.R., et al. 1978. The effects of arsenate and arsenite on the growth and morphology of the marine unicellular algae Tetraselmis chui (Chlorophyta) and Hymenomonas carterae (Chrysophyta). Jour. Exp. Mar. Biol. Ecol. 33: 153.

Braman, R.S. 1983. Environmental reaction and analysis methods. In: B.A. Fowler (ed.), Biological and Environmental Effects of Arsenic. Elsevier, New York. p. 141.

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 the damaging effect of water pollutants on Daphnia magna. Z. Wasser Abwasser Forsch. 10: 161.

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

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

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

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

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

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

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

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

Brooks, R.R., et al. 1982. Pollution by arsenic in a gold-mining district in Nova Scotia. Environ. Pollut. (Series B) 4: 109.

Brunskill, G.J., et al. 1980. Experimental studies on the effect of arsenic on microbial degradation of organic matter and algal growth. Can. Jour. Fish. Aquat. Sci. 37: 417.

Bryan, G.W. 1976. Heavy metal contamination in the sea. In: R. Johnson (ed.), Marine Pollution, Part 3. Academic Press, New York. p. 185.

Bryan, G.W., et al. 1983. An assessment of the gastropod, *Littorina littorea*, as an indicator of heavy-metal contamination in United Kingdon estuaries. Jour. Mar. Biol. Assoc. U.K. 63: 327.

Budd, K. and S.R. Craig. 1981. Resistance to arsenate toxicity in the bluegreen alga (*Synechococcus leopoliensis*). Can. Jour. Bot. 59: 1518.

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

Call, D.J., et al. 1983. Toxicity and metabolism studies with EPA priority pollutants and related chemicals in freshwater organisms. PB83-263665. National Technical Information Service, Springfield, Virginia.

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

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

Cardwell, R.D., et al. 1976. Acute toxicity of selected toxicants to six species of fish. EPA-600/3-76-008. National Technical Information Service, Springfield, Virginia.

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

Christensen, E.R. and P.A. Zielski. 1980. Toxicity of arsenic and PCB to a green alga (Chlamydomonas). Bull. Environ. Contam. Toxicol. 25: 43.

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

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

Clemens, H.P. and K.E. Sneed. 1959. Lethal doses of several commercial chemicals for fingerling channel catfish. Special Scientific Report - Fisheries No. 316. U.S. Fish and Wildlife Service, Washington, D.C.

Comparetto, G.M., et al. 1982. Arsenic activation analysis of freshwater fish through the precipitation of elemental arsenic. Jour. Radioanal. Chem. 72: 479.

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

Copeland, R.A., et al. 1973. Trace element distributions in Lake Michigan fish: a baseline study with calculations of concentration factors and equilibrium radioisotope distributions. Special Report No. 2. Environmental Research Group, Inc.

Cowell, B.C. 1965. The effects of sodium arsenite and silvex on the plankton populations in farm ponds. Trans. Am. Fish. Soc. 94: 371.

Crosby, D.G. and R.K. Tucker. 1966. Toxicity of aquatic herbicides to *Daphnia magna*. Science 154: 289.

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

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

Dabrowski, K.R. 1976. The effect of arsenic and embryonal development of rainbow trout (Salmo gairdneri). Water Res. 10: 793.

DeFoe, D.L. 1982. Memorandum to Robert L. Spehar. U.S. EPA, Duluth, Minnesota. July 9.

Devi Prasad, P.V. and Y.B.K. Chowdary. 1981. Effects of metabolic inhibitors on the calcification of a freshwater green algae. Gloeotaenium loitlesbergarianum Hansgirg. I. effects of some photosynthetic respiratory inhibitors. Ann. Bot. 47: 451.

Dixon, D.G. and J.B. Sprague. 1981. Acclimation-induced changes in toxicity of arsenic and cyanide to rainbow trout, Salmo gairdneri Richardson. Jour. Fish Biol. 18: 579.

Dupree, H.K. 1960. The arsenic content of water, plankton, soil and fish from ponds treated with sodium arsenite for weed control. Proc. 14th Annual Conf. S. E. Assoc. Game Fish Comm., Columbia, South Carolina. p. 132.

Eipper, A.W. 1959. Effects of five herbicides on farm pond plants and fish. New York Fish Game Jour. 6: 46.

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

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

Ellis, M.M. 1937. Detection and measurement of stream pollution. (Bulletin No. 22, U.S. Bureau of Fisheries) Bull. Bureau Fish. 48: 365.

Ellis, M.M., et al. 1941. Arsenic in freshwater fish. Ind. Eng. Chem. 33: 1331.

Fichlin, W.H. 1983. Separation of arsenic(III) and arsenic(V) in ground waters by ion-exchange. Talanta 30: 371.

Foley, R.E., et al. 1978. Arsenic concentrations in water and fish from Chautauqua Lake, New York. Environ. Biol. Fish. 3: 361.

Fowler, B.A., et al. 1977. Ultrastructural and biochemical effects of prolonged oral arsenic exposure on liver mitochondria of rats. Environ. Health Perspect. 19: 197.

Gentile, S.M. 1981. Memorandum to John H. Gentile. U.S. EPA, Narragansett, Rhode Island.

Gibbs, P.E., et al. 1983. Tharyx marioni (Polychaeta): a remarkable accumulator of arsenic. Jour. Mar. Biol. Assoc. U.K. 63: 313.

Gilderhus, P.A. 1966. Some effects of sublethal concentrations of sodium arsenite on bluegills and the aquatic environment. Trans. Am. Fish. Soc. 95: 289.

Grabinski, A.A. 1981. Determination of arsenic(III), arsenic(V), monomethylarsonate, and dimethylarsinate by ion-exchange chromatography with flameless atomic absorption spectrometric detection. Anal. Chem. 53: 966.

Grindley, J. 1946. Toxicity to rainbow trout and minnows of some substances known to be present in waste water discharged to rivers. Ann. Appl. Biol. 33: 103.

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

Harden, J.M. 1976. Arsenic in water and fish from Lakes Hartwell, Keowee, and Jocassee, South Carolina. PB 367671. National Technical Information Service, Springfield, Virginia.

Hiltibran, R.C. 1967. Effects of some herbicides on fertilized fish eggs and fry. Trans. Am. Fish. Soc. 96: 414.

Holcombe, G.W., et al. 1983. The toxicity of selected priority pollutants to various aquatic organisms. Ecotoxicol. Environ. Safety 7: 400.

Holland, A.A., et al. 1960. Toxic effects of organic and inorganic pollutants on young salmon and trout. Research Bulletin No. 5. Washington Department of Fisheries. p. 188.

Hollibaugh, J.T., et al. 1980. A comparison of the acute toxicities of ions of ten heavy metals to phytoplankton from Saanick Inlet, B. C. Canada. Estuarine Coastal Mar. Sci. 10: 93.

Holm, T.R., et al. 1979. Heterogeneous interactions of arsenic in aquatic systems. In: E.A. Jenne (ed.), Chemical Modeling in Aqueous Systems. ACS Symposium Series No. 93. American Chemical Society, Washington, D.C. p. 712.

Hughes, J.S. and J.T. Davis. 1967. Effects of selected herbicides on bluegill sunfish. Proc. 18th Annual Conf. S.E. Assoc. Game Fish Comm., Columbia, South Carolina. p. 480.

Hunter, R.G., et al. 1981. The relationship of trophic level of arsenic burden in fish of a southern Great Plains lake. Jour. Freshwater Ecol. 1: 121.

Inglis, A. and E.L. Davis. 1972. Effects of water hardness on the toxicity of several organic and inorganic herbicides to fish. Technical Paper 67. U.S. Fish and Wildlife Service, Washington, D.C.

Irgolic, K.J., et al. 1977. Characterization of arsenic compounds formed by *Daphnia magna* and *Tetraselmia chuii* from inorganic arsenate. Environ. Health Perspect. 19: 61.

Irgolic, K.J. 1982. Speciation of arsenic compounds in water supplies. EPA-600/1-82-010. National Technical Information Service, Springfield, Virginia.

Isensee, A.R., et al. 1973. Distribution of alkyl arsenicals in model ecosystem. Environ. Sci. Technol. 7: 841.

Jennett, J.C., et al. 1982. Factors influencing metal accumulation in algae. PB83-149377. National Technical Information Service, Springfield, Virginia.

Johnson, C.R. 1978. Herbicide toxicities in the mosquitofish (*Gambusia affinis*). Proc. R. Soc. Queensl. 89: 25.

Johnson, W.W. and M.T. Finley. 1980. Handbook of acute toxicity of chemicals to fish and aquatic invertebrates. Resource Publication 137. U.S. Fish and Wildlife Service, Washington, D.C.

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

Jones, J.R.E. 1941. A study of the relative toxicity of anions, with Polycelis nigra as test animal. Jour. Exp. Biol. 18: 170.

Jurewicz, S. and A.L. Buikema. 1980. Effects of arsenate on algae, Daphnia, and mosquito fish. Virginia Jour. Sci. 31: 124.

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

Klumpp, D.W. and P.J. Peterson. 1981. Chemical characteristics of arsenic in a marine food chain. Mar. Biol. 62: 297.

La Touche, Y.D. and M.C. Mix. 1982. Seasonal variations of arsenic and other trace elements in bay mussels (Mytilus edulis). Bull. Environ. Contam. Toxicol. 29: 665.

Lawrence, J.M. 1958. Recent investigations on the use of sodium arsenite as an algacide and its effects on fish production in ponds. Proc. 11th Annual Conf. S. E. Assoc. Game Fish Comm., Columbia, South Carolina. p. 281.

Lima, A.R., et al. 1984. Acute and chronic toxicities of arsenic(III) to fathead minnows, flagfish, daphnids, and an amphipod. Arch. Environ. Contam. Toxicol. 13: 595.

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

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

Maeda, S., et al. 1983. Bioaccumulation of arsenic by freshwater algae and the application to the removal of inorganic arsenic from an aqueous phase. Part 1. screening of freshwater algae having high resistance to inorganic arsenic. Sep. Sci. Technol. 18: 375.

Maher, W.A. 1983. Inorganic arsenic in marine organisms. Mar. Pollut. Bull. 14: 308.

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

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

May, T.W. and G.L. McKinney. 1981. Cadmium, lead, mercury, arsenic, and selenium concentrations in freshwater fish. 1976-77 National Pesticide Monitoring Program. Pestic. Monit. Jour. 15: 14.

McLarty, D.A. 1960. Cladophora investigations. Observations on the nature and control of excessive growth of Cladophora sp. in Lake Ontario and Lake Erie. Ontario Water Resources Commission.

Mehrle, P.M., et al. 1982. Relationships between body contaminants and bone development in East Coast striped bass. Trans. Am. Fish. Soc. 111: 231.

Morris, R.J., et al. 1984. The ability of a field population of diatoms to discriminate between phosphate and arsenate. Mar. Chem. 14: 259.

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

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

Nichols, J.W. 1981. Effects of chronic exposure to arsenic trioxide on smoltification, downstream migration, and seawater adaptation of coho salmon (Oncorhynchus kisutch). Masters Thesis. University of Washington.

Nichols, J.W., et al. 1984. Effects of freshwater exposure to arsenic trioxide on the parr-smolt transformation of coho salmon (Oncorhynchus kisutch). Environ. Toxicol. Chem. 3: 143.

Nissen, P. and A.A. Benson. 1982. Arsenic metabolism in freshwater and terrestrial plants. Physiol. Plant. 54: 446.

Oladimeji, A.A., et al. 1979. Metabolism of inorganic arsenic to organoarsenicals in rainbow trout (Salmo gairdneri). Ecotoxicol. Environ. Safety 3: 349.

Oladimeji, A.A., et al. 1982. Effect of acclimation of rainbow trout (Salmo gairdneri) to arsenic on retention of a subsequent dose of arsenic. Ecotoxicol. Environ. Safety 6: 196.

Oladimeji, A.A., et al. 1984a. Long-term effects of arsenic accumulation in rainbow trout, Salmo gairdneri. Bull. Environ. Contam. Toxicol. 32: 732.

Oladimeji, A.A., et al. 1984b. Measuring the elimination of arsenic by the gills of rainbow trout (Salmo gairdneri) by using a two compartment respirometer. Bull. Environ. Contam. Toxicol. 32: 661.

Olson, D.L. and G.M. Christensen. 1980. Effects of water pollutants on other chemicals on fish acetylcholinesterase (in vitro). Environ. Res. 21: 327.

Ontario Water Resources Commission. 1959. *Cladophora* investigations: a report of observation on the nature and control of excessive growth of *Cladophora sp.* in Lake Ontario.

Paladino, F.V. 1976. The effect of arsenic on the thermal tolerance and survival of newly hatched muskellunge fry (*Esox masquinongy*). Masters Thesis. State University College, Buffalo, New York.

Paladino, F.V. and J.R. Spotila. 1978. The effect of arsenic on the thermal tolerance of newly hatched muskellunge (*Esox masquinongy*). Jour. Thermal Biol. 3: 223.

Passino, D.R.M. and J.M. Kramer. 1980. Toxicity of arsenic and PCBs to fry of deepwater ciscoes (*Coregonus*). Bull. Environ. Contam. Toxicol. 24: 527.

Passino, D.R.M. and A.J. Novak. 1984. Toxicity of arsenate and DDT to the cladoceran *Bosmina longirostris*. Bull. Environ. Contam. Toxicol. 33: 325.

Pennington, C.H., et al. 1982. Contaminant levels in fishes from Brown's Lake, Mississippi. Jour. Mississippi Acad. Sci. 27: 139.

Penrose, W.R. 1975. Biosynthesis of organic arsenic compounds in brown trout (*Salmo trutta*). Jour. Fish. Res. Board Can. 32: 2385.

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.

Planas, D. and F.P. Healey. 1978. Effects of arsenate on growth and phosphorus metabolism of phytoplankton. Jour. Phycol. 14: 337.

Planas, D. and A. Lamarche. 1983. Lack of effect of arsenic on phytoplankton communities in different nutrient conditions. Can. Jour. Fish. Aquat. Sci. 40: 156.

Reay, P.F. 1972. The accumulation of arsenic from arsenic-rich natural waters by aquatic plants. Jour. Appl. Ecol. 9: 557.

Richter, J.E. 1982. Memorandum to Charles E. Stephan. U.S. EPA, Duluth, Minnesota. June 30.

Sanders, H.O. and O.B. Cope. 1966. Toxicities of several pesticides to two species of cladocerans. Trans. Am. Fish. Soc. 95: 165.

Sanders, H.O. and O.B. Cope. 1968. The relative toxicities of several pesticides to naiads of three species of stoneflies. Limnol. Oceanogr. 13: 112.

Sanders, J.C. 1979. Effects of arsenic speciation and phosphate concentration on arsenic inhibition of Skeletonema costatum (Bacillaris phyceae). Jour. Phycol. 15: 424.

Sandhu, S.S. 1977. Study of the post-mortem identification of pollutants in fish killed by water pollution: detection of arsenic. Bull. Environ. Contam. Toxicol. 17: 373.

Schaefer, E.D. and W.O. Pipes. 1973. Temperature and the toxicity of chromate and arsenate to the rotifer, Philodina roseola. Water Res. 7: 1781.

Schiller, C.M., et al. 1977. Effects of arsenic on pyruvate dehydrogenase activation. Environ. Health Perspect. 19: 205.

Schuth, C.K., et al. 1974. Distribution of ^{14}C-arsenic derived from ^{14}C cacodylic acid in an aquatic ecosystem. Jour. Agric. Food Chem. 22: 999.

Scott, K.J. and C.E. Pesch. 1981. Memorandum to John H. Gentile. U.S. EPA, Narragansett, Rhode Island.

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

Scudlark, J.R. and D.L. Johnson. 1982. Biological oxidation of arsenite in seawater. Estuarine Coastal Shelf Sci. 14: 693.

Shariatpanahi, M., et al. 1982. Uptake and distribution of sodium arsenate by bacterial cells. In: D.D. Hemphill (ed.), Trace Substances in Environmental Health-XVI. University of Missouri, Columbia, Missouri. p. 170.

Sohacki, L.P. 1968. Dynamics of arsenic in the aquatic environment. Dissertation. Michigan State University, East Lansing, Michigan.

Sorenson, E.M.B. 1976a. Toxicity and accumulation of arsenic in green sunfish, Lepomis cyanellus, exposed to arsenate in water. Bull. Environ. Contam. Toxicol. 15: 756.

Sorenson, E.M.B. 1976b. Ultrastructural changes in the hepatocytes of green sunfish, Lepomis cyanellus Rafinesque, exposed to solutions of sodium arsenate. Jour. Fish Biol. 8: 229.

Sorenson, E.M.B. 1976c. Thermal effects on the accumulation of arsenic in green sunfish, Lepomis cyanellus. Arch. Environ. Contam. Toxicol. 4: 8.

Sorenson, E.M.B. and N.K.R. Smith. 1981. Hemosiderin granules: cytoxic responses to arsenic exposure in channel catfish. Bull. Environ. Contam. Toxicol. 27: 645.

Sorenson, E.M.B., et al. 1979. Arsenic accumulation, tissue distribution and cytotoxicity in teleosts following indirect aqueous exposures. Bull. Environ. Contam. Toxicol. 21: 162.

Sorenson, E.M.B., et al. 1980. Cytological changes in fish liver following chronic, environmental exposure. Bull. Environ. Contam. Toxicol. 25: 93.

Sorenson, E.M.B., et al. 1982. Electron probe x-ray microanalysis of arsenic inclusion in fish. Arch. Environ. Contam. Toxicol. 11: 469.

Spehar, R.L., et al. 1980. Comparative toxicity of arsenic compounds and their accumulation in invertebrates and fish. Arch. Environ. Contam. Toxicol. 9: 55.

Speyer, M.R. 1974. Some effects of combined chronic arsenic and cyanide poisoning on the physiology of rainbow trout. M.S. Thesis. Concordia University, Montreal, Canada.

Speyer, M.R. and G. Leduc. 1975. Effects of arsenic trioxide on growth of rainbow trout. In: International Conference on Heavy Metals in the Environment (Abstracts). Toronto, Ontario, Canada. p. C.17.

Spotila, J.R. and F.V. Paladino. 1979. Toxicity of arsenic to developing muskellunge fry (Esox masquinongy). Comp. Biochem. Physiol. 62: 67.

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

Stary, J. and K. Kratzer. 1982. The cumulation of toxic metals on alga. Int. Jour. Environ. Anal. Chem. 12: 65.

Stary, J., et al. 1982. The cumulation of chromium and arsenic species in fish (Poecilia reticulata). Int. Jour. Environ. Anal. Chem. 12: 253.

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

Surber, E.W. 1943. Weed control in hard-water ponds with copper sulphate and sodium arsenate. In: E.M. Quee (ed.), Transactions of the Eighth North American Wildlife Conference, 1943. Washington, D.C.: American Wildlife Institute 8: 132.

Surber, E.W. and O.L. Meehean. 1931. Lethal concentrations of arsenic for certain aquatic organisms. Trans. Am. Fish. Soc. 61: 225.

Taylor, D. 1981. A summary of the data on the toxicity of various materials to aquatic life. 9. arsenic. BL/A/2098. Imperial Chemical Industries, Brixham, England.

Thomas, W.H., et al. 1980. Toxicity of a mixture of ten metals to phytoplankton. Mar. Ecol. Progress Series 2: 213.

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

Thursby, G.B. and R.L. Steele. 1984. Toxicity of arsenite and arsenate to the marine macroalga *Champia parvula* (Rhodophyta). Environ. Toxicol. Chem. 3: 309.

Tsui, P.T.P. and P.J. McCart. 1981. Chlorinated hydrocarbon residues and heavy metals in several fish species from the Cold Lake area in Alberta, Canada. Int. Jour. Environ. Anal. Chem. 10: 277.

U.S. EPA. 1975. Initial scientific review of MSMA/DSMA. EPA-540/1-75-020. National Technical Information Service, Springfield, Virginia.

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

U.S. EPA. 1976b. Arsenic. EPA-600/1-76-036. National Technical Information Service, Springfield, Virginia.

U.S. EPA. 1980. Ambient water quality criteria for arsenic. EPA-440/5-80-021. National Technical Information Service, Springfield, Virginia.

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

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

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

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

Vocke, R.W., et al. 1980. Growth responses of selected freshwater algae to trace elements and scrubber ash slurry generated by coal-fired power plants. Water Res. 14: 141.

Wagemann, R., et al. 1978. Arsenic in sediments, water and aquatic biota from lakes in the vicinity of Yellowknife, Northwest Territories, Canada. Arch. Environ. Contam. Toxicol. 7: 169.

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

Weir, P.A. and C.H. Hine. 1970. Effects of various metals on behavior of conditioned goldfish. Arch. Environ. Health 20: 45.

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

Whyte, J.N.C. and J.R. Englar. 1983. Analysis of inorganic and organic-bound arsenic in marine brown algae. Bot. Mar. 26: 159.

Wiebe, A.H., et al. 1931. The arsenic content of largemouth bass (Micropterus salmoides) fingerlings. Trans. Am. Fish. Soc. 61: 150.

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

Woolson, F.A., et al. 1976. Distribution and isolation of radioactivity from ^{74}As-arsenate and ^{14}C-methanearsonic acid in an aquatic model ecosystem. Pestic. Biochem. Physiol. 6: 261.

Zaroogian, G.E. and G.L. Hoffman. 1982. Arsenic uptake and loss in the American oyster, _Crassostrea virginica_. Environ. Monit. Assessment 1: 345.