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AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA

ATRAZINE

Prepared by

University of Wisconsin - Superior
Superior, Wisconsin 54880

and

Great Lakes Environmental Center
Traverse City, Michigan 49686

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Office of Research and Development
Environmental Research Laboratories
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Narragansett, Rhode Island

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AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR

ATRAZINE

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DULUTH, MINNESOTA
NARRAGANSETT, RHODE ISLAND

NOTICES

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FOREWORD

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

The term "water quality criteria" is used in two sections of the Clean Water Act, section 304(a)(1) and section 303(c)(2). The term has a different program impact in each section. In section 304, the term represents a non-regulatory, scientific assessment of ecological effects. Criteria presented in this document are such scientific assessments. If water quality criteria associated with specific stream uses are adopted by a state as water quality standards under section 303, they become enforceable maximum acceptable pollutant concentrations in ambient waters within that state. Water quality criteria adopted in state water quality standards could have the same numerical values as criteria developed under section 304. However, in many situations states might want to adjust water quality criteria developed under section 304 to reflect local environmental conditions and human exposure patterns. Alternatively, states may use different data and assumptions than EPA in deriving numeric criteria that are scientifically defensible and protective of designated uses. It is not until their adoption as part of state water quality standards that criteria become regulatory. Guidelines to assist the states and Indian tribes in modifying the criteria presented in this document are contained in the Water Quality Standards Handbook (U.S. EPA, 1994). This handbook and additional guidance on the development of water quality standards and other water-related programs of this Agency have been developed by the Office of Water.

This final document is guidance only. It does not establish or affect legal rights or obligations. It does not establish a binding norm and cannot be finally determinative of the issues addressed. Agency decisions in any particular situation will be made by applying the Clean Water Act and EPA regulations on the basis of specific facts presented and scientific information then available.

Tudor T. Davies
Director
Office of Science and Technology

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Daniel J. Call
(freshwater author)
University of Wisconsin-Superior
Superior, Wisconsin

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Introduction

Atrazine is an herbicide with the empirical formula $C_8H_{14}Cl_5N_5$ and a molecular weight of 215.7. It is a white, crystalline solid with a melting point of 173-177°C, a boiling point of 279°C, and solubility in water of 33 mg/L at 25°C (Hunter et al. 1985; Farm Chemicals Handbook 1987). Atrazine has an n-octanol-water partition coefficient (log P) of 2.82, a vapor pressure of 7.34×10^{-4} mm Hg, a Henry's Constant of 8.32×10^{-6} atm·m^3/M, and a hydrolysis half-life in excess of 1,000 days (Hunter et al. 1985). These physico-chemical properties contribute to its environmental partitioning and degree of persistence in the aquatic environment.

Atrazine is used extensively in the United States, Canada and other countries for control of weeds in agricultural crops, especially in crops such as corn, sorghum, wheat and soybeans. It is one of the most heavily used pesticides in North America, generally being among the top few for total pounds of herbicide used (Council on Environmental Quality 1984; Pike 1985; Braden et al. 1989; Moxley 1989; Richards and Baker 1993; Ciba-Geigy 1994; Burridge and Haya, 1988). Annual domestic usage during the past two decades has been in the general range of 40-50 million kilograms applied to approximately 25 million hectares of farm land in the U.S. (Eisler 1989). It is also commonly used in other countries (Galassi et al. 1992,1993; Bester and Huhnerfuss 1993; Hendriks and Stouten 1993; Lode et al. 1994; Bester et al. 1995; Caux and Kent 1998).

With this magnitude of application, atrazine has been commonly detected in surface waters of agricultural watersheds where it is used. Being relatively mobile from soil, atrazine surface water concentrations are highest in field runoff, with concentration peaks generally following early major

storm events within a few weeks of application (Muir et al. 1978; Triplett et al. 1978; Wauchope 1978; Wauchope and Leonard 1980; Glotfelty et al. 1984). Concentrations in the low mg/L range may be encountered in edge-of-field run-off (Hall et al. 1972; Kadoum and Mock 1978; Roberts et al. 1979; Klaine et al. 1988). Field run-off is diluted upon entering a stream or lake, resulting in atrazine concentrations that are generally much lower (e.g., 1-10 μg/L range) in such waters (Richard et al. 1975; Frank and Sirons 1979; Frank et al. 1979; Roberts et al. 1979; Wu 1981; Richards and Baker 1993). Only trace levels (i.e., <1.0-33 ng/L) were reported in a pesticide monitoring study in California (Pereira et al. 1996). However, individual maximum concentrations may be considerably higher. When considered over several years, maximum concentrations reported in some creeks and rivers from midwestern agricultural areas have ranged between 5 and 70 μg/L (Muir et al. 1978; Frank and Sirons 1979; Frank et al. 1979, 1982; Roberts et al. 1979; Illinois State Water Survey 1990; Richards and Baker 1993; Ciba-Geigy 1992a,e, 1994).

Surface waters surrounded by agricultural lands may receive several pulsed doses over the growing season corresponding to rainfall events (Herman et al. 1986). Annual patterns of atrazine concentrations in Ohio streams show peak time-weighted mean concentrations of about 6 μg/L in early June, with a rapid increase between April and June followed by a rapid decrease between June and August (Richards and Baker 1993). Time-weighted mean concentrations between August and December are considerably lower, most frequently being less than 1.0 μg/L. Atrazine concentrations are the lowest, and uniformly so, between January and April. Also, smaller streams were shown to have higher peak concentrations, but of shorter duration, than larger streams (Richards and Baker 1993). The annual cycle is similar in southwestern Ontario, but with the annual peak concentrations occurring several weeks later and peak

concentrations being lower than in Ohio (Bodo 1991). Nonetheless, atrazine concentrations in Ontario have regularly exceeded 2 μg/L, the Canadian water quality guideline for aquatic life protection (Trotter et al. 1990). Exceedances have similarly been reported in surface waters of Quebec (Caux and Kent 1995).

Among the highest surface water concentrations of atrazine are those in small reservoirs in southern Illinois. These are currently being intensively monitored (Tierney et al. 1994a). Maximum concentrations as high as 55 μg/L have been reported from these reservoirs.

Similar seasonal trends in concentrations of atrazine to those in Ohio streams have been observed in streams in Illinois (Illinois State Water Survey 1990; Ciba-Geigy 1992a), in Iowa (Ciba-Geigy 1994), and in other midwestern states (Ciba-Geigy 1992e). In large rivers, such as the Mississippi, Missouri and Ohio Rivers, peak concentrations have most commonly occurred in June, with the means during the spring period being less than 5.0 μg/L (Ciba-Geigy 1992b). The maximum concentrations were generally between 2 and 8 μg/L, with a single maximum as high as 17.25 μg/L (Ciba-Geigy 1992b,c). Atrazine concentrations in the Mississippi River between Minneapolis, Minnesota, and New Orleans, Louisiana, from July to August, 1991, ranged from 0.054 ug/L to 4.7 ug/L (Pereira and Hostetler 1993).

Atrazine residues in Illinois lakes tended to be lower than those in the streams, with less pronounced peak values, but the lower concentrations were sustained for longer durations (Ciba-Geigy 1992a). It should be noted that the maximum observed atrazine concentration was less than 3.0 μg/L at 61 percent of 42 sites monitored over 6 years between 1975 and 1988 (Ciba-Geigy 1992a).

Atrazine concentrations were considerably lower in Chesapeake Bay and its tributaries (Ciba-Geigy 1992d). Here, the maximum observed concentration in a tributary was 14.6 μg/L, and only 3 out of 600 samples analyzed between 1976 and 1991 exceeded 3.0 μg/L. The highest observed maxima in Upper and Lower Chesapeake Bay were 1.7 and 0.38 μg/L, respectively. Models for the Great Lakes suggest that concentrations should be quite low, not likely to exceed 0.13 μg/L (Tierney et al. 1994b). Individual measurements from Lake Erie taken at Toledo, Ohio, have not exceeded 0.35 μg/L, while concentrations measured from samples collected in Lake Michigan at Michigan City, Indiana, have been below 0.20 μg/L (Ciba-Geigy 1992e).

In addition to field run-off, atrazine residues are also transported by volatilization into the atmosphere and subsequent deposition. Atrazine has been measured in fog (Glotfelty et al. 1987), and trace amounts have been shown to be transported by the wind (Elling et al. 1987). Atrazine was present year-round in rainwater samples in Maryland, with the highest concentration of 2.2 μg/L occurring in May (Wu 1981).

Atrazine has been shown to be enriched at the microsurface layer of water (Wu et al. 1980; Wu 1981). This may be due to the presence of microsurface films which tend to concentrate certain chemicals. Wu (1981) suggested that atrazine enrichment in the microsurface layer was more likely a source of atmospheric input rather than a result of atmospheric deposition, and that the main source of atrazine at the site studied in Maryland was agricultural runoff.

Studies of atrazine persistence in water have produced varying results. Huckins et al. (1986) reported the loss of atrazine from water within 4 days in a simulated prairie pond microcosm. In shallow artificial streams, a 50% loss of atrazine occurred in 3.2 days (Kosinski 1984; Moorhead

and Kosinski 1986). Lay et al. (1984) reported an 82% loss in 5 days and a 95% loss in 55 days. The half-life of atrazine in wetland mesocosms was from 8 to 14 days (Detenbeck et al. 1996). The half-life of ^{14}C-labeled atrazine has been measured in estuarine water as 3 to 12 days, compared to 15 to 30 days in estuarine sediment and 330 to 385 days in agricultural soils (Kemp et al., 1981; Jones et al., 1982). These rapid losses in small artificial systems and in an estuarine environment are contrasted with reports of a 300-day half-life in a larger lake system (Yoo and Solomon 1981), surface water losses of only 33% in 120 days and 0% in 85 days in two separate 0.49 hectare pond applications (Klaassen and Kadoum 1979), and a loss of only 40-50% in pond water over a period of more than 5 months (Gunkel 1983). In two months time, approximately 25-30% of single 20 and 500 μg/L atrazine applications to a 0.045 hectare Kansas pond had disappeared from the water (deNoyelles et al. 1982). Approximately 25 percent of the initial applications remained after 12 months. The half-life of atrazine was approximately 3 months in Tasmanian streams (Davies et al. 1994). Thus, the persistence of atrazine in water appears highly variable, dependent perhaps upon both the nature of the aquatic system into which it is introduced as well as the climatic conditions at the exposure site.

Biodegradation is considered to be one of the most important processes governing the environmental fate of atrazine (Radosevich et al. 1996). Microbes isolated from aquatic ecosystems that are capable of degrading atrazine have been reported. Mirgain and colleagues (1993) isolated a *Pseudomonas putida/Xanthomonas maltophilia* pair with atrazine-degrading ability. Certain soil bacteria have also been shown to be capable of degrading atrazine both aerobically and anaerabically (Behki et al. 1993; Radosevich et al., 1995,1996). Some soil fungi also can degrade atrazine

(Donnelly et al., 1993). The degradation products of atrazine were less toxic to submerged aquatic vascular plants than the parent compound (Jones and Winchell, 1984). In a salt marsh environment, the incorporation of atrazine into the sediment appeared to be a prerequisite for its degradation (Meakins et al. 1995). Very little degradation occurred in the water column.

The mode of atrazine's toxic action toward plants is blockage of electron transport within the Hill reaction of photosystem II, thereby inhibiting photosynthesis (Moreland 1980). Vascular plants and algae are both affected by this mode of action. In this way, atrazine has the demonstrated capacity to reduce primary productivity in aquatic ecosystems (deNoyelles et al. 1982; Kosinski and Merkle 1984; Dewey 1986; Herman et al. 1986; Pratt et al. 1988).

Atrazine is also used in combination with other herbicides. These include alachlor, ametryne, linuron, paraquat, propachlor, amitrole, and cyanazine (Farm Chemicals Handbook 1987).

Several reviews exist on atrazine and its environmental impact (CCREM 1989; Eisler 1989; Huber 1993; deNoyelles et al. 1994; Solomon et al. 1996). These reviews indicated that a few species of aquatic plants have been shown to be slightly affected by atrazine at concentrations below 10 μg/L. The review by deNoyelles et al. (1994) stated that herbicides have little direct effects upon animals, and that they tend to produce ecosystem effects from the bottom of the food chain upward, in contrast to insecticides which act in the opposite direction. Huber (1993) and Solomon et al. (1996) stated that plants readily recovered from the inhibitory effects of atrazine once the exposure was reduced or eliminated.

An understanding of the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses"

(Stephan et al. 1985), hereafter referred to as the Guidelines, and the response to public comment (U.S. EPA 1985a) is necessary to evaluate the following text, tables, and calculations.

Whenever adequately justified, a national criterion may be replaced by a site-specific criterion (U.S. EPA 1983a), which may include not only site-specific criterion concentrations (U.S. EPA 1983b), but also site-specific durations of averaging periods and site-specific frequencies of allowed excursions (U.S. EPA 1985b). The latest comprehensive literature search for this document was conducted in January, 1997. Data in the files of the U.S. EPA's Office of Pesticide Programs concerning the effects of atrazine on aquatic organisms and their uses have been evaluated for use in the derivation of aquatic life criteria. Some more recent information was also included.

Acute Toxicity to Aquatic Animals

The data that are available according to the Guidelines concerning the acute toxicity of atrazine are presented in Table 1. Acute toxicity data for eight freshwater invertebrate species ranged from 720 µg/L for first instar larvae of a midge, *Chironomus tentans*, (Macek et al. 1976) to >37,100 µg/L for an annelid, *Lumbriculus variegatus* (Brooke 1990). A hydroid coelenterate (*Hydra* sp.) was the second most sensitive invertebrate tested, with an EC50 of 3,000 µg/L (Brooke 1990). Stonefly (*Acroneuria* sp.) nymphs had an LC50 of 6,700 µg/L and the amphipod, *Hyalella azteca*, had an LC50 of 14,700 µg/L (Brooke 1990). A cladoceran (*Daphnia magna*) had a Species Mean Acute Value (SMAV) of 49,000 ug/L (Putt 1991), a value greater than the solubility of atrazine in water (i.e., 32,000 µg/L). The remaining invertebrate species

tested, a snail (Physa sp.) had an LC50 in excess of 34,100 ug/L (Brooke 1990).

The brook trout (Salvelinus fontinalis) was the most sensitive freshwater vertebrate species tested, with an LC50 of 6,300 µg/L (Macek et al. 1976; Table 1). The fathead minnow (Pimephales promelas) had a SMAV of 20,000 µg/L, while the LC50 for the brown trout (Salmo trutta) was 27,000 µg/L (Grande et al. 1994). The LC50's for the remaining four vertebrate species, all fishes, were "greater than" values of 8,000, 10,000, 10,000, and 18,000 µg/L for the bluegill (Lepomis macrochirus) (Macek et al. 1976), largemouth bass (Micropterus salmoides) (Jones 1962), channel catfish (Ictalurus punctatus) (Jones 1962), and coho salmon (Oncorhynchus kisutch) (Lorz et al. 1979), respectively. The SMAV was based upon flow-through tests with measured toxicant concentrations in the cases of Daphnia magna and the fathead minnow, where other test results were also available.

Genus Mean Acute Values (Table 3) were identical to the SMAVs in all cases. Of the 15 freshwater genera for which acute values are available, the most sensitive genus, Chironomus, was over 50 times more sensitive than the most tolerant, Lumbriculus. Both the most sensitive and most tolerant were invertebrates. The freshwater Final Acute Value for atrazine was calculated to be 657.3 ug/L using the procedure described in the Guidelines and the Genus Mean Acute Values for invertebrates and fish in Table 3. The Final Acute Value is lower than all available freshwater Species Mean Acute Values.

The acute toxicity of atrazine to resident North American saltwater animals has been determined with eight species of invertebrates and two species of fish (Table 1). Although only two fish species were tested, fish appear to have a similar sensitivity to atrazine as do invertebrates. The acute values range from 1,000 µg/L for mysids, Mysidopsis bahia (Ward and

Ballantine, 1985) to >30,000 µg/L for the eastern oyster, Crassostrea virginica (Ward and Ballantine, 1985). The copepod, Acartia tonsa, had similar LC50 values between a static unmeasured test (Ward and Ballantine, 1985) and two renewal tests (Thursby et al. 1990) with measured values of 94, 91.73 and 210.1 µg/L, respectively. An additional flow-through measured test (McNamara, 1991a) with the same species yielded an LC50 of 4,300 µg/L. It is unclear why there is such a large difference between the flow-through measured value and the other measured results. There was nothing unusual about the variability of the chemistry data from the flow-through tests to indicate a problem (coefficient of variations ranged from 2 to 15%). A possible explanation is that the renewal, measured values were from tests conducted with 70% technical grade atrazine (compared to 97.1% atrazine used in the flow-through test). The "other 30%" may have contributed to the higher toxicity. Because there is no obvious problem with the flow-through data set for A. tonsa, the Guidelines state that the flow-through measured value must be used. Therefore, the SMAV for this species is 4,300 µg/L. LC50s for the copepod, Eurytemora affinis, were 500, 2,600 and 13,200 µg/L at salinities of 5, 15 and 25 g/L, respectively (Hall et al. 1994a,b). The resultant SMAV was 2,579 µg/L.

Genus Mean Acute Values (Table 3) were identical to the SMAVs in all cases with the exception of Acartia where the two species tested had different SMAVs. The four most sensitive saltwater genera to atrazine are all crustacean genera. The saltwater Final Acute Value for atrazine, 611.7 µg/L, was calculated using the procedure described in the Guidelines and the Genus Mean Acute Values in Table 3. This saltwater Final Acute Value is lower than all available saltwater SMAVs.

Chronic Toxicity to Aquatic Animals

The available data concerning the chronic toxicity of atrazine that are usable according to the Guidelines are presented in Table 2. Freshwater tests have been completed with three invertebrate and three fish species.

The cladoceran, *Ceriodaphnia dubia*, was exposed to atrazine over its entire life cycle in two 7-day tests (Oris et al. 1991). The end result was identical in both tests, with chronic limits of 2,500 and 5,000 µg/L, and a calculated chronic value (geometric mean) of 3,500 µg/L. An accompanying acute toxicity test resulted in an LC50 of >30,000 µg/L. The resultant acute-chronic ratio was >8.571.

In another 7-day life cycle exposure (Jop 1991d), atrazine did not affect survival at any of the test concentrations (i.e., 290, 600, 1,200, 2,500 or 4,900 µg/L. However, reproduction was significantly reduced at the two highest treatment levels. An average of 10 young per female were produced at these two treatments compared to a mean of 23 for the pooled controls. The chronic limits in this study were 1,200 and 2,500 µg/L, and the chronic value was 1,732 µg/L. An accompanying acute value of >4,900 µg/L resulted in an acute-chronic ratio of >2.829.

The cladoceran, *Daphnia magna*, was continuously exposed to atrazine over three generations for a total of 64 days (Macek et al. 1976). Mean measured concentrations of 250, 550 and 1,150 µg/L significantly reduced young production in the first generation animals, while production at mean concentrations of 60 and 140 µg/L was similar to controls. Variability in the data for second and third generations precluded statistical significance of generally reduced production with increased atrazine concentration. Chronic limits based on young production by first generation daphnids were 140 and 250

μg/L, with a resultant chronic value (geometric mean) of 187 μg/L. A corresponding acute value of 6,900 μg/L (Macek et al. 1976) yielded an acute-chronic ratio of 36.90.

The midge, Chironomus tentans, was continuously exposed to atrazine for two generations in a life-cycle test (Macek et al. 1976). The test was initiated by exposing first generation eggs through the various larval instar stages, pupation and emergence. Eggs from first generation adults were then continuously exposed in a similar fashion. Mean measured concentrations were 110, 230, 420, 780 and 1,330 μg/L. No significant differences between controls and the lowest exposure (110 μg/L) were noted in hatchability, survival, pupation or emergence in first generation animals. Significant reductions in the number of adults emerging in the first generation exposure occurred at atrazine concentrations of 230 and 420 μg/L. First generation larvae exposed to higher concentrations experienced high mortality at the early instar stages.

In the second generation, hatchability was reduced at 420 μg/L, while pupation and emergence were reduced at 230 and 420 μg/L of atrazine. Exposure to 110 μg/L had no effect on growth or development of the chironomid larvae. Based on these observations, the chronic limits were 110 and 230 μg/L, and the resultant chronic value (geometric mean) was 159 μg/L. A corresponding acute value of 720 μg/L (Macek et al. 1976) yielded an acute-chronic ratio of 4.528 for Chironomus tentans.

Yearling brook trout (Salvelinus fontinalis) and their offspring were continuously exposed to atrazine for 306 days at mean measured concentrations of 65, 120, 240, 450 and 720 μg/L (Macek et al. 1976). At 90 days, significant reductions in weight and total length of first generation fish occurred at concentrations of 240 μg/L and above. At 306 days, weight and

total length of first generation fish were significantly less than controls at atrazine exposures of 120 μg/L and above. Fish at these exposures also appeared lethargic in comparison to the controls and fish at 65 μg/L.

Spawning activity and hatchability of second generation fry did not appear to be affected, although considerable variability between replicates in the parameters of total number of eggs spawned, number of eggs per female, percent fertilization and hatchability precluded statistical interpretation. High replicate variability was also observed in morphological development of the embryos. At 30 days of exposure, fry survival was similar for all treatments, but was significantly reduced at concentrations of 240 μg/L and above after both 60 and 90 days. As in first generation fry, length and weight of second generation fry at 90 days were significantly less than controls at atrazine exposures of 240 μg/L and above. Based on the most sensitive measure, i.e. growth of first generation fish at 306 days, the chronic limits were 65 and 120 μg/L, with a resultant chronic value of 88.3 μg/L. A corresponding acute value of 6,300 μg/L (Macek et al. 1976) yielded an acute-chronic ratio of 71.35 for brook trout.

Fathead minnows (Pimephales promelas) were continuously exposed to atrazine for 43 weeks starting with 18-day old fish, continuing through spawning and into a second generation for 60 days (Macek et al. 1976). Mean measured atrazine concentrations were 15, 33, 54, 112 and 213 μg/L. Control fish survival was low (53.5 percent) for the first 60 days of exposure, but after thinning at 60 days, control survival was 93 percent for the remaining 34 weeks. No significant differences in survival or growth were observed between weeks 9 and 43 in first generation fish. A lack of spawning activity at 33 and 213 μg/L was thought to be an artifact of different sex ratios and not due to treatment. Otherwise, there were no significant differences in the

reproductive parameters of mean number of eggs produced per female and mean number of eggs per spawn; or in hatchability, survival and growth of second generation fish through 30 and 60 days. Based on a lack of any observed adverse effect at the highest exposure of 213 µg/L and an observation of 25 percent mortality in 3 to 5-day old fry after 96 hr of exposure at 870 µg/L, the chronic limits were set at 213 and 870 µg/L, with a resultant chronic value (geometric mean) of 430 µg/L. A corresponding acute value of 15,000 µg/L (Macek et al. 1976) yielded an acute-chronic ratio of 34.88.

A fathead minnow full life-cycle chronic test that extended for 274 days was performed, with mean measured atrazine concentrations of 0, 150, 250, 460, 990 and 2,000 µg/L (Dionne 1992). At 30 days, F_0 larval length was significantly reduced by concentrations ≥990 µg/L, whereas at 60 days, length was reduced at concentrations ≥460 µg/L. At 274 days, survival was significantly reduced at 990 and 2,000 µg/L of atrazine. There was no effect upon the reproductive parameters of number of eggs per spawn, total number of eggs produced, number of spawns per female, or number of eggs per female at any treatment level. Hatching success was slightly, but significantly, reduced at concentrations of 250 µg/L and above. F_1 larval growth (length and weight) was significantly reduced at ≥460 µg/L of atrazine. The chronic limits were reported to be 250 and 460 µg/L, based upon F_0 and F_1 larval growth. This resulted in a chronic value of 339 µg/L. An accompanying acute value of 20,000 µg/L yielded an acute-chronic ratio of 59.00.

Bluegills (Lepomis macrochirus) were continuously exposed to atrazine for 18 months, starting with 7-10 cm long fish, continuing through spawning, and into a second generation for 60 days (Macek et al 1976). Mean measured exposure concentrations were 8, 14, 25, 49 and 95 µg/L. Survival and growth of first generation fish exposed to atrazine for 6 and 18 months were similar

to the controls. Spawning activity was too sporadic to indicate any adverse effects. Percent hatchability of eggs was similar to controls at concentrations between 14 and 95 μg/L. Low fry survival in the second generation controls for the first 30 days precluded observations on survival effects due to atrazine in this time interval. However, between 30 and 90 days, survival was near 100 percent in the controls and all atrazine treatments. Total length of second generation fish through 90 days was considered to be unaffected by any of the atrazine exposures. From a lack of any adverse effect at concentrations as high as 95 μg/L, and from an observed loss of equilibrium in bluegills exposed to 500 μg/L for 28 days, the chronic limits were set at 95 and 500 μg/L. The resultant chronic value was 218 μg/L. A corresponding acute value of >8,000 μg/L (Macek et al. 1976) yielded an acute-chronic ratio of >36.70.

The acute values for Daphnia magna, Chironomus tentans, Salvelinus fontinalis, Pimephales promelas and Lepomis macrochirus in tests reported by Macek et al. (1976) were used in calculating acute-chronic ratios even though the acute test concentrations were not measured. This was because of close agreement between nominal and measured concentrations in the chronic tests. For six chronic tests, the overall agreement between measured and nominal concentrations was 94.4 percent. Therefore, it appeared likely that the nominal concentrations presented for acute tests were also in good agreement with actual concentrations.

The chronic toxicity of atrazine to saltwater species has been determined in an 8-day test with the copepod, Eurytemora affinis and in two 28-day tests; a life cycle test with the mysid, Mysidopsis bahia, and an early life-stage test with the sheepshead minnow, Cyprinodon variegatus (Table 2). Survival was the most sensitive endpoint in the 8-day chronic tests with

Eurytemora affinis. Tests were performed at salinity levels of 5, 15 and 25 g/L. At a salinity of 5 g/L, survival was significantly reduced to 37 percent at 17,500 µg/L, while survival (71 percent) at the next lower concentration of 12,250 µg/L was similar to controls (Hall et al., 1994a,b). The chronic value was 14,600 µg/L. At a salinity of 15 g/L, the chronic limits were 17,500 and 25,000 µg/L, and the chronic value was 20,900 µg/L. Sensitivity appeared greater at a salinity of 25 g/L, with chronic limits of 4,200 and 6,000 µg/L, and a chronic value of 5,010 µg/L. Only at this highest salinity level was the acute value greater than the chronic value. The resultant Acute-Chronic Ratio of 2.635 was considered to be the correct ratio for this species, and was used in subsequent calculations involving the Species Mean Acute-Chronic Ratio.

Survival was the most sensitive endpoint in the mysid test (Ward and Ballantine, 1985). Survival was 60% at 190 µg/L, and 30% and 20% at 290 and 470 µg/L, respectively. There was no statistically significant effect on survival at ≤80 µg/L. There was no reproduction at 470 µg/L, but no effect on reproduction at all lower concentrations. The chronic value for mysids, based on survival, is 123.3 µg/L. The acute value is 1,000 µg/L and the acute-chronic ratio is 8.110 (Table 2). In the sheepshead minnow test (Ward and Ballantine, 1985), juvenile survival was significantly reduced at 3,400 µg/L, but not at ≤1,900 µg/L. All fish exposed to 5,700 µg/L died. There was no effect on either hatching success or growth at all concentrations with surviving fish (≤5,700 µg/L). The chronic value for sheepshead minnows, based on mortality of juveniles, is 2,542 µg/L. The acute value for sheepshead is a "greater than" value (>16,000 µg/L). Therefore the acute-chronic value was >6.294.

The species mean acute-chronic ratios for both freshwater and saltwater differ by more than a factor of 10, and are not related to rank order of acute sensitivity. For both freshwater and saltwater, separate chronic values were calculated for fish and invertebrates using separate fish and invertebrate Acute-Chronic Ratios. "Greater than" values were not used. The freshwater Fish Chronic Value of 11.56 µg/L is the quotient of the Final Acute Value (657.3 µg/L) and the Fish Final Acute-Chronic Ratio (56.88). Likewise, the Invertebrate Chronic Value of 71.14 µg/L is the quotient of the Final Acute Value (657.3 ug/L) and the Invertebrate Final Acute-Chronic Ratio (9.239). The Final freshwater Chronic Value is 11.56 µg/L, the lesser of the two chronic values.

The saltwater Fish Chronic Value of 10.75 µg/L is the quotient of the Final Acute Value (611.7 µg/L) and the Fish Final Acute-Chronic Ratio (56.88). Likewise, the Invertebrate Chronic Value of 66.21 µg/L is the quotient of the Final Acute Value and the Invertebrate Final Acute-Chronic Ratio (9.239). The Final Saltwater Chronic Value is 10.75 µg/L, the lesser of the two chronic values.

Toxicity to Aquatic Plants

For inclusion in Table 4, according to the Guidelines, exposures with algae must have been for a minimum of 4 days. With vascular plants, chronic exposures must have been conducted. In both cases, it is a requirement that the concentrations of atrazine were measured during the tests. A Final Plant Value can be obtained by selecting the lowest result from a test with an important aquatic species in which the concentrations of test material were measured and the endpoint was biologically important.

Two species of freshwater green algae were exposed to atrazine in studies in which the exposure duration was 4 days or longer, and the atrazine concentrations were measured (Table 4). Chlamydomonas reinhardtii cell numbers were reduced 50 percent after 4 days of exposure to 51 ug/L, after 7 days of exposure to 21 ug/L, and after 10 days of exposure to 10.2 ug/L (Schafer et al. 1993). The "no observable effect concentrations" (NOECs) were 3.4, 5.1 and 3.7 µg/L at 4, 7 and 10 days, respectively (Schafer et al. 1994).

Selenastrum capricornutum had a 4-day EC50 of 4 µg/L, based upon cell numbers (University of Mississippi 1990). The EC50 for pheophytin a and chlorophyll a content was 20 and 150 µg/L, respectively. With the same species and cell number as an endpoint, Gala and Giesy (1990) reported a 4-day EC50 of 128.2 µg/L, and Hoberg (1991) reported a 4-day EC50 of 130 µg/L. Hoberg (1993a) calculated a 5-day EC50 of 55 µg/L. EC10 values at 4 and 5 days were 90 and 26 µg/L, whereas EC90 values at 4 and 5 days were 190 and 120 µg/L, respectively (Hoberg 1991, 1993a).

Exposure of the duckweed, Lemna minor, to atrazine for 14 days resulted in a NOEC of 10 µg/L based upon a biomass endpoint (University of Mississippi 1990). In this study, "lowest observable effect concentrations" (LOECs) of 10 and 100 µg/L were obtained for the endpoints of mature frond production and biomass, respectively. The EC50, based on biomass, was 8,700 µg/L. A 7-day exposure of a different species of duckweed, Lemna gibba G3, resulted in an EC50 of 180 µg/L, based upon frond production (Hoberg 1991b). Two 14-day studies were also conducted with L. gibba (Hoberg 1993b,c). A major difference in these two studies was that in the latter study the effect concentrations were calculated based upon the atrazine concentrations that were measured on the last day only. This may have resulted in effect levels that appeared to be lower than in the first study, where concentrations were

measured more often during the test. In the first study, using frond number as an endpoint, the EC10, EC50 and EC90 were 6.2, 37, and 220 µg/L, respectively, after 14 days of exposure (Hoberg 1993b). Using frond biomass, the EC10, EC50 and EC90 were 12, 45 and 170 µg/L, respectively. In the second study (Hoberg 1993c), the EC10, EC50 and EC90 were 2.2, 50, and 98 µg/L, respectively, using the frond number endpoint; while the respective values for frond biomass were 4.2, 22, and 110 µg/L.

Ten-day exposures of L. gibba to atrazine (Kirby and Sheahan 1994) yielded EC50s that were comparable to those of Hoberg et al. (1993b,c). EC50 values of 56, 60 and 62 µg/L were obtained based upon frond number, fresh weight and chlorophyll content, respectively (Kirby and Sheahan 1994).

Elodea (Elodea canadensis) was exposed to atrazine both in the absence and presence of sediment. In the absence of sediment, LOECs of 10 and 100 µg/L were observed, based upon mature frond production and biomass, respectively (University of Mississippi 1990). With sediment present, the biomass LOEC was 100 µg/L. Biomass EC50s were 1,200 and 25,400 µg/L when sediment was absent and present, respectively, in the test systems. A freshwater Final Plant Value was not calculated, as none of the species tested met the Guidelines criteria for such a determination.

Information on the sensitivity of saltwater plants to atrazine is available for five phytoplankton species, one seaweed and four vascular plants, representing five phyla (Table 4). All of the plant effect concentrations were less than the acute values for aquatic animals. Short-term (two and three day) growth tests with phytoplankton resulted in EC50s ranging from 79 to 265 µg/L (Mayer, 1987; Walsh 1983); a factor of only 3.4. Two species of estuarine submerged vascular plants, Potamogeton perfoliatus and Myriophyllum spicatum, exposed for 28-35 days to various concentrations of

atrazine had IC50s for growth and photosynthesis between 25 and 117 ug/L, with the growth endpoint being more sensitive in both species (Kemp et al. 1982, 1985). The sago pondweed, Potamogeton pectinatus, was tested for atrazine toxicity for 28 days at three different salinities (1, 6 and 12 ppt) (Hall et al., 1997). Dry weight was the most sensitive endpoint with chronic values of 21.2, 21.2 and 10.6 ug/L at salinities of 1, 6 and 12 ppt, respectively. A two-way ANOVA yielded a chronic value of 5.3 ug/L of atrazine. Four separate 21-day exposures of the seagrass, Zostera marina, resulted in LC50s ranging from 100 to 540 µg/L (Delistraty and Hershner 1984). A saltwater Final Plant Value was not calculated, as none of the species tested met the Guidelines criteria for such a determination.

Bioaccumulation

Macek et al. (1976) analyzed muscle tissue or the eviscerated carcasses of fish at the end of extended exposure periods. Brook trout exposed to atrazine at 740 µg/L for 308 days contained less than 200 ug/kg of atrazine in muscle tissue, resulting in a bioconcentration factor (BCF) of <0.27 (Table 5). Bluegills exposed to 94 µg/L for 546 days also contained less than 200 ug/kg in their muscle tissue, for a BCF of <2.1. Fathead minnows exposed to atrazine at 210 µg/L for 301 days had less than 1,700 ug/kg of atrazine in pooled samples of eviscerated carcasses, for a BCF of <8.1.

Dionne (1992) exposed fathead minnows to atrazine for up to 274 days. Using ^{14}C-atrazine and measuring the radiolabel in fish tissue, the values obtained would represent maximum possible BCFs. Regardless of the life-stage or exposure duration, maximum BCFs were less than 8.5 in all cases.

There is no U.S. Food and Drug Administration action level or any other established maximum allowable concentration of chemical residues in tissue available for atrazine. Therefore, a Final Residue Value cannot be determined.

Other Data

Many tests with atrazine and various freshwater or saltwater organisms have been conducted either for a different duration or by different protocols than those specified in the Guidelines for inclusion in Tables 1, 2, 4 and 5. For example, plant tests were included in Table 6 rather than Table 4 if the test duration was less than 4 days or the exposure concentrations were not measured. Tests with animals were included in Table 6 for a number of reasons, including considerations of test duration, type of test, and test endpoints other than those of toxicity or bioaccumulation. These test results are presented in Table 6.

Mixed nitrifying bacteria were unaffected regarding ammonium oxidation at 28-day exposures up to 2,000 µg/L (Gadkari 1988). Cell growth in the bacterium, *Pseudomonas putida*, was not inhibited following a 16 hr exposure at 10,000 µg/L (Bringmann and Kuhn 1976, 1977). The cyanobacterium, *Microcystis aeruginosa*, exhibited the onset of cell growth inhibition at a concentration of 3 µg/L in an 8-day exposure (Bringmann and Kuhn 1976; 1978a,b). After 5 days of exposure, cell numbers were significantly reduced at 108 µg/L, and the minimum algistatic concentration was 440 µg/L (Parrish 1978). Kallqvist and Romstad (1994) obtained a 6-day EC50 of 630 µg/L with *M. aeruginosa*. Photosynthetic ^{14}C uptake was highly reduced (84-96 percent) in *M. aeruginosa* following a 22 hr exposure to 2,667 ug/L of atrazine (Peterson et al. 1994).

A 4-day EC50 of 90 μg/L was reported for an unidentified species of Microcystis (Fairchild et al. 1994a; 1998). An EC50 of 130 μg/L was reported for Synechococcus leopoliensis (Kallqvist and Romstad 1994).

Two different species of cyanobacteria, Anabaena inaequalis and Anabaena variabilis, had highly different EC50s of 30 and 4,000 μg/L, respectively after 14 days (Stratton 1984). Stratton (1984) obtained a 12-14 day EC50 of 1,200 μg/L for Anabaena cylindrica, while Larsen et al. (1986) reported EC50s of 253, 178 and 182 μg/L for this species.

A number of tests have been performed with the cyanobacterium, Anabaena flos-aquae (Table 6). Hughes (1986) reported an EC50 of 230 μg/L following a 5-day exposure. A concentration of 40 μg/L non-radiolabeled atrazine reduced ^{14}C uptake by approximately 50 percent after 1 to 3 days of exposure, after which the reduction was less (Abou-Waly et al. 1991a). Chlorophyll a content was reduced by atrazine, followed by recovery. The 3-day EC50 was 58 μg/L, while the 7-day EC50 was 766 μg/L (Abou-Waly 1991b). Anabaena flos-aquae had a 4-day EC50 that exceeded 3,000 μg/L in a study by Fairchild et al. (1994a; 1998). Anabaena inaequalis and Pseudoanabaena sp. exhibited reduced photosynthetic uptake of ^{14}C in the amounts of 65 and 91 percent, respectively, following a 22 hr exposure to 2,667 ug/L (Peterson et al. 1994).

Toxicity studies of atrazine toward several other species of cyanobacteria have been reported. A 31-day exposure of Plectonema boryanum to 10,000 μg/L resulted in a 69 percent decrease in cell numbers (Mallison and Cannon 1984). A 5-day exposure of Synechoccus leopolensis yielded an EC50 of 130 μg/L (Kallqvist and Romstad 1994). Aphanizomeonon flos-aquae and Oscillatoria sp. exhibited highly reduced photosynthetic uptake of ^{14}C with a 22-hr exposure to 2,667 ug/L of atrazine (Peterson et al. 1994).

The green alga, Chlorella pyrenoidosa, had 70-95 percent reduced growth following a 2-week exposure of 500 to 10,000 µg/L of atrazine (Virmani et al. 1975). Photosynthesis by C. pyrenoidosa was inhibited by approximately 64 percent following an 8 hr exposure to 10 µg/L atrazine (Valentine and Bingham 1976). Stratton (1984) obtained an EC50 of 300 µg/L following a 12-14 day exposure. A 30 percent reduction in growth and 40 percent reduction in chlorophyll a was observed in a 10-day exposure to 53.9 µg/L (Gonzalez-Muruaa et al. 1985). A 110 hr exposure to 49.6 µg/L reduced chlorophyll by 39 percent (Hiranpradit and Foy 1992). Photosynthetic CO_2 uptake was inhibited by more than 80 percent in C. pyrenoidosa following a 50-minute exposure to 125 ug/L (Hannan 1995).

Chlorella vulgaris had 24 hr EC50s of 325, 305 and 293 µg/L in three separate tests based upon ^{14}C uptake (Larsen et al. 1986). Following 7 days of exposure to 250 to 5,000 µg/L (only 2.3 to 4.7 percent remained on day 7), dry weight of C. vulgaris was reduced from 31 to 62 percent (Veber et al. 1981). This same species had an EC50 of 94 ug/L based upon chlorophyll concentration after 96 hr of exposure (Fairchild et al. 1998).

Chlorella fusca cell numbers were reduced by atrazine, and an EC50 of 26 µg/L was calculated following a 24 hr exposure (Altenburger et al. 1990). Faust et al. (1993) obtained an EC50 of 15 µg/L for this species. In undefined species of Chlorella, a 72-96 hr atrazine exposure at 52 µg/L resulted in a 31 percent inhibition of growth and a 39 percent reduction in chlorophyll (Foy and Hiranpradit 1977). Higher exposures generally resulted in larger adverse effects. A 2-3 day atrazine exposure of 21.6 µg/L reduced the growth rate by 55 percent (Hersh and Crumpton 1987). Chlorella sp. exhibited very rapid responses to atrazine with EC50s of 35-41 µg/L based upon photosynthetic oxygen evolution following a 2-minute exposure (Hersh and

Crumpton 1989). Fairchild et al. (1994) reported a 4-day EC50 (biomass) of 92 μg/L for Chlorella sp.

The green alga, Chlamydomonas reinhardtii, exhibited approximately a 32 percent inhibition of photosynthesis in an 8-hr exposure to 10 μg/L (Valentine and Bingham 1976), and a 50 percent reduction in photosynthetic activity (^{14}C uptake) in 24-hr exposures to 19-48 μg/L (Larsen et al. 1986). Atrazine-sensitive and atrazine-resistant strains of C. reinhardtii responded to 2-minute exposures by a difference of approximately an order of magnitude in their respective EC50 values of 45 and 484 μg/L (Hersh and Crumpton 1989). A 65-hr exposure to 49.6 μg/L resulted in a 13 percent reduction of chlorophyll (Hiranpradit and Foy 1992). Fairchild et al. (1998) obtained a 96-hr EC50 of 176 ug/L for C. reinhardi.

Chlamydomonas noctigama had a 3-day EC50 of 330 μg/L (Kallqvist and Romstad 1994). C. geitleri had a similar level of sensitivity after a 1-hr exposure, with an EC50 of 311 μg/L (Francois and Robinson 1990). Foy and Hiranpradit (1977) exposed Chlamydomonas sp. to various concentrations of atrazine for 72-96 hr. A concentration of 50-52 μg/L inhibited growth by 84.9 percent and reduced chlorophyll by 12.8 percent. Slight additional increases in growth inhibition were observed with increased atrazine concentrations up to 832 μg/L. Fairchild et al. (1994) obtained a 4-day EC50 of 176 μg/L.

The green alga, Scenedesmus quadricauda, had photosynthesis inhibited by approximately 42 percent after 8 hr at an atrazine exposure of 10 μg/L (Valentine and Bingham 1976). Bringmann and Kuhn (1977; 1978a,b) found 30 μg/L to cause the onset of cell multiplication inhibition after 8 days of exposure with this species. S. quadricauda had a 12 to 14-day EC50 of 100 μg/L (Stratton 1984). Bogacka et al. (1990) studied photosynthesis reductions at various concentrations after 8 days of exposure, and observed a gradation

from 4.5 percent reduction at 4 µg/L to a 99.3 percent reduction at 337 µg/L. Photosynthetic ^{14}C uptake was highly inhibited (96 percent) after 22 hr at 2,667 ug/L (Peterson et al. 1994). This species had a 96-hr EC50 of 169 ug/L, based upon chlorophyll concentration (Fairchild et al. 1998).

In three tests with Scenedesmus obliquus the 24 hr EC50s for ^{14}C uptake were between 38 and 57 µg/L (Larsen et al. 1986). S. subspicatus had a 4-day EC50 of 110 µg/L (Geyer et al. 1985). Schafer et al. (1994) found 37 µg/L to inhibit the effective photosynthetic rate by 57.4 percent. Kirby and Sheahan (1994) reported a 48-hr EC50 of 21 µg/L for S. subspicatus. Reinold et al. (1994) observed a 50 percent reduction in dry mass at 21.5 µg/L. Exposure of an unidentified species of Scenedesmus for 72-96 hr at 50 µg/L resulted in 60.2 percent growth inhibition (Foy and Hiranpradit 1977). Increased concentrations resulted in increased growth inhibition. Fairchild et al. (1994) obtained a 4-day EC50 of 169 µg/L.

The green alga, Selenastrum capricornutum, exhibited a reduction in cell numbers following a 5-day exposure to 54 µg/L of atrazine (Parrish 1978). Chlorophyll a was reduced in increasing amounts at increasing concentrations between 32 and 200 µg/L. The minimum algistatic concentration was determined to be 200 µg/L. A 7-day exposure at 100 µg/L resulted in a 13.8 percent increase in biomass, whereas 1,000 µg/L resulted in decreases (Johnson 1986). Larsen et al. (1986) obtained 24 hr EC50s of 53, 34 and 42 µg/L based upon ^{14}C uptake. Roberts et al. (1990) reported 5-day EC50s of 100 and 95 µg/L. In 21-day exposures (Turbak et al. 1986), EC50s of 58.7 and 410 µg/L were obtained using algal assay media and creek water for test media, respectively. EC50 values were 69.7 and 854 µg/L, respectively, using these two media in 24-hr tests that measured photosynthetic oxygen evolution. An EC50 of 50 µg/L was reported in a 4-day exposure (Versteeg 1990). Reductions in chlorophyll

content and in ^{14}C uptake occurred at 130 µg/L in 1- to 7-day exposures (Abou-Waly et al. 1991a). EC50s were 283, 218 and 214 µg/L for chlorophyll a content at 3, 5, and 7 days, respectively (Abou-Waly et al. 1991b). Fairchild et al. (1994a; 1998) reported a 4-day EC50 of 117 µg/L, while Kallqvist and Romstad (1994) obtained 3-day EC50s of 200 and 110 µg/L. Photosynthetic ^{14}C uptake was nearly completely inhibited (99 percent) at an exposure of 2,667 ug/L (Peterson et al. 1994). A 96-hr EC50 of 147 µg/L was reported by Gaggi et al. 1995. Additional EC50s ranging from 26 to 359 µg/L were reported for 72- to 96-hr exposures by Radetski et al. 1995, Caux et al. 1996, Van der Heever and Grobbelaar 1996, and Fairchild et al. 1997, respectively.

The green alga, Ankistrodesmus braunii, had an 11-day EC50 of 60 µg/L (Burrell et al. 1985). ^{14}C uptake EC50s of 72 and 61 µg/L resulted from 24-hr exposures of Ankistrodesmus sp. (Larsen et al. 1986). Two tests with Stigeoclonium tenue yielded 24-hr EC50s of 127 and 224 µg/L, while a test with Ulothrix subconstricta yielded an EC50 of 88 µg/L (Larsen et al. 1986). Virmani et al. (1975) observed reduced growth of Chlorococcum hypnosporum following 2-week exposures to 5,000 and 10,000 µg/L. Similarly, a high test concentration (2,157 µg/L) inhibited calcification in Gloetaenium loitlesbergarianum (Prasad and Chowdary 1981). Short exposures (2 minutes) of Franceia sp. yielded EC50s between 430 and 774 µg/L, measured as photosynthetic oxygen evolution (Hersh and Crumpton 1989).

Several diatom species have been tested for their sensitivities to atrazine. Cyclotella meneghiniana yielded 7-minute EC50s based upon photosynthesis between 99 and 243 µg/L (Millie and Hersh 1987). A 22-hr exposure to 2,667 ug/L inhibited photosynthetic ^{14}C uptake by 97 percent (Peterson et al. 1994). A 6-day EC50 of 430 µg/L was obtained by Kallqvist and Romstad (1994). Hughes (1986; 1988) determined several endpoints in 5-day

exposures of Navicula pelliculosa, including a 5-day EC50 of 60 ug/L. Photosynthesis was almost completely inhibited (99 percent) in Nitzschia sp. by a 22-hr exposure to 2,667 ug/L of atrazine (Peterson et al. 1994). The EC50 was 60 µg/L. Using a 9-day recovery period following the 5-day exposure, the algistatic and algicidal concentrations were 1,730 and >3,200 µg/L, respectively. The cryptomonad, Cryptomonas pyrinoidifera, had a 6-day EC50 of 500 µg/L (Kallqvist and Romstad 1994).

The duckweed, Lemna minor, when exposed to 20 µg/L of atrazine for 20 days did not exhibit any adverse effects, but reduced growth occurred at concentrations between 50 and 1,000 µg/L (Beaumont et al. 1976,a,b,c; Grenier et al. 1979). Biochemical and ultrastructural changes in the chloroplasts of Lemna minor were observed at an exposure of 248 µg/L (Grenier et al. 1987; 1989; Simard et al. 1990). Growth was inhibited 95 percent by a 7-day exposure to 2,667 ug/L (Peterson et al. 1994). Four-day EC50s of 92 and 153 µg/L were reported for L. minor with biomass as the endpoint (Fairchild et al. 1994a; 1997; 1998). Hughes (1986; 1998) exposed a different species of duckweed, Lemna gibba, to atrazine for 5 days, and obtained an EC50 of 170 µg/L. Using a 9-day recovery period, the phytostatic and phytocidal concentrations were 1,720 and >3,200 µg/L, respectively.

Exposure of wild rice, Zizania aquatica, to 50 µg/L of atrazine for 83 days resulted in a visible state of senescence and a 75 percent reduction in chlorophyll a in the leaves (Detenbeck et al. 1996). Wildcelery, Vallisneria americana, had reduced leaf growth and whole plant biomass at an exposure of 8 µg/L and had reduced over-wintering success of tubers at 4 µg/L (Cohn 1985). A 14-day EC50 of 22 µg/L was reported for coontail, Ceratophyllum sp. (Fairchild et al. 1994; 1998). Stem elongation occurred at 50 µg/L (Detenbeck et al. 1996). Cattails, Typha latifolia, were unaffected at 25 µg/L

(Detenbeck et al. 1996). Eurasian watermilfoil, Myriophyllum spicatum, had a 28-day EC50 of 1,104 µg/L (Davis 1980; Forney and Davis 1981) and a 14-day EC50 of 132 µg/L (Fairchild et al. 1994a; 1998). M. spicatum exhibited a 30 percent increase in net photosynthetic rate at 10 ug/L (Hoffmann and Winkler 1990), and a 50 percent reduction in branch number at 3,700 ug/L (Bird 1993). Sago pondweed, Potamogeton pectinatus, had reduced biomass after 28 days at 100 µg/L (Fleming et al. 1991), and bushy pondweed, Najas sp., had a 14-day EC50 of 24 µg/L (Fairchild et al. 1994a; 1998). The 14-day EC50 was <38 µg/L for Egeria sp. (Fairchild et al. 1994a). Elodea canadensis had EC50s of 80 and 109 µg/L in exposures of 21 to 28 days (Davis 1980; Forney and Davis 1981). In a 20-day exposure to 10 ug/L, the dark respiration rate exceeded the net photosynthetic rate (Hoffmann and Winkler 1990). Its growth was unaffected at 75 µg/L in another study (Detenbeck et al. 1996). Fairchild et al. (1998) reported a 14-day EC50 of 21 ug/L for E. canadensis based upon wet weight. Three species of water moss (Fontinalis antipyretica, F. squamosa and F. hypnoides) were affected in their photosynthetic production at concentrations of 10 ug/L or less (Hoffmann and Winkler 1990). F. hypnoides had a 90 percent reduction in net photosynthesis in a 24-hr exposure to 2 ug/L. Johnson (1986) found that 10 µg/L stimulated growth of mixed macrophytes, Ceratophyllum sp. and Elodea sp., but that 100 and 1,000 µg/L decreased plant biomass.

The protozoan, Acanthamoeba castellanii, had population decreases of from 5 to 40 percent when exposed for 6 days to atrazine at 100 to 10,000 µg/L (Prescott et al. 1977). Photosynthesis was inhibited by about 11 percent in Euglena gracilis at 10 µg/L, and increasingly inhibited at higher concentrations (Valentine and Bingham 1976). Two species of protozoans, Colpidium campylum and Tetrahymena pyriformis, had 24 hr EC50s of >50,000 and

118,500 μg/L, respectively (Huber et al. 1991; Roberts et al. 1990). Schafer et al. (1994) reported a 48 hr EC50 of 96,000 μg/L for T. pyriformis.

In representatives from higher animal phyla, relatively high concentrations were required to produce notably adverse responses. A concentration of 5,000 μg/L reduced the budding rate in Hydra viridis (Benson and Boush 1983). Two species of leeches, Glossiphonia complanata and Helobdella stagnalis, had LC50s of 6,300 and 9,900 μg/L, respectively, after a 27-28 day exposure (Streit and Peter 1978). Snail (Lymnaea palustris) growth, fecundity and tissue glycogen content were unaffected at concentrations up to 125 μg/L (Baturo et al. 1995), but the activities of benzo[a]pyrene and glutathione-s-transferase enzymes were inhibited at 5 μg/L (Baturo and Lagadic 1996). The LC50 was greater than 60,000 μg/L for larval and juvenile mussels (Anadonta imbecilis) (Johnson et al. 1993). The rotifer, Brachionus calyciflorus, had an LC50 of 7,840 μg/L (Crisinel et al. 1994).

The anostracan crustacean, Streptocephalus texanus, had a 24-hr LC50 >30,000 μg/L (Crisinel et al. 1994). The cladoceran, Ceriodaphnia dubia, had maximum acceptable toxicant concentrations (MATCs) of 7,100 and 14,100 μg/L in two 4-day tests (Oris et al. 1991). A 26-hr LC50 of 3,600 μg/L was reported for Daphnia magna (Frear and Boyd 1967). In 48 hr exposures of D. magna to a nominal atrazine concentration of 10 μg/L, whole body residues were only 4.4 and 2.2 times greater than the nominal concentration in water (Ellgehausen et al. 1980). Young production was reduced in D. magna at 2,000 μg/L (Kaushik et al. 1985). After 96 hr of exposure, Bogacka et al. (1990) observed 30 percent mortality in D. magna at 16,900 μg/L, and 60 percent mortality at 48,300 μg/L. Johnson et al. (1993) reported a 48-hr LC50 of 9,400 μg/L, while Crisinel et al. (1994) obtained a 24-hr EC50 of >30,000 μg/L. Detenbeck et al. 1996) observed a significant decrease in D. magna survival at 25 μg/L, but not at 50

µg/L. Exposures of Daphnia pulex for 28 to approximately 70 days resulted in decreased survival and reproduction at concentrations between 1,000 and 20,000 µg/L, with reproduction affected more greatly than survival (Schober and Lampert 1977). Food consumption was reduced by 10 percent at 350 µg/L and by 50 percent at 1,600 µg/L in D. pulex after 10 minutes (Pott 1980).

The 3-hr LC50 was in excess of 40,000 µg/L for the cladoceran, Moina macrocopa (Nishiuchi and Hashimoto 1967, 1969). A concentration of 1,000 µg/L caused 40 percent mortality and reduced population growth in M. macrocopa (Scherban 1972a,b).

The amphipod, Gammarus fasciatus, had a 48-hr LC50 of 5,700 µg/L (Macek et al. 1976). For the midge, Chironomus riparius, a 10-day exposure yielded an LC50 of 18,900 µg/L (Taylor et al. 1991), while a 4-day exposure of C. tentans did not kill 50 percent of the test animals at 28,000 µg/L (McNamara 1991b).

Rainbow trout, Oncorhynchus mykiss, embryos and sac fry exposed continuously for 23 and 27 days had LC50s between 696 and 888 µg/L (Birge et al. 1979). Water hardness did not have any appreciable effect. A concentration of 4,020 µg/L was required to produce over 60 percent teratic larvae. Pluta (1989) reported a 48-hr LC50 of 5,660 µg/L. Changes in the ultrastructure of trout renal corpuscles and tubules were observed following 28-day exposures to 5-10 µg/L of atrazine (Fischer-Scherl et al. 1991). Twenty-eight day exposures resulted in slight ultrastructural changes in trout renal corpuscles at 5 µg/L, in slight histopathological changes in the liver and increased ultrastructural changes in renal corpuscles at 10 µg/L, and in further changes in renal corpuscles and liver cells at 20 µg/L (Schwaiger et al. 1991). A 14-day exposure to 10 µg/L of atrazine did not affect survival, body weight, liver weight or liver enzyme activity (Egaas et al. 1993).

Concentrations of 3.0 and 50 μg/L for 10 days were reported to reduce plasma protein in rainbow trout (Davies et al. 1994b). Oulmi et al. (1995) observed kidney changes at the cellular level in the proximal tubules at 12.4 μg/L, and in both the proximal and distal tubules at 24.0 μg/L.

The 48 hr LC50 for the common carp, Cyprinus carpio, was >10,000 μg/L (Nishiuchi and Hashimoto 1967, 1969). Short-term exposures of from 4 to 24 hr to lesser concentrations between 100 and 1,000 μg/L resulted in increased serum cortisol and serum glucose (Hanke et al. 1983; Gluth and Hanke 1984). Serum acetylcholinesterase first increased and then decreased with time of exposure. Changes were also noted in gill ATPase activity. Juvenile carp yielded a 48-hr LC50 of 16,100 μg/L (Pluta 1989), and a 96-hr LC50, in which the fish were fed, of 18,800 μg/L (Neskovic et al. 1993). Biochemical changes in the serum, heart, liver and kidneys of carp were observed after 14 days of exposure to 1,500 μg/L, as well as hyperplasia of gill epithelial cells (Neskovic et al. 1993). Goldfish, Carassius auratus, had a 48-hr LC50 of >10,000 μg/L (Nishiuchi and Hashimoto 1967, 1969). Jop (1991b) reported the "no observed effect concentration" (NOEC) to be in excess of 4,900 μg/L for fathead minnows exposed to atrazine for 7 days. Survival and growth were unaffected in fathead minnows, Pimephales promelas, exposed to 75 μg/L (Detenbeck et al. 1996).

Channel catfish (Ictalurus punctatus) embryos and sac fry had LC50s between 176 and 272 μg/L after exposures of either 4.5 or 8.5 days (Birge et al. 1979). Concentrations of approximately 340 μg/L caused an incidence of 13-16 percent teratic larvae, while concentrations of about 3,850 μg/L resulted in 47-69 percent teratic larvae.

Mosquitofish (Gambusia affinis) survival was unaffected in a 48-hr exposure to 10,000 μg/L (Darwazeh and Mulla 1974). LC50s of 38,200 and 31,600

μg/L were reported for the guppy (Poecilia reticulata) after exposures of 48 and 72 hr, respectively (Tscheu-Schluter 1976). Mortalities of 40 and 53.2 percent were observed at 96 hr exposures of 28,600 and 37,200 μg/L, respectively (Bogacka et al. 1990). Exposure of the Mozambique tilapia, Tilapia mossambica, to 1,100 μg/L of atrazine for 30 to 90 days affected blood composition, oxygen consumption, water content, and the biochemistry of the brain and liver (Prasad et al. 1991a,b; Srinivas et al. 1991). It also resulted in increased serum sodium and potassium, and decreased serum calcium, magnesium and bicarbonate (Prasad and Reddy 1994).

The embryo and larval stages of several amphibian species were exposed to atrazine (Birge et al 1980). LC50s for continuous exposure of embryos and larvae through 4 days post-hatch were 410 μg/L for the bullfrog (Rana catesbiana), 7,680 μg/L for the leopard frog (Rana pipiens), 17,960 μg/L for the pickerel frog (Rana palustris), and >48,000 μg/L for the American toad (Bufo americanus). Concentrations of atrazine in excess of 5,000 μg/L were required to cause an incidence of teratic larvae in excess of 7 percent. Survival and growth of R. pipens tadpoles were unaffected after 41 days of exposure to 25 μg/L (Detenbeck et al. 1996). A 96-hr exposure of African clawed frog (Xenopus laevis) embryos to 8,000 μg/L resulted in 100 percent abnormal embryos (Morgan et al. 1996).

Several aquatic ecosystem studies, either artificial laboratory microcosms or field mesocosms, have provided valuable insight into ecosystem structural and functional responses to atrazine. A mixed assemblage of algal species exposed to 10 μg/L of atrazine for periods of time ranging from 1 day to 3 weeks exhibited reductions in gross productivity between 39 and 78 percent (Kosinski et al. 1983; Kosinski and Merkle 1984). Exposure of an experimental stream periphyton community to 1,000 μg/L for 14 days caused

severe population density reductions in several species, and total destruction of the green alga, Cladophora glomerata (Kosinski 1984). The extreme toxicity to C. glomerata is notable because of the dominant role that it often plays in structuring a benthic community. By contrast, no effects were observed upon stream macroinvertebrate community structure, periphyton production or biomass, and the community photosynthesis/respiration ratio following a 30-day exposure at 25 μg/L (Lynch et al. 1985).

Malanchuk and Kollig (1985) observed chemical changes in an experimental stream community consisting of microscopic autotrophs and heterotrophs following the introduction of atrazine at a nominal concentration of 100 μg/L for a 2-week exposure period, followed by its removal from the ecosystem. They observed decreased diurnal fluctuations in pH and dissolved oxygen concentrations, as well as lower mean values for these parameters while atrazine treatment was on-going. Nitrate nitrogen levels were increased. Following the cessation of atrazine treatment, there was a rapid recovery for each of these parameters back to control levels.

Moorhead and Kosinski (1986) observed reduced net primary productivity at 100 μg/L. Biomass reductions were noted in a stream Aufwuchs community exposed to 24 or 134 μg/L of atrazine for 12 days (Krieger et al. 1988). A 24-hr exposure of 77.5 μg/L had no effect upon algal cell numbers or biomass in a natural stream periphyton community (Jurgenson and Hoagland 1990). An exposure of approximately 0.5 μg/L for 6 months resulted in an initial decrease in phytoplankton species followed by a recovery (Lakshminarayana et al. 1992). In contrast, Gruessner and Watzin (1996) did not observe any effect upon a stream community of attached algae and benthic invertebrates at 5 μg/L. Pearson and Crossland (1996) reported an inhibition of photosynthesis

by the periphyton community of an artificial stream following exposure of 100 μg/L of atrazine for 30 days.

In a static pond microcosm (1 L beaker), Brockway et al. (1984) found that a 7-day exposure to 5.0 μg/L had no effect upon diurnal oxygen production, a measure of photosynthesis, by the various species of green and blue-green algae present. A 50 μg/L exposure for 12 days resulted in a 25-30 percent reduction in diurnal oxygen production, while 7-12 day exposures at 100 to 5,000 μg/L further decreased oxygen production. Exposure of a freshwater microcosm to 5.1 μg/L of atrazine for 7 weeks did not affect the species composition of phytoplankton, zooplankton or benthic macroinvertebrates, but did cause a slight decrease in photosynthetic activity (Van den Brink 1995). Hamala and Kollig (1985) found an approximate 75 percent decrease in the productivity/respiration (P/R) ratio in a 14 day exposure to 100 μg/L of a periphyton-dominated microcosm which contained 33 algal taxa. They also observed reduced algal densities, decreased species diversity, altered species composition and reduced biomass accumulation. In a 21-day recovery period, net community productivity returned to control values within 16 days, while very little recovery occurred in community structural parameters. This fairly rapid recovery in a functional parameter indicated that the primary effect of atrazine at this exposure level was algistatic and not algicidal for those species involved in the recovery.

Stay et al. (1985), using a 3.7 L laboratory microcosm consisting of 10 algal species and 5 animal species (one protozoan, one rotifer, and three crustaceans), found that reduction in the ratio of ^{14}C uptake/chlorophyll a was the most sensitive measure of atrazine effect. This suggested that the effectiveness of the photosynthetic system was impaired. The lowest exposure (i.e., 43.8 μg/L over 60 days) resulted in significant reductions

(approximately 60-90 percent) in the ratio throughout most of the study. Higher exposures (nominal concentrations of 100 to 500 μg/L) caused further reductions in this ratio, but not as large a difference as between controls and the lowest exposure.

Experimental ponds in Kansas that were exposed for several years to single annual applications of atrazine at nominal concentrations of 20 μg/L or more exhibited reductions in the production and biomass of phytoplankton, in macrophyte populations and in populations of benthic insect grazers, bullfrog (Rana catesbiana) tadpoles, grass carp (Ctenopharyngodon idella) that had been introduced, and bluegills (deNoyelles et al. 1982, 1989, 1994). Initial nominal concentrations of 20, 100, 200 and 500 μg/L depressed phytoplankton growth within a few days in the ponds. However, after 3 weeks, phytoplankton production and biomass were similar to controls. deNoyelles and Kettle (1985) observed reduced photosynthesis of 40 percent or more in short-term (24-hr) bioassays at these same atrazine concentrations, but longer-term bioassays (20 days) and the experimental pond studies showed a recovery from this initial reduction.

Benthic insect community structure was studied in the same Kansas experimental ponds following two single annual treatments at 20, 100 and 500 μg/L (Dewey 1986; Dewey and deNoyelles, 1994). Significant reductions of both species richness and total abundance of emerging insects was observed at even the lowest exposure of 20 μg/L. Abundances of the herbivorous, non-predatory insects were reduced at 20 μg/L, but not abundances of the predatory species. This indicated that the observed loss of total insects was a secondary effect due to feeding habit and loss of plant life, rather than a direct toxic effect. Loss of insect habitat, particularly in the form of macrophytes, also

likely had some effect upon the insect community. These effects tended to destabilize the ecosystem (Dewey and deNoyelles 1994).

Species composition of macrophytes was altered in a pond mesocosm community following an 8-week exposure to 50 μg/L of atrazine (Fairchild et al. 1994a). However, functional parameters were unaffected, indicating functioning redundancy within the ecosystem. Juttner et al. (1995) did not observe any effects upon the plankton community of a pond mesocosm following a 2-month exposure to 5 μg/L, but did observe decreased oxygen production, pH and conductivity at 10 μg/L, and decreased phytoplankton populations at 182 μg/L. At 318 μg/L, reproduction was affected in Daphnia longispina and a population of rotifers, Polyarthra sp., was eliminated.

In a laboratory microcosm using a naturally derived microorganism community, Pratt et al. (1988) observed that a 21-day exposure to a mean measured concentration of 10 μg/L of atrazine did not affect the dissolved oxygen, a measure of photosynthetic function, but that a concentration of 32.0 μg/L caused significant reductions in this parameter. This resulted in a calculated maximum acceptable toxicant concentration (MATC) of 17.9 μg/L based upon this functional endpoint. Several other endpoints, such as protozoan colonization, biomass protein, chlorophyll a and potassium levels, were less sensitive than dissolved oxygen, and had a calculated MATC of 193 μg/L.

Stay et al. (1989) studied atrazine effects in 1 L laboratory microcosms containing mixed phyto- and zooplankton cultured from three Oregon lakes and one pond. A 42-day exposure of approximately 15 μg/L atrazine did not affect net primary productivity, the P/R ratio, or pH, but these parameters were significantly reduced from controls at a mean measured concentration of approximately 84 μg/L.

Larsen et al. (1986) measured photosynthetic ^{14}C uptake in a 3 L Taub microcosm community at different time intervals for up to 373 days after treatment with atrazine. EC50s ranged from 24 µg/L at 177 days to 131 µg/L at 43 days after atrazine treatment.

A 50 m^2 pond community exposed to atrazine for 4 months at a concentration between 60 and 120 µg/L eliminated a population of duckweed, Lemna minor, within 27 days (Gunkel 1983). Gunkel also observed a rapid succession of algal species and a reduced rate of reproduction in Daphnia pulicaria. Treatments of a pond mesocosm community with 20, 100 and 300 µg/L of atrazine caused decreases in cell numbers of green algae and of cladoceran populations, but increased numbers of cryptomonads (Neugebauer et al. 1990).

In experimental ponds treated with 20 µg/L of atrazine in May and June for two years, there was decreased abundance of Endochironomus nigricans in June and of total invertebrates in both May and June, followed by recovery in July (Huggins et al. 1994). Epiphytes, detritovores and generalists also exhibited initial decreases in populations, followed by a recovery.

A short-term exposure (>3 hr) of pond algae to 10 µg/L of atrazine was observed to increase the rate of fluorence for photosystem II (Ruth 1996).

In two reports of studies conducted at the same site, a lake community was enclosed with a limnocorral (5 m x 5 m x 5 m deep) to which atrazine was added. Both studies focused on the periphyton community. In the first study (Herman et al. 1986), the limnocorrals received two nominal atrazine applications of 100 ug/L, one on day 0 and another on day 35. After 34 days of exposure to measured concentrations ranging between 80 and 140 µg/L, a reduction in periphyton ash-free dry weight was observed. Over a 9 week period with the two atrazine applications, which resulted in measured concentrations of approximately 80 to 140 ug/L after the first application and

110 to 190 ug/L after the second application, reductions occurred in chlorophyll a, organic matter and total periphyton algal biomass. In the second study (Hamilton et al. 1987), a 230-day exposure to a mean measured atrazine concentration of 80 µg/L caused approximate reductions of 60 percent in biomass, 22 percent in cell numbers and 32 percent in number of species. The results were more pronounced in exposures to mean measured atrazine concentrations of 140 and 1,560 µg/L. A shift in community structure occurred from a chlorophyte-dominated community to a diatom-dominated community.

Aquatic enclosures exposed to a nominal atrazine application of 100 µg/L on June 1 followed by a second application of the same concentration 35 days later, exhibited a gradual die-off of the phytoplankton, a long period of recovery for the green algal community, and a distinct shift in the taxonomic composition of algae (Hamilton et al. 1988). Thirteen days after the first application, significant declines occurred in populations of the green algal species Elakatothrix gelatinosa, Tetraedon minimum, Sphaerocystis schroeteri, and Oocystis lacustris; and of the dinoflagellate, Gymnodinium spp. Seventy-seven days after the second application, phytoplankton communities were still distinctly different, and total fresh weight biomass was reduced. By 323 days after the first application, the phytoplankton assemblages were again similar between control and treated enclosures.

From day 1 to day 114, control enclosures had an average of five more taxa than the atrazine-treated enclosures (Hamilton et al. 1988). During the period between days 49 and 77, the green algal (Chlorophyta) biomass represented <7 percent of that found in the controls. By the following spring (day 323), the biomass had returned to control levels. The herbicide treatment did not affect the rotifer or crustacean communities. In the same exposures, Hamilton et al. (1989) observed that the atrazine-treated

enclosures became clearer with increased Secchi disc readings, while readings of dissolved oxygen, chlorophyll, dissolved organic carbon, and particulate organic carbon decreased.

Using 1.70 m^2 enclosures in a moderately entrophic lake, Lampert et al. (1989) observed decreased photosynthesis and decreased populations of certain zooplankters at atrazine concentrations of 0.1 and 1.0 μg/L. At 0.1 μg/L, populations of Daphnia sp. were severely reduced by 15 days, and oxygen concentrations were reduced after 10 days. At 1.0 μg/L, concentrations of chlorophyll a and oxygen were reduced by 10 days as were populations of Daphnia, Cyclops, and Bosmina species, and nauplii larvae. At 0.1 μg/L, there was an apparent recovery after about 25 days. Genoni (1992) observed a decreased algal population density and a decreased "scope for change in ascendency" in a microcosm community exposed to 250 μg/L. The "scope for change in ascendency" is a biological system response endpoint, considered to be analagous to the "scope for growth" endpoint for individual organisms.

Gustavson and Wangberg (1995) observed some minor changes in species composition of the phytoplankton community in a lake mesocosm community after a 20-day exposure to 20 μg/L. EC50s were 58 and 52 μg/L for the phytoplankton community, and 52 and 54 μg/L for the periphyton community. Brown and Lean (1995) found that a short-term exposure (3 hr) of lake phytoplankton to atrazine resulted in a much lower EC50 based upon photosynthetic carbon assimilation (i.e., 100 μg/L), than when based upon phosphate or ammonium assimilation (14,000 and >33,000 μg/L, respectively). A stream periphyton community exhibited a significant reduction in chlorophyll a following a brief exposure (< 4 hr) to 109 ug/L (Day 1993). Caux and Kent (1995) observed a reduction in green algae in Quebec streams following the spring atrazine runoff pulse, with a maximum stream concentration of approximately 40 ug/L.

Detenbeck et al. (1996) observed a decrease in the gross productivity of a wetland mesocosm community at an atrazine concentration of 15 μg/L. There also was an increase in the concentrations of dissolved nutrients in the water.

From the various studies of ecosystem effects (i.e., microcosm, mesocosm and limnocorral studies), the lowest concentrations of atrazine that have resulted in temporary negative effects upon abundance of aquatic plants (primary effect) and animals (secondary effect) have generally occurred at 15-20 μg/L and above. Studies by Kosinski et al. (1983), Kosinski and Merkle (1984), Lakshminarayana et al. (1992), and Lampert et al. (1989) have observed effects at lower concentrations. It appears that for effects at concentrations up to 15 μg/L, the communities can recover quite rapidly following dissipation of the atrazine concentration. In a review of microcosm and mesocosm studies with atrazine, Giddings and Biever (1994) concluded that concentrations of 20 μg/L or less typically caused minor effects, if any, on primary production and plant community composition, and recovery occurred quickly, even if atrazine remained in the system. Concentrations above 50 μg/L caused more severe reductions in productivity, plant biomass, and community structure, as well as indirect effects on herbivorous invertebrates and fish. They further stated that freshwater ecosystems can recover from the effects of atrazine in a year or less except at very high exposures of 500 ug/L or greater.

In summary, various cyanobacteria had EC50 values for exposure durations of 30 ug/L or greater, while EC50 values for green algae, diatoms and cryptomonads were ≥15 ug/L. Among vascular plants, duckweed had a minimal 4-day EC50 of 92 ug/L. Wild rice was affected at 50 ug/L, and wild celery had reduced growth at 8 ug/L. Several rooted vascular plants had (i.e., coontail,

bushy pondweed and Elodea) EC50 values between 21 and 24 ug/L. Several species of water moss (Fontinalis sp.) exhibited reduced photosynthetic activity at 10 ug/L, with one species affected at 2 ug/L. EC/LC 50 values for protozoans, coelenterates, annelids, molluscs and rotifers were ≥7,480 ug/L. Various crustaceans had LC50 values ≥5,700 ug/L. The most sensitive endpoints among fish were rainbow trout plasma protein and kidney ultrastructural changes at atrazine exposures of 3 and 3.5 ug/L, respectively. The lowest LC50 values in fish were 176-272 ug/L for 4.5 to 8.5-day exposures with early life-stages of channel catfish. Frog embryo and tadpole life-stages had LC50 values ≥410 ug/L. In most aquatic ecosystem studies, reductions in algal or vascular plant biomass were observed at concentrations ≥15 ug/L. This commonly resulted in the reduction of herbivore populations, as well. One exception reported effects at much lower concentrations (as low as 0.1 ug/L).

From these freshwater "Other Data", most of the "effect" levels of possible biological significance appear to be ≥ 15 ug/L. This concentration is greater than the Final Acute Values and Final Chronic Values, and therefore does not determine the Criterion Continuous Concentration.

Additional data are available for saltwater algae, kelp, submerged vascular plants, emergent vascular plants, and aquatic animals (Table 6). EC50 values for various green algal species ranged from 37 ug/L to 1,500 ug/L (Walsh 1972; Hollister and Walsh 1973; Hughes 1986, 1988; Samson and Popovich 1988; Gaggi et al. 1995). A 48-hr exposure of the green alga, Dunaliella bioculata, to 216 ug/L of atrazine resulted in a growth reduction of approximately 35 percent (Felix et al. 1988). Seven-day growth tests with the green alga, Nannochloris oculata, suggested that atrazine toxicity was dependent on light and temperature (Karlander et al., 1983; Mayasich et al.,

1986), although the effect was not dramatic. A concentration of 15 ug/L changed the doubling time in N. oculata (Mayasich et al. 1987).

Diatom species were similar to green algae in their sensitivities to atrazine. EC50 values for exposures of various durations were generally between 20 and 600 ug/L (Walsh 1972; Hollister and Walsh; Walsh et al. 1988). Plumley and Davis (1980) observed reduced photosynthesis in Nitschia sigma in a 7-day exposure to 220 ug/L.

The kelp, Laminaria saccharina, had a similar sensitivity. A two-day exposure was sufficient to significantly reduce sexual reproduction at concentrations ≥72.2 ug/L, with no effect at 33.2 ug/L (Thursby and Tagliabue 1990).

Inhibition concentrations of 77 to 120 ug/L for a 50% effect on photosynthesis by vascular plants in short-term (2 to 4 hours) exposures to atrazine (Jones and Winchell, 1984) were similar to the effects upon growth and photosynthesis in longer exposures with several other species (Table 4). Eelgrass, Zostera marina, had reduced oxygen evolution at 100 ug/L (Kemp et al. 1981), and complete inhibition of photosynthesis and growth at 1,000 (Kemp et al. 1981) and 1,900 ug/L (Schwarzschild et al. 1994). The emergent salt-marsh rush, Juncus roemerianus, exhibited effects indicative of stress after a 35-day exposure to 30 ug/L (Lytle and Lytle 1998).

Values for LC50s for the copepod, Acartia tonsa, at 24, 48 and 72 hours showed that the sensitivity to atrazine increased with increasing duration of exposure (Tables 1 and 6). Adult fiddler crabs, Uca pugnax, were not very sensitive to one-time applications of atrazine either in field or laboratory exposures (Plumley et al., 1980). There was, however, a seasonal effect on the sensitivity of this species even when the laboratory conditions were the same. Animals collected in the summer were more sensitive to

atrazine than those collected in either the spring or fall (Plumley et al., 1980). Two other species of crabs, Sesarma cinereum and Panopeus sp., were also insensitive to very high levels of atrazine (Plumley et al. 1980).

A mesocosm study of a mixed assemblage of marine phytoplankton species demonstrated reduced photosynthesis and primary production at concentrations of 0.12 and 0.56 ug/L (Bester et al 1995). This is much lower than effect levels demonstrated from the other studies.

Unused Data

Data from some studies were not used in this document, as they did not meet the criteria for inclusion as specified in the Guidelines (Stephan et al., 1985). The reader is referred to the Guidelines for further information regarding these criteria.

Some data on the effects of atrazine on aquatic organisms were not used because the studies were conducted with species that are not resident in North America or Hawaii (e.g., Portmann 1972; Gzhetotskii et al. 1977; Gunkel and Kausch 1976; Juhnke and Luedemann 1978; Prasad et al. 1990, 1995; Nagel 1992; Hendriks and Stouten 1993; Hendriks and Stouten 1993; Lewis et al. 1993; L'Haridon et al. 1993; Biagianti-Risbourg and Bastide 1995; Steinberg et al. 1995; Alazemi et al. 1996; Hussein et al. 1996). Results were not used if the duration of the exposure was not specified or was unclear (e.g., Hopkin and Kain 1968; Portmann 1972; Tellenbach et al. 1983; Sampson and Popovic 1988), or if the procedures or test materials were not adequately described or translated (e.g. Braginskii 1973; Shcherban 1973; Schmidt 1987; Mark and Solbe 1998).

The acute toxicity data of Bathe et al. (1973,1975) were not used due to an insufficient number of test organisms. A chronic study with Gammarus fasciatus was not used due to low survival in the controls (Macek et al. 1976). Studies published only as abstracts of presentations were not used (e.g. Palmstrom and Krieger 1983; Zora and Paladino 1986; Fairchild et al. 1994b). Secondary observations reported in a review were not used (Hurlbert 1975). Similarly, a paper by Pratt et al. (1993) was not used, as the data it contained had been previously published. A study by Butler et al. (1975) was not used since data from several algal taxa were grouped in the reporting of results. Stratton and Giles (1990) expressed toxicity on the basis of cell numbers.

Toxicity data from laboratory tests were generally not used if the test material was a formulation and atrazine comprised less than 80 percent of its weight (Walker 1964; Hiltibran 1967; Semov and Iosifov 1973; Pavlov 1976; Antychowicz et al. 1979; Hartman and Martin 1985; Sreenivas and Rana 1991, 1994); if atrazine was a component of a pesticide mixture (Ort et al. 1994); or if atrazine was dosed in the diet (Cossarini-Dunier et al. 1988). Toxicity tests by Tubbing et al. (1993) and Schmitz et al. (1994) were not used because the tests were performed in river water which was likely contaminated with various other chemicals. Similarly, a cytopathological study of fish exposed to a spill of atrazine plus other pesticides was not used (Spazier et al. 1992). Effects data were not used if the atrazine exposure was part of a soil mixture (Jones and Estes 1984). McBride and Richards (1975) exposed excised tissue.

A study of atrazine accumulation by Bohn and Muller (1976) was not used due to expression of results on a volume basis rather than a weight basis. A bioconcentration study by Walsh and Ribelin (1973) was not used due

to the use of nominal atrazine concentrations in the exposure water rather than measured concentrations. Data were not used if the exposure was to radiolabeled atrazine (Davis et al., 1979; Jones et al., 1982, 1986; McEnerney and Davis, 1979; Pillai et al., 1977, 1979; Weeter et al. 1980; Neumann et al. 1987). Uptake and accumulation from exposures in flasks or microcosms were not used if ^{14}C only was measured and not atrazine itself (e.g. Isensee 1976, 1987; Kearney et al. 1977; Huckins et al. 1986; Mailhot 1987). A strictly methodological report (e.g., Holland et al. 1994) was not used.

A biochemical study of resistant strains of mutated Chlamydomonas reinhardtii was not used (Ottmeier et al. 1991). A study of atrazine effects upon promutagen activation by Selenastrum capricornutum was not used (Sauser and Klaine 1990).

Summary

Atrazine is not highly toxic to aquatic animals on an acute basis. SMAVs for 15 freshwater species ranged from 720 µg/L for a midge, Chironomus tentans, to >37,100 µg/L for an annelid, Lumbriculus variegatus. Within this overall range, SMAVs for seven fish species ranged from 6,300 µg/L for the brook trout, Salvelinus fontinalis, to 27,000 µg/L for the brown trout, Salmo trutta. Genus Mean Acute Values for atrazine are available for eight genera of saltwater animals and range from 1,000 to >30,000 µg/L; a factor of greater than 30. Acute values for the four most sensitive genera (three crustaceans and one fish) differed by a factor of 8.5.

Chronic effects of atrazine exposure to aquatic animals have been studied with six freshwater species, three of which are invertebrates and three of which are fish. In three tests with Ceriodaphnia dubia, chronic

values were 3,500, 3,500, and 1,732 µg/L. Reproduction was reduced in Daphnia magna at 250 µg/L, but not at 140 µg/L. A chronic value of 187 µg/L was derived, and a corresponding acute-chronic ratio of 36.90. The growth of a midge, Chironomus tentans, was retarded at 230 µg/L of atrazine, but not at 110 µg/L. A chronic value of 159 µg/L was calculated, and a corresponding acute-chronic ratio of 4.528 was derived.

Brook trout, Salvelinus fontinalis, had reduced growth at 120 µg/L, but not at 65 µg/L, in a chronic exposure. A chronic value of 88.3 µg/L and an acute-chronic ratio of 71.35 were calculated. In two life-cycle tests with the fathead minnow, Pimephales promelas, the chronic limits were set in the first test at 210 and 870 µg/L based upon no adverse effects observed in a chronic exposure at 210 µg/L and 25 percent mortality in 3 to 5-day old fry at 870 µg/L. The chronic value was 430 µg/L, and the acute-chronic ratio was 34.88. In the second test, chronic limits were 250 and 460 µg/L, based upon growth of larval fish, resulting in a chronic value of 339 µg/L and an acute-chronic ratio of 59.00. The acute-chronic ratio for this species was calculated at 45.36, the geometric mean. Bluegills, Lepomis macrochirus, were unaffected in a chronic exposure to 95 µg/L, while an equilibrium loss occurred in bluegills exposed to 500 µg/L. These were established as the chronic limits, with a chronic value of 218 µg/L. Since the acute value was a "greater than" value, the acute-chronic ratio was >36.70.

SMAVs for 9 saltwater species ranged from 1,000 ug/L for the mysid, Mysidopsis bahia, to >30,000 ug/L for the eastern oyster, Crassostrea virginica. The chronic value for M. bahia was 123.3 µg/L, based on survival. The chronic value for Cyprinodon variegatus was 2,542 µg/L, based on mortality of juveniles. The acute-chronic ratio for M. bahia was 8.110, while the

acute-chronic ratio for C. variegatus was > 6.294. Effect concentrations for plants were lower than the acute and chronic values for aquatic animals.

Atrazine toxicity to aquatic plants, both algae and macrophytes, commonly occurs at concentrations of 15 µg/L and above, with several reports of toxicity to specific plant taxa at concentrations below 10 µg/L. Effects are thought to be algistatic rather than algicidal at these lower concentrations, with recovery occurring once the atrazine is removed. The lowest EC50 values for green algae with exposure durations of 4 days or longer were 10.2 and 4 µg/L for Chlamydomonas reinhardtii and Selenastrum capricornutum, respectively. Mean EC50s for these species would be considerably higher. The lowest reported EC50 for a vascular plant species, Elodea canadensis, was 21 µg/L in a 14-day exposure, using wet weight as an endpoint. A Final Plant Value was not determined, as there were not any tests performed of sufficient duration (i.e., 4 days) in which the exposure concentrations were measured to meet the requirements of the Guidelines (Stephan et al., 1985).

Atrazine has a limited tendency to accumulate in tissues of aquatic plants and animals. BCFs ranged from <0.27 to a maximum of 8.5 in three species of fish. Accumulation in Daphnia magna was less than five-fold over the concentration in water.

Aquatic ecosystem structural and functional parameters have most frequently been observed to be adversely affected by atrazine concentrations of 15 µg/L and above. However, in a few studies, adverse effects have been observed at lower exposure levels. The observed effects have been on both the plant and animal communities, with the effects upon the animal community being secondary in nature as a result mainly of decreased availability of shelter and plant matter for food.

The national criteria given below were determined on the basis of atrazine toxicity to aquatic animals. The Criterion Maximum Concentrations for freshwater and saltwater were one-half of the respective Final Acute Values, which were based upon Table 1 acute toxicity values for all invertebrate and vertebrate species. The Criterion Continuous Concentrations for freshwater and saltwater were based upon the Final Chronic Values for fish. These were calculated by dividing the Final Fish Acute-Chronic Ratio into the Final Acute Value in each case. Separate Final Acute-Chronic Ratios were determined for fish and invertebrates due to the large differences in the ratios for the two groups. The Fish Chronic Values became the Criterion Continuous Concentrations, since there were no Final Plant or Final Residue Values; and the results from studies in the "Other Data" section did not appear to warrant the establishment of a lower concentration at this time.

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 animals and their uses should not be directly affected unacceptably if the four-day average concentration of atrazine does not exceed 12 μg/L more than once every three years on the average and if the one-hour average concentration does not exceed 330 μg/L more than once every three years on the average. The four-day average of 12 ug/L for the protection of freshwater animals should also be protective of most freshwater plants.

The procedures described in the "Guidelines for Deriving Numerical National Water Quality 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 atrazine does not exceed 11 μg/L more than once every three years on the average and if the one-hour average concentration does not exceed 310 μg/L more than once every three years on the average. The four-day average of 11 ug/L for the protection of saltwater animals should also be protective of most saltwater plants.

Implementation

As discussed in the Water Quality Standards Regulation (U.S. EPA 1983) and the Foreword to this document, a water quality criterion for aquatic life has regulatory impact only when it has been adopted in a state water quality standard. Such a standard specifies a criterion for a pollutant that is consistent with a particular designated use. With the concurrence of the U.S. EPA, states designate one or more uses for each body of water or segment thereof and adopt criteria that are consistent with the use(s) (U.S. EPA 1983, 1987, 1994). Water quality criteria adopted in state water quality standards could have the same numerical values as criteria developed under Section 304, of the Clean Water Act. However, in many situations states might want to adjust water quality criteria developed under Section 304 to reflect local environmental conditions and human exposure patterns. Alternatively, states may use different data and assumptions than EPA in deriving numeric criteria that are scientifically defensibly defensible and protective of designated uses. State water quality standards include both numeric and narrative

criteria. A state may adopt a numeric criterion within its water quality standards and apply it either state-wide to all waters designed for the use the criterion is designed to protect or to a specific site. A state may use an indicator parameter or the national criterion, supplemented with other relevant information, to interpret its narrative criteria within its water quality standards when developing NPDES effluent limitations under 40 CRF 122.44(d) (1) (vi).2.

Site-specific criteria may include not only site-specific criterion concentrations (U.S. EPA 1994), but also site-specific, and possibly pollutant-specific, durations of averaging periods and frequencies of allowed excursions (U.S. EPA 1994), but also site-specific, and possibly pollutant-specific, durations of averaging periods and frequencies of allowed excursions (U.S. EPA 1991). The averaging periods of "one hour" and "four days" were selected by the U.S. EPA on the basis of data concerning how rapidly some aquatic species react to increases in the concentrations of some aquatic pollutants, and "three years" is the Agency's best scientific judgment of the average amount of time aquatic ecosystems should be provided between excursions (Stephan et al. 1985; U.S. EPA 1991). However, various species and ecosystems react and recover at greatly differing rates. Therefore, if adequate justification is provided, site-specific and/or pollutant-specific concentrations, durations, and frequencies may be higher or lower than those given in national water quality criteria for aquatic life.

Use of criteria, which have been adopted in state water quality standards, for developing water quality-based permit limits and for designing waste treatment facilities requires selection of an appropriate wasteload allocation model. Although dynamic models are preferred for the application

of these criteria (U.S. EPA 1991), limited data or other considerations might require the use of a steady-state model (U.S. EPA 1986).

Guidance on mixing zones and the design of monitoring programs is also available (U.S. EPA 1987, 1991).

Table 1. Acute Toxicity of Atrazine to Aquatic Animals

Species	Method[a]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)[b]	Species mean Acute value (µg/L)	References
			FRESHWATER SPECIES			
Hydra, *Hydra* sp.	R,M	≥98.5%	48.9	3,000	3,000	Brooke 1990
Annelid, *Lumbriculus variegatus*	F,M	≥98.5%	67.3	>37,100	>37,100	Brooke 1990
Snail (adult), *Physa* sp.	R,M	≥98.5%	48.9	>34,100	>34,100	Brooke 1990
Cladoceran (<12 hr), *Ceriodaphnia dubia*	S,M	>99%	57.1	>30,000	>30,000	Oris et al. 1991
Cladoceran (<24 hr), *Ceriodaphnia dubia*	S,M	97%	52	>4,900	-	Jop 1991c
Cladoceran (<24 hr), *Daphnia magna*	S,U	94%	-	6,900	-	Macek et al. 1976
Cladoceran (>24 hr), *Daphnia magna*	S,U	≥96%	250	>39,000	-	Marchini et al. 1988
Cladoceran, *Daphnia magna*	F,M	79.6%	170	49,000	49,000	Putt 1991
Amphipod, *Hyalella azteca*	F,M	≥98.5%	67.4	14,700	14,700	Brooke 1990
Stonefly (nymph), *Acroneuria* sp.	F,M	≥98.5%	67.4	6,700	6,700	Brooke 1990
Midge (1st instar), *Chironomus tentans*	S,U	94%	-	720	720	Macek et al. 1976
Coho salmon (yearling), *Oncorhynchus kisutch*	R,M	≥80%	101	>18,000	>18,000	Lorz et al. 1979
Brown trout, *Salmo trutta*	R,U	-	11	27,000	27,000	Grande et al. 1994
Brook trout (juvenile), *Salvelinus fontinalis*	F,U	94%	-	6,300	6,300	Macek et al. 1976

Table 1. (continued)

Species	Method[a]	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)	Species Mean Acute Value (µg/L)	References
Fathead minnow *Pimephales promelas*	R,U	94%	-	15,000	-	Macek et al. 1976
Fathead minnow (juvenile), *Pimephales promelas*	S,M	97%	52	>4,900	-	Jop 1991a
Fathead minnow, *Pimephales promelas*	F,M	97.1%	20-40	20,000	20,000	Dionne 1992
Channel catfish (sac fry), *Ictalurus punctatus*	S,U	80%	78	>10,000	>10,000	Jones 1962
Bluegill (juvenile), *Lepomis macrochirus*	F,U	94%	-	>8,000	>8,000	Macek et al. 1976
Largemouth bass (fry), *Micropterus salmoides*	S,U	80%	78	>10,000	>10,000	Jones 1962
			SALTWATER SPECIES			
Eastern oyster (embryo/larval), *Crassostrea virginica*	S,U	97.4%	16[b]	>30,000	>30,000	Ward & Ballantine 1985
Copepod (adult), *Acartia clausii*	R,U	70%	6[b]	7,925	7,925	Thursby et al. 1990
Copepod (field), *Acartia tonsa*	S,U	97.4%	20[b]	94	-	Ward & Ballantine, 1985
Copepod (adult), *Acartia tonsa*	R,M	70%	31-32[b]	210.1	-	Thursby et al., 1990
Copepod (adult), *Acartia tonsa*	R,M	70%	31[b]	91.73	-	Thursby et al. 1990
Copepod (adult), *Acartia tonsa*	F,M	97.1%	30-34[b]	4,300	4,300	McNamara, 1991
Copepod (nauplius), *Eurytemora affinis*	S,M	97.1%	5[b]	500	-	Hall et al. 1994a,b

Table 1. (continued)

Species	Method[a]	Chemical	Salinity[b]	LC50 or EC50 (µg/L)	Species Mean Acute Value (µg/L)	References
Copepod (nauplius), *Eurytemora affinis*	S,M	97.1%	15	2,600	-	Hall et al. 1994a,b
Copepod (nauplius), *Eurytemora affinis*	S,M	97.1%	25	13,200	2,579	Hall et al. 1994a,b
Mysid (lab), *Mysidopsis bahia*	F,M	97.4%	20	1,000	1,000	Ward & Ballantine, 1985
Pink shrimp (field), *Penaeus duorarum*	S,U	97.4%	26	6,900	6,900	Ward & Ballantine, 1985
Grass shrimp (field), *Palaemonetes pugio*	S,U	97.4%	26	9,000	9,000	Ward & Ballantine, 1985
Fiddler crab, (field), *Uca pugilator*	S,U	97.4%	26	>29,000	>29,000	Ward & Ballantine, 1985
Sheepshead minnow (lab), *Cyprinodon variegatus*	F,M	97.4%	13	>16,000	-	Ward & Ballantine, 1985
Sheepshead minnow (larva), *Cyprinodon variegatus*	S,M	97.1%	5	16,200	-	Hall et al. 1994a,b
Sheepshead minnow (larva), *Cyprinodon variegatus*	S,M	97.1%	15	2,300	-	Hall et al. 1994a,b
Sheepshead minnow (larva), *Cyprinodon variegatus*	S,M	97.1%	25	2,000	5,660	Hall et al. 1994a,b
Spot (field), *Leiostomus xanthurus*	S,U	97.4%	12	8,500	8,500	Ward & Ballantine, 1985

[a] S = static; R = renewal; F = flow-through; M = measured; U = unmeasured.
[b] Salinity expressed as g/L.

Table 2. Chronic Toxicity of Atrazine to Aquatic Animals

Species	Test[a]	Chemical	Hardness (mg/L as $CaCO_3$)	Chronic Limits (µg/L)[b]	Chronic Value (µg/L)	References
			FRESHWATER SPECIES			
Cladoceran, *Ceriodaphnia dubia*	LC	>99%	57.1	2,500-5,000	3,500	Oris et al. 1991
Cladoceran, *Ceriodaphnia dubia*	LC	>99%	57.1	2,500-5,000	3,500	Oris et al. 1991
Cladoceran, *Ceriodaphnia dubia*	LC	97%	52	1,200-2,500	1,732	Jop 1991d
Cladoceran, *Daphnia magna*	LC	94%	32.2	140-250	187	Macek et al. 1976
Midge, *Chironomus tentans*	LC	94%	43.0	110-230	159	Macek et al. 1976
Brook trout, *Salvelinus fontinalis*	LC	94%	35.7	65-120	88.3	Macek et al. 1976
Fathead minnow, *Pimephales promelas*	LC	94%	36.2	213-870	430	Macek et al. 1976
Fathead minnow, *Pimephales promelas*	LC	97.1%	24-36	250-460	339	Dionne 1992
Bluegill, *Lepomis macrochirus*	LC	94%	33.9	95-500	218	Macek et al. 1976
			SALTWATER SPECIES			
Copepod, *Eurytemora affinis*	LC	97.1%	5	12,250-17,500	14,600	Hall et al. 1995
Copepod, *Eurytemora affinis*	LC	97.1%	15	17,500-25,000	20,900	Hall et al. 1995
Copepod, *Eurytemora affinis*	LC	97.1%	25	4,200-6,000	5,010	Hall et al. 1995
Mysid, *Mysidopsis bahia*	LC	97.4%	20	80-190	123.3	Ward & Ballantine, 1985
Sheepshead minnow, *Cyprinodon variegatus*	ELS	97.4%	13	1,900-3,400	2,542	Ward & Ballantine, 1985

Table 2. (continued)

Acute-Chronic Ratios

Species	Hardness (mg/L as $CaCO_3$)	Acute Value (µg/L)	Chronic Value (µg/L)	Ratio
Cladoceran, *Ceriodaphnia dubia*	57.1	>30,000	3,500	>8.571
Cladoceran, *Ceriodaphnia dubia*	57.1	>30,000	3,500	>8.571
Cladoceran, *Ceriodaphnia dubia*	52	>4,900	1,732	>2.829
Cladoceran, *Daphnia magna*	32.2	6,900	187	36.90
Midge, *Chironomus tentans*	43.0	720	159	4.528
Brook trout, *Salvelinus fontinalis*	35.7	6,300	88.3	71.35
Fathead minnow, *Pimephales promelas*	36.2	15,000	430	34.88
Fathead minnow, *Pimephales promelas*	24-36	20,000	339	59.00
Bluegill, *Lepomis macrochirus*	33.9	>8,000	218	>36.70
Copepod, *Eurytemora affinis*	5[c]	500	14,600	0.0342
Copepod, *Eurytemora affinis*	15[c]	2,600	20,900	0.1244
Copepod, *Eurytemora affinis*	25[c]	13,200	5,010	2.635
Mysid, *Mysidopsis bahia*	20[c]	1,000	123.3	8.110
Sheepshead minnow, *Cyprinodon variegatus*	13[c]	5,660	2,542	-

[a] LC = Life-cycle or partial life-cycle; ELS = early life-stage.
[b] Results are based on measured concentrations of atrazine.
[c] Salinity in g/L.

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

Rank[a]	Genus Mean Acute Value (µg/L)	Species	Species Mean Acute Value (µg/L)[b]	Species Mean Acute-Chronic Ratio[c]
		FRESHWATER SPECIES		
15	49,000	Cladoceran, *Daphnia magna*	49,000	36.90
14	>37,100	Annelid, *Lumbriculus variegatus*	>37,100	-
13	>34,100	Snail, *Physa* sp.	>34,100	-
12	>30,000	Cladoceran *Ceriodaphnia dubia*	>30,000	>3.163
11	27,000	Brown trout, *Salmo trutta*	27,000	-
10	20,000	Fathead minnow, *Pimephales promelas*	20,000	45.36
9	>18,000	Coho salmon, *Oncorhynchus kisutch*	>18,000	-
8	14,700	Amphipod, *Hyalella azteca*	14,700	-
7	>10,000	Channel catfish, *Ictalurus punctatus*	>10,000	-
6	>10,000	Largemouth bass, *Micropterus salmoides*	>10,000	-
5	>8,000	Bluegill, *Lepomis macrochirus*	>8,000	>36.70
4	6,700	Stonefly, *Acroneuria* sp.	6,700	-
3	6,300	Brook trout, *Salvelinus fontinalis*	6,300	71.35

Table 3 (continued)

Rank[a]	Genus Mean Acute Value (µg/L)	Species	Species Mean Acute Value (µg/L)[b]	Species Mean Acute-Chronic Ratio[c]
2	3,000	Hydra, *Hydra* sp.	3,000	-
1	720	Midge, *Chironomus tentans*	720	
		SALTWATER SPECIES		
9	>30,000	Eastern oyster, *Crassostrea virginica*	>30,000	-
8	>29,000	Fiddler crab, *Uca pugilator*	>29,000	-
7	9,000	Grass shrimp, *Palaemonetes pugio*	9,000	-
6	8,500	Spot, *Leiostomus xanthurus*	8,500	-
5	6,900	Pink shrimp, *Penaeus duorarum*	6,900	-
4	5,838	Copepod, *Acartia clausii*	7,925	-
4	5,838	Copepod, *Acartia tonsa*	4,300	-
3	5,660	Sheepshead minnow, *Cyprinodon variegatus*	5,660	>6.291
2	2,579	Copepod, *Eurytemora affinis*	2,579	2.635
1	1,000	Mysid, *Mysidopsis bahia*	1,000	8.110

[a] Ranked from most resistant to most sensitive based on Genus Mean Acute Value. Inclusion of "greater than" value does not necessarily imply a true ranking, but does allow use of all genera for which data are available so that the Final Acute Value is not unnecessarily lowered.
[b] From Table 1.
[c] From Table 2.

Table 3 (continued)

Fresh Water

Final Acute Value = 657.3 µg/L

Criterion Maximum Concentration = (657.3 µg/L)/2 = 328.6 µg/L

Final Fish Acute-Chronic Ratio = 56.88

Fish Chronic Value = 11.56 µg/L

Final Invertebrate Acute-Chronic Ratio = 9.239

Invertebrate Chronic Value = 71.14 µg/L

Salt Water

Final Acute Value = 611.7 µg/L

Criterion Maximum Concentration = (611.7 µg/L)/2 = 305.8 µg/L

Final Fish Acute-Chronic Ratio = 56.88

Fish Chronic Value = 10.75 µg/L

Final Invertebrate Acute-Chronic Ratio = 9.239

Invertebrate Chronic Value = 66.21 µg/L

Table 4. Toxicity of Atrazine to Aquatic Plants

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)[a]	Reference
			FRESHWATER SPECIES			
Green alga, *Chlamydomonas reinhardtii*	-	-	4	EC50 (cell number)	51	Schafer et al. 1993, 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	7	EC50 (cell number)	21	Schafer et al. 1993, 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	7	EC50 (cell number)	10.2	Schafer et al. 1993, 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	4	NOEC (growth inhibition)	3.4	Schafer et al. 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	4	EC50 (growth inhibition)	51.0	Schafer et al. 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	7	NOEC (growth inhibition)	5.1	Schafer et al. 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	7	EC50 (growth inhibition)	21.0	Schafer et al. 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	10	NOEC (growth inhibition)	3.7	Schafer et al. 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	10	EC50 (growth inhibition)	10.2	Schafer et al. 1994
Green alga, *Selenastrum capricornutum*	-	-	4	NOEC (cell number, biomass)	0.5	Univ of Mississippi 1990
Green alga, *Selenastrum capricornutum*	-	-	4	NOEC (chorohyll *a*, pheophytin *a*)	10	Univ of Mississippi 1990

Table 4. (cont.)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)	Reference
Green alga, *Selenastrum capricornutum*	-	-	4	LOEC (cell density, biomass)	1.0	Univ of Mississippi 1990
Green alga, *Selenastrum capricornutum*	-	-	4	LOEC (chlorophyll *a*, pheophytin *a*)	100	Univ of Mississippi 1990
Green alga, *Selenastrum capricornutum*	-	-	4	EC50 (cell number)	4	Univ of Mississippi 1990
Green alga, *Selenastrum capricornutum*	-	-	4	EC50 (pheophytin *a*)	20	Univ of Mississippi 1990
Green alga, *Selenastrum capricornutum*	-	-	4	EC50 (chlorophyll *a*)	150	Univ of Mississippi 1990
Green alga, *Selenastrum capricornutum*	99.1%	-	4	EC50 (cell number)	128.2	Gala and Giesy 1990
Green alga, *Selenastrum capricornutum*	97.0%	-	4	NOEC (cell number)	76	Hoberg 1991
Green alga, *Selenastrum capricornutum*	97.0%	-	4	MATC (cell number)	99	Hoberg 1991
Green alga, *Selenastrum capricornutum*	97.0%	-	4	LOEC (cell number)	130	Hoberg 1991
Green alga, *Selenastrum capricornutum*	97.0%	-	4	EC10 (cell number)	90	Hoberg 1991
Green alga, *Selenastrum capricornutum*	97.0%	-	4	EC50 (cell number)	130	Hoberg 1991
Green alga, *Selenastrum capricornutum*	97.0%	-	4	EC90 (cell number)	190	Hoberg 1991
Green alga, *Selenastrum capricornutum*	97.1%	-	5	NOEC (cell number)	16	Hoberg 1993a

Table 4. (cont.)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)	Reference
Green alga, *Selenastrum capricornutum*	97.1%	-	5	EC10 (cell number)	26	Hoberg 1993a
Green alga, *Selenastrum capricornutum*	97.1%	-	5	LOEC (cell number)	31	Hoberg 1993a
Green alga, *Selenastrum capricornutum*	97.1%	-	5	EC50 (cell number)	55	Hoberg 1993a
Green alga, *Selenastrum capricornutum*	97.1%	-	5	EC90 (cell number)	120	Hoberg 1993a
Duckweed, *Lemna minor*	-	-	14	NOEC (biomass)	10	Univ of Mississippi 1990
Duckweed, *Lemna minor*	-	-	14	LOEC (mature frond production)	10	Univ of Mississippi 1990
Duckweed, *Lemna minor*	-	-	14	LOEC (biomass)	100	Univ of Mississippi 1990
Duckweed, *Lemna minor*	-	-	14	EC50 (biomass)	8,700	Univ of Mississippi 1990
Duckweed, *Lemna gibba*	97%	-	7	EC50 (frond production)	180	Hoberg 1991b
Duckweed, *Lemna gibba*	97.1%	-	14	NOEC (frond number)	<3.4	Hoberg 1993b
Duckweed, *Lemna gibba*	97.1%	-	14	LOEC (frond number)	3.4	Hoberg 1993b
Duckweed, *Lemna gibba*	97.1%	-	14	EC10 (frond number)	6.2	Hoberg 1993b
Duckweed, *Lemna gibba*	97.1%	-	14	NOEC (frond biomass)	7.7	Hoberg 1993b
Duckweed, *Lemna gibba*	97.1%	-	14	EC10 (frond biomass)	12	Hoberg 1993b

Table 4. (cont.)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)	Reference
Duckweed, *Lemna gibba*	97.1%	-	14	LOEC (frond biomass)	17	Hoberg 1993b
Duckweed, *Lemna gibba*	97.1%	-	14	EC50 (frond number)	37	Hoberg 1993b
Duckweed, *Lemna gibba*	97.1%	-	14	EC50 (frond biomass)	45	Hoberg 1993b
Duckweed, *Lemna gibba*	97.1%	-	14	EC90 (frond biomass)	170	Hoberg 1993b
Duckweed, *Lemna gibba*	97.1%	-	14	EC90 (frond number)	220	Hoberg 1993b
Duckweed, *Lemna gibba*	97.4%	-	14	EC10 (frond number)	2.2[b/]	Hoberg 1993c
Duckweed, *Lemna gibba*	97.4%	-	14	EC10 (frond biomass)	4.2[b/]	Hoberg 1993c
Duckweed, *Lemna gibba*	97.4%	-	14	NOEC (frond number & biomass)	8.3[b/]	Hoberg 1993c
Duckweed, *Lemna gibba*	97.4%	-	14	LOEC (frond number & biomass)	18[b/]	Hoberg 1993c
Duckweed, *Lemna gibba*	97.4%	-	14	EC50 (frond biomass)	22[b/]	Hoberg 1993c
Duckweed, *Lemna gibba*	97.4%	-	14	EC50 (frond number)	50[b/]	Hoberg 1993c
Duckweed, *Lemna gibba*	97.4%	-	14	EC90 (frond number)	98[b/]	Hoberg 1993c
Duckweed, *Lemna gibba*	97.4%	-	14	EC90 (frond biomass)	110[b/]	Hoberg 1993c
Duckweed, *Lemna minor*	98%	-	10	EC50 (frond number)	56	Kirby and Sheahan 1994

Table 4. (cont.)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)	Reference
Duckweed, *Lemna minor*	98%	-	10	EC50 (fresh weight)	60	Kirby and Sheahan 1994
Duckweed, *Lemna minor*	98%	-	10	EC50 (chlorophyll)	62	Kirby and Sheahan 1994
Elodea, *Elodea canadensis*	-	-	10	NOEC (biomass)	10[c/]	Univ of Mississippi 1990
Elodea, *Elodea canadensis*	-	-	10	LOEC (biomass)	100[c/]	Univ of Mississippi 1990
Elodea, *Elodea canadensis*	-	-	10	LOEC (mature frond production)	10[c/]	Univ of Mississippi 1990
Elodea, *Elodea canadensis*	-	-	10	EC50 (biomass)	1,200[c/]	Univ of Mississippi 1990
Elodea, *Elodea canadensis*	-	-	10	LOEC (biomass)	100[d/]	Univ of Mississippi 1990
Elodea, *Elodea canadensis*	-	-	10	ECt0 (biomass)	25,400[d/]	Univ of Mississippi 1990
			SALTWATER SPECIES			
Diatom, *Skeletonema costatum*	-	30°	2	EC50 growth	265	Walsh, 1983
Green alga, *Platymonas* sp.	99.7%	30°	3	EC50 growth	100	Mayer, 1987
Green alga, *Chlorella* sp.	99.7%	30°	3	EC50 growth	140	Mayer, 1987
Green alga, *Neochloris* sp.	99.7%	30°	3	EC50 growth	82	Mayer, 1987

Table 4. (cont.)

Species	Chemical	Salinity*	Duration (days)	Effect	Concentration (ug/L)	Reference
Sago pondweed, *Potamogeton pectinatus*	97.1%	6	28	Dry weight LOEC	30	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	6	28	Wet weight LOEC	30	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	6	28	Rhizome tip Mass LOEC	300	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	6	28	Dry weight Chronic value	21.2	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	6	28	Wet weight Chronic value	21.2	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	6	28	Rhizome tip mass Chronic value	94.9	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Dry weight NOEC	7.5	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Wet weight NOEC	15	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Rhizome tip mass NOEC	30	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Dry weight LOEC	15	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Wet weight LOEC	30	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Rhizome tip Mass LOEC	300	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Dry weight Chronic value	10.6	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Wet weight Chronic value	21.2	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Rhizome tip mass Chronic value	94.9	Hall et al., 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	1-12	28	Dry weight Chronic value	5.3	Hall et al., 1997

Table 4. (cont.)

Species	Chemical	Salinity[e]	Duration (days)	Effect	Concentration (ug/L)	Reference
Eurasian watermilfoil, *Myriophyllum spicatum*	96.4%	9	28	IC50 photosynthesis	117	Kemp et al., 1983; Kemp et al., 1985
Eurasian watermilfoil, *Myriophyllum spicatum*	96.4%	9	35	IC50 growth (final biomass)	25	Kemp et al., 1983; Kemp et al., 1985
Eelgrass, *Zostera marina*	-	22	21	LC50	540	Delistraty & Hershner, 1984
Eelgrass, *Zostera marina*	-	20	21	LC50	100	Delistraty & Hershner, 1984
Eelgrass, *Zostera marina*	-	20	21	LC50	365	Delistraty & Hershner, 1984
Eelgrass, *Zostera marina*	-	19	21	LC50	367	Delistraty & Hershner, 1984

[a] Effect concentrations are based upon measured concentrations of atrazine during the exposure period.
[b] Effect concentration is based upon measured concentration of atrazine on the last day of exposure only.
[c] No sediment present.
[d] Sediment present.
[e] Salinity expressed as g/L.

Table 5. Bioaccumulation of Atrazine by Aquatic Organisms

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Concentration in Water (µg/L)	Duration (days)	Tissue	BCF or BAF	Reference
			FRESHWATER SPECIES				
Brook trout, *Salvelinus fontinalis*	94%	35.7	740	308	Muscle	<0.27	Macek et al. 1976
Bluegill, *Lepomis macrochirus*	94%	33.9	94	546	Muscle	<2.1	Macek et al. 1976
Fathead minnow, *Pimephales promelas*	94%	36.2	210	301	Eviscerated carcass	<8.1	Macek et al. 1976
Fathead minnow F_0 larvae, *Pimphales promelas*	97.1%	24-36	2,000	60	Whole body	6.5[a]	Dionne 1992
Fathead minnow adult males, *Pimephales promelas*	97.1%	24-36	2,000	274	Whole body	8.5[a]	Dionne 1992
Fathead minnow adult females, *Pimephales promelas*	97.1%	24-36	2,000	274	Whole body	8.5[a]	Dionne 1992
Fathead minnow F_1 embryos, *Pimephales promelas*	97.1%	24-36	2,000	3	Whole body composite sample	4.6[a]	Dionne 1992
Fathead minnow 14 day old larvae, *Pimephales promelas*	97.1%	24-36	2,000	14	Whole body	3.3[a]	Dionne 1992
Fathead minnow 30 day old larvae, *Pimephales promelas*	97.1%	24-36	2,000	30	Whole body	6.0[a]	Dionne 1992

[a] Based on ^{14}C measurements, and therefore represents a maximum possible bioconcentration factor.

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

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
			FRESHWATER SPECIES			
Mixed nitrifying, bacteria	-	-	28 days	Increased nitrite oxidation; ammonium oxidation unaffected	1,000	Gadkari 1988
Mixed nitrifying, bacteria	-	-	28 days	Ammonium oxidation unaffected	2,000	Gadkari 1988
Bacterium, *Pseudomonas putida*	-	214	16 hr	Incipient inhibition	>10,000	Bringmann and Kuhn 1976, 1977
Cyanobacterium, *Microcystis aeruginosa*	-	214	8 days	Incipient inhibition	3	Bringmann and Kuhn 1976; 1978a,b
Cyanobacterium, *Microcystis aeruginosa*	97.4%	-	5 days	Reduced cell numbers	108	Parrish 1978
Cyanobacterium, *Microcystis aeruginosa*	97.4%	-	5 days	Minimum algistatic concentration	440	Parrish 1978
Cyanobacterium, *Microcystis aeruginosa*	-	-	6 days	EC50 (growth)	630	Kallqvist and Romstad 1994
Cyanobacterium, *Microcystis aeruginosa*	-	-	6 days	EC50 (microplate method)	630	Kallqvist and Romstad 1994
Cyanobacterium, *Microcystic aeruginosa*	Technical or analytical	-	22 hr	96% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994
Cyanobacterium, *Microcystic aeruginosa*	Technical or analytical	-	22 hr	84% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Cyanobacterium, *Microcystis* sp.	Technical or analytical	-	4 days	EC50 (biomass)	90	Fairchild et al. 1998
Cyanobacterium, *Synechococcus leopoliensis*	-	-	5 days	EC50 (microplate method)	130	Kallqvist and Romstad 1994
Cyanobacterium, *Anabaena inaequalis*	>95%	-	12-14 days	EC50 (cell number)	30	Stratton 1984
Cyanobacterium, *Anabaena variabilis*	>95%	-	12-14 days	EC50 (cell number)	4,000	Stratton 1984
Cyanobacterium, *Anabaena cylindrica*	>95%	-	12-14 days	EC50 (cell number)	1,200	Stratton 1984
Cyanobacterium, *Anabaena cylindrica*	-	-	24 hr	EC50 (^{14}C uptake)	253[a]	Larsen et al. 1986
Cyanobacterium, *Anabena cylindrica*	-	-	24 hr	EC50 (^{14}C uptake)	178[a]	Larsen et al. 1986
Cyanobacterium, *Anabaena cylindrica*	-	-	24 hr	EC50 (^{14}C uptake)	182[b]	Larsen et al. 1986
Cyanobacterium, *Anabaena flos-aquae*	97%	-	5 days	EC50 (cell number)	230	Hughes 1986, 1988
Cyanobacterium, *Anabaena flos-aquae*	97%	-	5 day exposure, 9 day recovery	NOEC (cell number)	<100	Hughes 1986, 1988
Cyanobacterium, *Anabaena flos-aquae*	97%	-	5 day exposure, 9 day recovery	Algistatic concentration	4,970	Hughes 1986, 1988
Cyanobacterium, *Anabaena flos-aquae*	97%	-	5 day exposure, 9 day recovery	Algicidal concentration	>3,200	Hughes 1986, 1988
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	1 day	56.2% reduction in ^{14}C uptake	40	Abou-Waly et al. 1991a
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	3 days	50.0% reduction in ^{14}C uptake	40	Abou-Waly et al. 1991a

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	5 days	9.5% reduction in ^{14}C uptake	40	Abou-Waly et al. 1991a
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	1 day	49.0% reduction in chlorophyll	100	Abou-Waly et al. 1991a
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	3 days	2.0% reduction in chlorophyll	100	Abou-Waly et al. 1991a
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	5 days	21.8% reduction in chlorophyll	100	Abou-Waly et al. 1991a
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	7 days	29.9% reduction in chlorophyll	100	Abou-Waly et al. 1991a
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	3 days	EC50 (chlorophyll *a*)	58	Abou-Way et al. 1991b
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	5 days	EC50 (chlorophyll *a*)	469	Abou-Way et al. 1991b
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	7 days	EC50 (chlorophyll *a*)	766	Abou-Way et al. 1991b
Cyanobacterium, *Anabaena flos-aquae*	92.2%	-	4 days	EC50 (chlorophyll *a*)	>3,000	Fairchild et al. 1998
Cyanobacterium, *Anabaena inaequalis*	Technical or analytical	-	22 hr	65% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994
Cyanobacterium, *Pseudoanabaena* sp.	Technical or analytical	-	22 hr	91% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994
Cyanobacterium, *Plectonema boryanum*	-	-	31 days	69% decrease in cell number	10,000	Mallison and Cannon 1984
Cyanobacterium, *Synechoccus leopolensis*	-	-	5 days	EC50 (growth)	130	Kallqvist and Romstad 1994
Cyanobacterium, *Aphanizomenon flos-aquae*	Technical or analytical	-	22 hr	97% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Cyanobacterium, *Oscillatoria* sp.	Technical or analytical	-	22 hr	87% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994
Green alga, *Chlorella pyrenoidosa*	-	-	2 weeks	70% reduced growth	500	Virmani et al. 1975
Green alga, *Chlorella pyrenoidosa*	-	-	2 weeks	95% reduced growth	2,500	Virmani et al. 1975
Green alga, *Chlorella pyrenoidosa*	-	-	2 weeks	92% reduced growth	10,000	Virmani et al. 1975
Green alga, *Chlorella pyrenoidosa*	-	-	8 hr	~64% inhibition of photosynthesis	100	Valentine and Bingham 1976
Green alga, *Chlorella pyrenoidosa*	-	-	8 hr	~96% inhibition of photosynthesis	1,000	Valentine and Bingham 1976
Green alga, *Chlorella pyrenoidosa*	>95%	-	12-14	EC50 (cell number)	300	Stratton 1984
Green alga, *Chlorella pyrenoidosa*	-	-	10 days	30% growth inhibition; 40% reduction in chlorophyll *a*	53.9	Gonzalez-Muruaa et al. 1985
Green alga, *Chlorella pyrenoidosa*	-	-	10 days	65% growth inhibition; 70% reduction in chlorophyll *a*	107.8	Gonzalez-Muruaa et al. 1985
Green alga, *Chlorella pyrenoidosa*	-	-	110 hr	39% reduction in chlorophyll	49.6	Hiranpradit and Foy 1992
Green alga, *Chlorella pyrenoidosa*	Analytical	-	<50 min	>80% inhibition of photosynthetic CO_2 uptake	125	Hannan 1995
Green alga, *Chlorella pyrenoidosa*	Analytical	-	<50 min	100% inhibition of photosynthetic CO_2 uptake	1,250	Hannan 1995

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Chlorella vulgaris*	-	-	7 days	31.0% reduction in dry wt.	250[c/]	Veber et al. 1981
Green alga, *Chlorella vulgaris*	-	-	7 days	43.6% reduction in dry wt.	500[c/]	Veber et al. 1981
Green alga, *Chlorella vulgaris*	-	-	7 days	56.4% reduction in dry wt.	2,500[c/]	Veber et al. 1981
Green alga, *Chlorella vulgaris*	-	-	7 days	61.8% reduction in dry wt.	5,000[c/]	Veber et al. 1981
Green alga, *Chlorella vulgaris*	-	-	24 hr	EC50 (^{14}C uptake)	325[a]	Larsen et al. 1986
Green alga, *Chlorella vulgaris*	-	-	24 hr	EC50 (^{14}C uptake)	305[a]	Larsen et al. 1986
Green alga, *Chlorella vulgaris*	-	-	24 hr	EC50 (^{14}C uptake)	293[b]	Larsen et al. 1986
Green alga, *Chlorella vulgaris*	92.2%	-	96 hr	EC50 (chlorophyll)	94	Fairchild et al. 1998
Green alga, *Chlorella fusca*	99%	-	15 min	EC50 (photosynthesis)	141	Altenburger et al. 1990
Green alga, *Chlorella fusca*	99%	-	14 hr	EC50 (cell volume growth)	36	Altenburger et al. 1990
Green alga, *Chlorella fusca*	99%	-	24 hr	EC50 (cell reproduction)	26	Altenburger et al. 1990
Green alga, *Chlorella fusca*	≥98%	-	24 hr	EC50 (cell number)	15	Faust et al. 1993

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Chlorella kessleri*	-	-	72 hr	30% growth inhibition and photosynthetic O_2 evolution; 6.7% reduction in protein synthesis; effects upon lipids	1,078	El-Sheekh et al. 1994
Green alga, *Chlorella* sp.	-	-	72-96 hr	31.0% growth inhibition[d/]; 38.8% reduction in chlorophyll	52	Foy and Hiranpradit 1977
Green alga, *Chlorella* sp.	-	-	72-96 hr	45.3% growth inhibition[d/]; 30.3% reduction in chlorophyll	104	Foy and Hiranpradit 1977
Green alga, *Chlorella* sp.	-	-	72-96 hr	52.3% growth inhibition[d/]; 83.7% reduction in chlorophyll	208	Foy and Hiranpradit 1977
Green alga, *Chlorella* sp.	-	-	72-96 hr	59.2% growth inhibition[d/]; 93.5% reduction in chlorophyll	416	Foy and Hiranpradit 1977
Green alga, *Chlorella* sp.	-	-	72-96 hr	53.7% growth inhibition[d/]; 95.4% reduction in chlorophyll	832	Foy and Hiranpradit 1977
Green alga, *Chlorella* sp.[e/]	-	-	1-2 days	Growth rate reduced by 86%	216	Hersh and Crumpton 1987
Green alga, *Chlorella* sp.[e/]	-	-	2-3 days	Growth rate reduced by 55%	21.6	Hersh and Crumpton 1987
Green alga, *Chlorella* sp.[e/]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	36	Hersh and Crumpton 1989

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Chlorella* sp.[e]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	41	Hersh and Crumpton 1989
Green alga, *Clorella* sp.[e]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	35	Hersh and Crumpton 1989
Green alga, *Chlorella* sp.	-	-	4 days	EC50 (biomass)	92	Fairchild et al. 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	8 hr	~32% inhibition of photosyntheseis	10	Valentine and Bingham 1976
Green alga, *Chlamydomonas reinhardtii*	-	-	8 hr	~74% inhibition of photosynthesis	100	Valentine and Bingham 1976
Green alga, *Chlamydomonas reinhardtii*	-	-	8 hr	~97% inhibition of photosynthesis	1,000	Valentine and Bingham 1976
Green alga, *Chlamydomonas reinhardtii*	-	-	24 hr	EC50 (^{14}C uptake)	48[a]	Larsen et al. 1986
Green alga, *Chlamydomonas reinhardtii*	-	-	24 hr	EC50 (^{14}C uptake)	19[a]	Larsen et al. 1986
Green alga, *Chlamydomonas reinhardtii*	-	-	24 hr	EC50 (^{14}C uptake)	44[a]	Larsen et al. 1986
Green alga, *Chlamydomonas reinhardtii*[g]	-	-	1-2 days	Growth rate reduced by 100%	216	Hersh and Crumpton 1987
Green alga, *Chlamydomonas reinhardtii*[h]	-	-	1-2 days	Growth rate reduced by 13%	21.6	Hersh and Crumpton 1987
Green alga, *Chlamydonomas reinhardtii*[g]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	45	Hersh and Crumpton 1989
Green alga, *Chlamydomonas reinhardtii*[h]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	484	Hersh and Crumpton 1989
Green alga, *Chlamydomonas reinhardtii*	-	-	65 hr	13% reduction in chlorophyll	49.6	Hiranpradit and Foy 1992

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Chlamydomonas reinhardi*	92.2%	-	96 hr	EC50 (chlorophyll)	176	Fairchild et al. 1998
Green alga, *Chlamydomonas noctigama*	-	-	72 hr	EC50 (growth)	330	Kallqvist and Romstad 1994
Green alga, *Chlamydomonas geitleri* Ettl	96.4%	-	1 hr	EC50 (CO_2 fixation)	311	Francois and Robinson 1990
Green alga, *Chlamydomonas geitleri* Ettl	96.4%	-	1 hr	EC50 (CO^2 fixation)	194[1/]	Francois and Robinson 1990
Green alga, *Chlamydomonas* sp.	-	-	72-96 hr	36.2% [d] and 84.9%[j] growth inhibition; 12.8% reduction in chlorophyll	50-52	Foy and Hiranpradit 1977
Green alga, *Chlamydomonas* sp.	-	-	72-96 hr	64.1% [d] and 93.3%[j] growth inhibition; 32.4% reduction in chlorophyll	100-104	Foy and Hiranpradit 1977
Green alga, *Chlamydomonas* sp.	-	-	72-96 hr	77.5% [d] and 96.6%[j] growth inhibition; 49.9% reduction in chlorophyll	200-208	Foy and Hiranpradit 1977
Green alga, *Chlamydomonas sp.*	-	-	72-96 hr	76.6% [d] and 100%[j] growth inhibition; 84.2% reduction in chlorophyll	400-416	Foy and Hiranpradit 1977
Green alga, *Chlamydomonas* sp.	-	-	72-96 hr	78.6% growth inhibition[d]; 90.5% reduction in chlorophyll	832	Foy and Hiranpradit 1977
Green alga, *Chlamydomonas* sp.	-	-	4 days	EC50 (biomass)	176	Fairchild et al. 1994
Green alga, *Scenedesmus quadricauda*	-	-	8 hrs	~42% inhibition of photosynthesis	10	Valentine and Bingham 1976

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Scenedesmus quadricauda*	-	-	8 hr	~84% inhibition of photosynthesis	100	Valentine and Bingham 1976
Green alga, *Scenedesmus quadricauda*	-	-	8 hr	~98% inhibition of photosynthesis	1,000	Valentine and Bingham 1976
Green alga, *Scenedesmus quadricauda*	-	214	8 days	Incipient inhibition	30	Bringmann and Kuhn 1977; 1978a,b
Green alga, *Scenedesmus quadricauda*	>95%	-	12-14 days	EC50 (cell number)	100	Stratton 1984
Green alga, *Scenedesmus quadricauda*	-	-	8 days	4.5% reduction in photosynthesis	4	Bogacka et al. 1990
Green alga, *Scenedesmus quadricauda*	-	-	8 days	9.9% reduction in photosynthesis	9	Bogacka et al. 1990
Green alga, *Scenedesmus quadricauda*	-	-	8 days	18.5% reduction in photosynthesis	30	Bogacka et al. 1990
Green alga, *Scenedesmus quadricauda*	-	-	8 days	68.1% reduction in photosynthesis	100	Bogacka et al. 1990
Green alga, *Scenedesmus quadricauda*	-	-	8 days	99.3% reduction in photosynthesis	337	Bogacka et al. 1990
Green alga, *Scenedesmus quadricauda*	Technical or analytical	-	22 hr	96% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al., 1994
Green alga, *Scenedesmus quadricauda*	92.2%	-	96 hr	EC50 (chlorophyll)	169	Fairchild et al., 1998
Green alga, *Scenedesmus obliquus*	-	-	24 hr	EC50 (^{14}C uptake)	38	Larsen et al. 1986
Green alga, *Scenedesmus obliquus*	-	-	24 hr	EC50 (^{14}C uptake)	57	Larsen et al. 1986
Green alga, *Scenedesmus obliquus*	-	-	24 hr	EC50 (^{14}C uptake)	49	Larsen et al. 1986

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Scenedesmus subspicatus*	99.0%	-	4 days	EC50 (cell number)	110	Geyer et al. 1985
Green alga, *Scenedesmus subspicatus*	-	-	24 hr	24.8% inhibition of effective photosynthesis rate	12.3	Schafer et al. 1994
Green alga, *Scenedesmus subspicatus*	-	-	24 hr	57.4% inhibition of effective photosynthesis rate	37	Schafer et al. 1994
Green alga, *Scenedesmus subspicatus*	-	-	24 hr	93.4% inhibition of effective photosynthesis rate	111.1	Schafer et al. 1994
Green alga, *Scenedesmus subspicatus*	-	-	24 hr	100.0% inhibition of effective photosynthesis rate	333.3	Schafer et al. 1994
Green alga, *Scenedesmus subspicatus*	98%	-	2 days	EC50 (cell numbers)	21	Kirby and Sheahan 1994
Green alga, *Scenedesmus subspicatus*	-	-	24 hr	50% reduction in dry mass	~21.5	Reinold et al. 1994
Green alga, *Scenedesmus* sp.	-	-	72-96 hr	60.2% growth inhibition[1]	50	Foy and Hiranpradit 1977
Green alga, *Scenedesmus* sp.	-	-	72-96 hr	72.4% growth inhibition[1]	100	Foy and Hiranpradit 1977
Green alga, *Scenedesmus* sp.	-	-	72-96 hr	81.6% growth inhibition[1]	200	Foy and Hiranpradit 1977
Green alga, *Scenedesmus* sp.	-	-	72-96 hr	84.7% growth inhibition[1]	400	Foy and Hiranpradit 1977
Green alga, *Scenedesmus* sp.	-	-	72-96 hr	83.7% growth inhibition[1]	800	Foy and Hiranpradit 1977

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Scenedesmus* sp.	-	-	4 days	EC50 (biomass)	169	Fairchild et al. 1994
Green alga, *Selenastrum capricornutum*	97.4%	-	5 days	Significantly reduced cell numbers	54	Parrish 1978
Green alga, *Selenastrum capricornutum*	97.4%	-	5 days	Minimum algistatic concentration	200	Parrish 1978
Green alga, *Selenastrum capricornutum*	97.4%	-	5 days	12% chlorophyll *a* reduction	32	Parrish 1978
Green alga, *Selenastrum capricornutum*	97.4%	-	5 days	42% chlorophyll *a* reduction	54	Parrish 1978
Green alga, *Selenastrum capricornutum*	97.4%	-	5 days	76% chlorophyll *a* reduction	90	Parrish 1978
Green alga, *Selenastrum capricornutum*	97.4%	-	5 days	92% chlorophyll *a* reduction	150	Parrish 1978
Green alga, *Selenastrum capricornutum*	97.4%	-	5 days	96% chlorophyll *a* reduction	200	Parrish 1978
Green alga, *Selenastrum capricornutum*	85.5%	47	7 days	13.8% increased biomass	100[k]	Johnson 1986
Green alga, *Selenastrum capricornutum*	85.5%	47	7 days	36.2% decreased biomass	1,000[k]	Johnson 1986
Green alga, *Selenastrum capricornutum*	85.5%	47	7 days	75.9% decreased biomass	1,000[l]	Johnson 1986
Green alga, *Selenastrum capricornutum*	-	-	24 hr	EC50 (^{14}C uptake)	53[a]	Larsen et al. 1986
Green alga, *Selenastrum capricornutum*	-	-	24 hr	EC50 (^{14}C uptake)	34[a]	Larsen et al. 1986
Green alga, *Selenastrum capricornutum*	-	-	24 hr	EC50 (^{14}C uptake)	42[b]	Larsen et al. 1986
Green alga, *Selenastrum capricornutum*	-	-	5 days	EC50 (cell number)	100	Roberts et al. 1990

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Selenastrum capricornutum*	-	-	5 days	EC50 (cell number)	95	Roberts et al. 1990
Green alga, *Selenastrum capricornutum*	80%	-	21 days	EC50 (biomass)	58.7[a]	Turbak et al. 1986
Green alga, *Selenastrum capricornutum*	80%	-	21 days	EC50 (biomass)	410[b]	Turbak et al. 1986
Green alga, *Selenastrum capricornutum*	80%	-	24 hr	EC50 (O_2 evolution)	69.7[a]	Turbak et al. 1986
Green alga, *Selenastrum capricornutum*	80%	-	24 hr	EC50 (O_2evolution)	854[a]	Turbak et al. 1986
Green alga, *Selenastrum capricornutum*	reagent grade	171	30 min.	EC50 (CO_2 fixation)	100	Versteeg 1990
Green alga, *Selenastrum capricornutum*	reagent grade	171	30 min.	EC50 (O_2 generation)	380	Versteeg 1990
Green alga, *Selenastrum capricornutum*	reagent grade	171	4 days	EC50 (cell number)	50	Versteeg 1990
Green alga, *Selenastrum capricornutum*	99.9%	-	1 day	22.0% reduction in chlorophyll; 69.3% reduction in ^{14}C uptake	130	Abou-Waly et al. 1991a
Green alga, *Selenastrum capricornutum*	99.9%	-	3 days	53.2% reduction in chlorophyll; 42.4% reduction in ^{14}C uptake	130	Abou-Waly et al. 1991a
Green alga, *Selenastrum capricornutum*	99.9%	-	5 days	24.5% reduction in chlorophyll; 60.6% reduction in ^{14}C uptake	130	Abou-Waly et al. 1991a
Green alga, *Selenastrum capricornutum*	99.9%	-	7 days	11.6% reduction in chlorophyll; 31.5% reduction in ^{14}C uptake	130	Abou-Waly et al. 1991a

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Selenastrum capricornutum*	99.9%	-	3 days	EC50 (chlorophyll *a*)	283	Abou-Way et al. 1991b
Green alga, *Selenastrum capricornutum*	99.9%	-	5 days	EC50 (chlorophyll *a*)	218	Abou-Way et al. 1991b
Green alga, *Selenastrum capricornutum*	99.9%	-	7 days	EC50 (chlorophyll *a*)	214	Abou-Way et al. 1991b
Green alga, *Selenastrum capricornutum*	92.2%	-	4 days	EC50 (chlorophyll)	117	Fairchild et al. 1994a, 1998
Green alga, *Selenastrum capricornutum*	-	-	72 hr	EC50 (growth)	200	Kallqvist and Romstad 1994
Green alga, *Selenastrum capricornutum*	-	-	72 hr	EC50 (growth)	110	Kallqvist and Romstad 1994
Green alga, *Selenastrum capricornutum*	Technical or analytical	-	22 hr	99% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994
Green alga, *Selenastrum capricornutum*	-	100	96 hr	EC50 (chlorophyll a)	147	Gaggi et al. 1995
Green alga, *Selenastrum capricornutum*	-	-	72 hr	EC50	118.2	Radetski et al. 1995
Green alga, *Selenastrum capricornutum*	-	-	96 hr	LC50	26	Caux et al. 1991
Green alga, *Selenastrum capricornutum*	-	-	96 hr	EC50 (cell numbers)	26	Caux et al. 1991
Green alga, *Selenastrum capricornutum*	-	-	72 hr	EC50 (cell numbers)	359	Van der Heever and Grobbelaar 1996
Green alga, *Selenastrum capricornutum*	-	-	72 hr	EC50 (chlorophyll a - spectrophotometric measurement)	902	Van der Heever and Grobbelaar 1996

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Selenastrum capricornutum*	-	-	72 hr	EC50 (chlorophyll a - fluorometric measurement)	960	Van der Heever and Grobbelaar 1996
Green alga, *Selenastrum capricornutum*	-	-	96 hr	EC50 (cell number; free culture)	200	Abdel-Hamid 1996
Green alga, *Selenastrum capricornutum*	-	-	96 hr	EC50 (cell number; immobilized culture)	220	Abdel-Hamid 1996
Green alga, *Selenastrum capricornutum*	Technical grade	-	96 hr	Biomass NOEC	75	Fairchild et al. 1997
Green alga, *Selenastrum capricornutum*	Technical grade	-	96 hr	Biomass LOEC	150	Fairchild et al. 1997
Green alga, *Selenastrum capricornutum*	Technical grade	-	96 hr	Biomass EC50	235	Fairchild et al. 1997
Green alga, *Ankistrodesmus braunii*	99.9%	-	11	EC50 (cell number)	60	Burrell et al. 1985
Green alga, *Ankistrodesmus* sp.	-	-	24 hr	EC50 (^{14}C uptake)	72[a]	Larsen et al. 1986
Green alga, *Ankistrodesmus* sp.	-	-	24 hr	EC50 (^{14}C uptake)	61[a]	Larsen et al. 1986
Green alga, *Stigeoclonium tenue*	-	-	24 hr	EC50 (^{14}C uptake)	127[a]	Larsen et al. 1986
Green alga, *Stigeoclonium tenue*	-	-	24 hr	EC50 (^{14}C uptake)	224[a]	Larsen et al. 1986
Green alga, *Ulothrix subconstricta*	-	-	24 hr	EC50 (^{14}C uptake)	88[a]	Larsen et al. 1986
Green alga, *Chlorococcum hypnosporum*	-	-	2 weeks	75% reduced growth	5,000	Virmani et al. 1975

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Chlorococcum hypnosporum*	-	-	2 weeks	92% reduced growth	10,000	Vermani et al. 1975
Green alga, *Gloetaenium loitlesbergarianum*	-	-	96 hr	inhibition of calcification	2,157	Prasad and Chowdary 1981
Green alga, *Franceia* sp.[f]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	466	Hersh and Crumpton 1989
Green alga, *Franceia* sp.[f]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	774	Hersh and Crumpton 1989
Green alga, *Franceia* sp.[f]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	710	Hersh and Crumpton 1989
Green alga, *Franceia* sp.[f]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	430	Hersh and Crumpton 1989
Green alga, *Franceia* sp.[f]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	720	Hersh and Crumpton 1989
Diatom, *Cyclotella meneghiniana* (Arizona race)	-	-	7 min.	EC50 (photosynthesis)	99	Millie and Hersh 1987
Diatom, *Cyclotella meneghiniana* (Iowa race)	-	-	7 min.	EC50 (photosynthesis)	105	Millie and Hersh 1987
Diatom, *Cyclotella meneghiniana*	Technical or analytical	-	22 hr	97% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994
Diatom, *Cyclotella* sp.	-	-	6 days	EC50 (growth)	430	Kallqvist and Romstad 1994
Diatom, *Navicula pelliculosa*	97%	-	5 days	EC50 (cell number)	60	Hughes 1986, 1988

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (ug/L)	Reference
Diatom, *Navicula pelliculosa*	97%	-	5 day exposure, 9 day recover	NOEC	<100	Hughes 1986, 1988
Diatom, *Navicula pelliculosa*	97%	-	5 day exposure, 9 day recovery	Algistatic concentration	1,710	Hughes 1986, 1988
Diatom, *Navicula pelliculosa*	97%	-	5 day exposure, 9 day recovery	Algicidal concentration	>3,200	Hughes 1986, 1988
Diatom, *Nitzschia* sp.	Technical or analytical	-	22 hr	99% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994
Cryptomonad, *Cryptomonas pyrinoidifera*	-	-	6 days	EC50 (growth)	500	Kallqvist and Romstad 1994
Duckweed, *Lemna minor*	-	-	20 days	No effect upon growth; increased soluble protein content; increased photosynthesis, increased respiration	20	Beaumont et al. 1976a,b,c
Duckweed, *Lemna minor*	-	-	20 days	~12% reduced growth; increased water, soluble protein content; increased photosynthesis and respiration	50	Beaumont et al. 1976a,b,c
Duckweed, *Lemna minor*	-	-	20 days	~23% reduced growth; increased water and soluble protein content; increased photosynthesis and respiration	100	Beaumont et al. 1976a,b,c

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Duckweed, *Lemna minor*	-	-	15 days	Increased total fatty acid and α-linolenic acid content; increased monogalatosyldiacyl-glycerol percentage	100	Grenier et al. 1979
Duckweed, *Lemna minor*	-	-	20 days	~74% reduced growth; increased water, chlorophyll, and soluble protein content; increased photosynthesis and respiration	250	Beaumont et al. 1976a,b,c
Duckweed, *Lemna minor*	-	-	15 days	Increased total fatty acid and α-linolenic acid content; decreased linoleic acid content; increased monogalactosyldiacyl-glycerol percentage	1,000	Grenier et al. 1979
Duckweed, *Lemna minor*	-	-	15 days	Increased amounts of polar lipids in chlorophyll-protein complexes of chloroplasts	248	Grenier et al. 1987
Duckweed, *Lemna minor*	-	-	10 days	Increased [^{14}C]-acetate incorporation into chloroplast lipids	248	Grenier et al. 1989

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Duckweed, *Lemna minor*	-	-	2 days	Changes in chloroplast ultrastructure; increased chlorophyll content	248	Simard et al. 1990
Duckweed, *Lemna minor*	Technical or analytical	-	7 days	95% inhibition of growth	2,667	Peterson et al. 1994
Duckweed, *Lemna minor*	92.2%	-	4 days	EC50 (frond production)	92	Fairchild et al. 1998
Duckweed, *Lemna minor*	Technical	-	96 hr	Biomass NOEC	75	Fairchild et al. 1997
Duckweed, *Lemna minor*	Technical	-	96 hr	Biomass LOEC	150	Fairchild et al. 1997
Duckweed, *Lemna minor*	Technical	-	96 hr	Biomass EC50	153	Fairchild et al. 1997
Duckweed, *Lemna gibba*	97%	-	5 days	EC50 (frond production)	170	Hughes 1986, 1988
Duckweed, *Lemna gibba*	97%	-	5 day exposure 9 day recovery	NOEC (frond production)	<100	Hughes 1986, 1988
Duckweed, *Lemna gibba*	97%	-	5 day exposure 9 day recovery	Phytostatic concentration	1,720	Hughes 1986, 1988
Duckweed, *Lemna gibba*	97%	-	5 day exposure 9 day recovery	Phytocidal concentration	>3,200	Hughes 1986, 1988
Wild rice, *Zizania aquatica*	85%	-	83 days	Visibly senescent; 75% reduction in chlorophyll a in leaves	50	Detenbeck et al. 1996
Wildcelery, *Vallisneria americana*	-	-	42 days	EC50 (total leaf length)	163	Davis 1980; Forney and Davis 1981

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Wildcelery, *Vallisneria americana*	-	-	-	Reduced leaf growth and whole plant biomass	8	Cohn 1985
Wildcelery, *Vallisneria americana*	-	-	-	Reduced tuber over-wintering success	4	Cohn 1985
Coontail, *Ceratophyllum* sp.	92.2%	-	14 days	EC50 (wet weight)	22	Fairchild et al. 1998
Coontail, *Ceratophyllum dermersum*	85%	-	6-8 days	Stem elongation	50	Detenbeck et al. 1996
Cattail, *Typha latifolia*	85%	-	19 days	No effect upon growth	25	Detenbeck et al. 1996
Eurasium watermilfoil, *Myriophyllum spicatum*	-	-	28 days	EC50 (length)	1,104	Davis 1980; Forney and Davis 1981
Water milfoil, *Myriophyllum spicatum*	-	-	24 hr	30% increase in net photosynthetic rate	10	Hoffmann and Winkler 1990
Water milfoil, *Myriophyllum spicatum*	-	-	5 days	50% reduction in branch number	3,700	Bird 1993
Water milfoil, *Myriophyllum heterophyllum*	92.2%	-	14 days	EC50 (wet weight)	132	Fairchild et al. 1998
Sago pondweed, *Potamogeton pectinatus*	-	-	28 days	Reduced biomass	100	Fleming et al. 1991
Bushy pondweed, *Najas* sp.	92.2%	-	14 days	EC50 (wet weight)	24	Fairchild et al. 1998
Egeria, *Egeria* sp.	-	-	14 days	EC50 (biomass)	<38	Fairchild et al. 1994
Elodea, *Elodea canadensis*	-	-	28 days	EC50 (length)	80	Davis 1980; Forney and Davis 1981

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Elodea, *Elodea canadensis*	-	-	21 days	EC50 (length)	109	Davis 1980; Forney and Davis 1981
Elodea, *Elodea canadensis*	-	-	20 days	Dark respiration rate exceeded net photosynthesis rate	10	Hoffmann and Winkler 1990
Elodea, *Elodea canadensis*	85%	-	19 days	No effect upon growth	75	Detenbeck et al. 1996
Elodea, *Elodea canadensis*	92.2%	-	14 days	EC50 (wet weight)	21	Fairchild et al. 1998
Water moss, *Fontinalis antipyretica*	-	-	20 days	Dark respiration rate exceeded net photosynthesis rate	10	Hoffmann and Winkler 1990
Water moss, *Fontinalis squamosa*	-	-	24 hr	20% reduction in net photosynthesis	10	Hoffmann and Winkler 1990
Water moss, *Fontinalis hypnoides*	-	-	24 hr	90% reduction in net photosynthesis	2	Hoffmann and Winkler 1990
Mixed macrophytes, *Ceratophyllum* sp. and *Elodea* sp.	85.5%	47	30 days	18.3% increased biomass	10	Johnson 1986
Mixed macrophytes, *Ceratophyllum* sp. and *Elodea* sp.	85.5%	47	30 days	11.6% decreased biomass	100	Johnson 1986
Mixed macrophytes, *Ceratophyllum* sp. and *Elodea* sp.	85.5%	47	30 days	47.6% decreased biomass	1,000	Johnson 1986
Protozoa, *Acanthamoeba castellanii*	-	-	6 days	5% population decrease	100	Prescott et al. 1977
Protozoa, *Acanthamoeba castellanii*	-	-	6 days	14% population decrease	1,000	Prescott et al. 1977

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Protozoa, *Acanthamoeba castellanii*	-	-	6 days	15% population decrease	4,000	Prescott et al. 1977
Protozoa, *Acanthamoeba castellanii*	-	-	6 days	40% population decrease	10,000	Prescott et al. 1977
Protozoa, *Euglena gracilis*	-	-	8 hr	~11% inhibition of photosynthesis	10	Valentine and Bingham 1976
Protozoa, *Euglena gracilis*	-	-	8 hr	~28% inhibition of photosynthesis	100	Valentine and Bingham 1976
Protozoa, *Euglena gracilis*	-	-	8 hr	~83% inhibition of phyotsynthesis	1,000	Valentine and Bingham 1976
Protozoa, *Colpidium campylum*	-	-	24 hr	EC50 (cell number)	>50,000	Roberts et al. 1990
Protozoa, *Tetrahymena pyriformis*	-	-	24 hr	EC50	118,500	Huber et al. 1991
Protozoa, *Tetrahymena pyriformis*	-	-	48 hr	EC50 (cell number)	96,000	Schafer et al. 1994
Hydra, *Hydra viridis*	-	-	21 days	Reduced budding rate	5,000	Benson and Boush 1983
Leech, *Glossiphonia complanata*	99.2%	-	27-28 days	LC50	6,300	Streit and Peter 1978
Leech, *Helobdella stagnalis*	99.2%	-	27-28 days	LC50	9,900	Streit and Peter 1978
Snail, *Lymnaea palustris*	97.8%	-	12 wks	No effect upon growth, fecundity or glycogen metabolism	125	Baturo et al. 1995
Snail, *Lymnaea palustris*	97.8%	-	12 wks	Inhibited BaPH and GST enzyme activities	5	Baturo and Lagadic 1996
Mussel (glochidia larva), *Anadonta imbecilis*	97.3%	40-50	24 hr	LC50	>60,000	Johnson et al. 1993

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Mussel (1-2d old juvenile), *Anadonta imbecilis*	97.3%	40-50	48 hr	LC50	>60,000	Johnson et al. 1993
Mussel (7-10 d old juvenile), *Anadonta imbecilis*	97.3%	40-50	48 hr	LC50	>60,000	Johnson et al. 1993
Rotifer, *Brachionus calyciflorus*	-	-	24 hr	LC50	7,840	Crisinel et al. 1994
Anostracan, *Streptocephalus texanus*	-	-	24 hr	LC50	>30,000	Crisinel et al. 1994
Cladoceran, *Ceriodaphnia dubia*	>99%	57.1	4 days	MATC	7,100	Oris et al. 1991
Cladoceran, *Ceriodaphnia dubia*	>99%	57.1	4 days	MATC	14,100	Oris et al. 1991
Cladoceran (≤26 h), *Daphnia magna*	-	-	26 hr	LC50	3,600	Frear and Boyd 1967
Cladoceran, *Daphnia magna*	-	100	48 hr	BCF = 4.4	10	Ellgehausen et al. 1980
Cladoceran, *Daphnia magna*	-	100	48 hr	BCF = 2.2	10	Ellgehausen et al. 1980
Cladoceran, *Daphnia magna*	-	-	21 days	Reduced young production	2,000	Kaushik et al. 1985
Cladoceran, *Daphnia magna*	-	-	48 hr	10% mortality	22,000	Bogacka et al. 1990
Cladoceran, *Daphnia magna*	-	-	96 hr	30% mortality	16,900	Bogacka et al. 1990
Cladoceran, *Daphnia magna*	-	-	96 hr	60% mortality	48,300	Bogacka et al. 1990
Cladoceran (<24 h), *Daphnia magna*	97.3%	40-50	48 hr	LC50	9,400[a]	Johnson et al. 1993
Cladoceran, *Daphnia magna*	-	-	24 hr	EC50	>30,000	Crisinel et al. 1994

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Cladoceran, *Daphnia magna*	-	-	48 hr	EC50	>30,000	Crisinel et al. 1994
Cladoceran, *Daphnia magna*	85%	-	48 hr	Significantly decreased survival	25	Detenbeck et al. 1996
Cladoceran, *Daphnia magna*	85%	-	48 hr	No effect upon survival	50	Detenbeck et al. 1996
Cladoceran (adult), *Daphnia pulex*	-	-	3 hr	LC50	>40,000	Nishiuchi and Hashimoto 1967, 1969
Cladoceran, *Daphnia pulex*	99.2%	-	28 days	11.7% decreased survival and 28.2% decreased reproduction	1,000	Schober and Lampert 1977
Cladoceran, *Daphnia pulex*	99.2%	-	28 days	4.2% decreased survival and 26.8% decreased reproduction	2,000	Schober and Lampert 1977
Cladoceran, *Daphnia pulex*	99.2%	-	~70 days	41.7% decreased reproduction	2,000	Schober and Lampert 1977
Cladoceran, *Daphnia pulex*	99.2%	-	28 days	20.2% decreased survival and 45.5% decreased reproduction	3,000	Schober and Lampert 1977
Cladoceran, *Daphnia pulex*	99.2%	-	28 days	9.6% decreased survival and 48.3% decreased reproduction	4,000	Schober and Lampert 1977
Cladoceran, *Daphnia pulex*	99.2%	-	28 days	42% decreased reproduction	5,000	Schober and Lampert 1977
Cladoceran, *Daphnia pulex*	99.2%	-	70 days	48.2% decreased reproduction	5,000	Schober and Lampert 1977

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Cladoceran, *Daphia pulex*	99.2%	-	28 days	14.9% decreased survival; 53.9% decreased reproduction	10,000	Schober and Lampert 1977
Cladoceran, *Daphnia pulex*	99.2%	-	70 days	62.6% decreased reproduction	10,000	Schober and Lampert 1977
Cladoceran, *Daphnia pulex*	99.2%	-	28 days	96.5% decreased reproduction	20,000	Schober and Lampert 1977
Cladoceran, *Daphnia pulex*	-	-	10 min.	10% reduction in food consumption	350	Pott 1980
Cladoceran, *Daphnia pulex*	-	-	10 min.	50% reduction in food consumption	1,600	Pott 1980
Cladoceran (adult), *Moina macrocopa*	-	-	3 hr	LC50	>40,000	Nishiuchi and Hashimoto 1967, 1969
Cladoceran, *Moina macrocopa*	-	-	4-6 weeks	40% mortality; 10% increase in potential production; reduced actual population growth	1,000	Shcherban 1972a,b
Amphipod (1st instar), *Gammarus fasciatus*	94%	-	48 hr	LC50	5,700	Macek et al. 1976
Midge (2nd instar), *Chironomus riparius*	-	151	10 days	LC50	18,900	Taylor et al. 1991
Midge (~10 d), *Chironomus tentans*	97.1	42-44	96 hr (fed)	LC50	>28,000	McNamara 1991
Rainbow trout (embryo), *Oncorhynchus mykiss*	80%	50	23 days (at hatching)	LC50	736	Birge et al. 1979
Rainbow trout (embryo), *Oncorhynchus mykiss*	80%	200	23 days (at hatching)	LC50	888	Birge et al. 1979

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Rainbow trout (sac fry), *Oncorhynchus mykiss*	80%	50	27 days (4 days post-hatch)	LC50	696	Birge et al. 1979
Rainbow trout (sac fry), *Oncorhynchus mykiss*	80%	200	27 days (4 days post-hatch)	LC50	864	Birge et al. 1979
Rainbow trout (sac fry), *Oncorhynchus mykiss*	80%	50	27 days (4 days post-hatch)	LC1	23.2	Birge et al. 1979
Rainbow trout (sac fry), *Oncorhynchus mykiss*	80%	200	27 days (4 days post-hatch)	LC1	61.8	Birge et al. 1979
Rainbow trout (sac fry), *Oncorhynchus mykiss*	80%	50	27 days (4 days post-hatch)	3% teratic larvae	43.2	Birge et al. 1979
Rainbow trout (sac fry), *Oncorhynchus mykiss*	80%	50	27 days (4 days post-hatch)	6% teratic larvae	432	Birge et al. 1979
Rainbow trout (sac fry), *Oncorhynchuls mykiss*	80%	50	27 days (4 days post-hatch)	62% teratic larvae	4,020	Birge et al. 1979
Rainbow trout (sac fry), *Oncorhynchuls mykiss*	80%	200	27 days (4 days post-hatch)	2% teratic larvae	13.6	Birge et al. 1979
Rainbow trout (sac fry), *Oncorhynchus mykiss*	80%	200	27 days (4 days post-hatch)	3% teratic larvae	48.0	Birge et al. 1979
Rainbow trout (sac fry), *Oncorhynchus mykiss*	80%	200	27 days (4 days post-hatch)	4% teratic larvae	416	Birge et al. 1979
Rainbow trout (sac fry), *Oncorhynchus mykiss*	80%	200	27 days (4 days post-hatch)	65% teratic larvae	4,020	Birge et al. 1979

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Rainbow trout (juvenile), *Oncorhynchus mykiss*	99.3%	-	48 hr	LC50	5,660	Pluta, 1989
Rainbow trout (juvenile), *Oncorhynchus mykiss*	-	-	28 days	Changes in renal corpuscle ultrastructure	5	Fischer-Scherl et al. 1991
Rainbow trout (juvenile), *Oncorhynchus mykiss*	-	-	28 days	Changes in renal corpuscle and tubule ultrastructure	10	Fischer-Scherl et al. 1991
Rainbow trout, *Oncorhynchus mykiss*	-	-	28 days	Slight ultrastructural changes in renal corpuscles	5	Schwaiger et al. 1991
Rainbow trout, *Oncorhynchus mykiss*	-	-	28 days	Slight histopathological changes in liver; increased ultrastructural changes in renal corpuscles	10	Schwaiger et al. 1991
Rainbow trout, *Oncorhynchus mykiss*	-	-	28 days	Ultrastructural changes in renal corpuscles and histopathological changes in liver	20	Schwaiger et al. 1991
Rainbow trout (juvenile), *Oncorhynchus mykiss*	93.7%	-	14 days	No effect upon survival, body weight, liver weight, or liver xenobiotic-metabolizing enzyme activities	10	Egaas et al. 1993
Rainbow trout (juvenile), *Oncorhynchus mykiss*	≥98%	-	10 days	Reduced plasma protein	3.0	Davies et al. 1994
Rainbow trout (juvenile), *Oncorhynchus mykiss*	≥98%	-	10 days	Reduced plasma protein	50	Davies et al. 1994

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Rainbow trout (juvenile), *Oncorhynchus mykiss*	99%	380	5 weeks	Ultrastructural alterations in kidney proximal tubules	12.4	Oulmi et al. 1995
Rainbow trout (juvenile), *Oncorhynchus mykiss*	99%	380	5 weeks	Ultrastructural alterations in kidney proximal and distal tubules	24.0	Oulmi et al. 1995
Common carp, *Cyprinus carpio*	-	-	48 hr	LC50	>10,000	Nishiuchi and Hashimoto 1967, 1969
Common carp (30-50g), *Cyprinus carpio*	-	-	12 hr	~125% increased serum cortisol	100	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	24 hr	~300% increased serum cortisol	100	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	6 hr	~40% increased serum cortisol	500	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	12 hr	~60% increased serum cortisol	500	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	24 hr	~250% increased serum cortisol	500	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	12 hr	~60% increased serum glucose	100	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	24 hr	~35% increased serum glucose	100	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	6 hr	~15% increased serum glucose	500	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	12 hr	~40% increased serum glucose	500	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	24 hr	~70% increased serum glucose	500	Hanke et al. 1983

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Common carp (30-50g), *Cyprinus carpio*	-	-	72 hr	~180% increased serum glucose; ~40% decreased liver glycogen	1,000	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	4 hr	~25% increase in gill total ATPase activity; ~20% increase in gill Na-K dependent ATPase	100	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	6 hr	~10% increase in gill total ATPase; ~30% decrease in gill Na-K dependent ATPase	100	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	12 hr	~40% decrease in gill total ATPase; ~30%decrease in gill Na-K dependent ATPase	100	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	24 hr	~5% decrease in gill total ATPase; ~25% decrease in gill Na-K dependent ATPase	100	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	4 hr	~60% increase in serum AChE	100	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	6 hr	~15% increase in serum AChE	100	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	12 hr	~35% increase in serum AChE	100	Hanke et al. 1983
Common carp (30-50g), *Cyprinus carpio*	-	-	24 hr	~25% decrease in serum AChE	100	Hanke et al. 1983

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Common carp, *Cyprinus carpio*	-	-	72 hr	Increased serum glucose and cortisol; decreased liver and muscle glycogen; decreased serum protein and cholesterol	100	Gluth and Hanke 1984, 1985
Common carp (juvenile), *Cyprinus carpio*	99.3%	-	48 hr	LC50	16,100	Pluta, 1989
Common carp (juvenile), *Cyprinus carpio*	93.7%	141-223	96 hr (fed)	LC50	18,800	Neskovic et al. 1993
Common carp (juvenile), *Cyprinus carpio*	93.7%	141-223	14 days	Increased serum alkaline phosphatase; decreased alkaline phosphatase in heart, liver and kidneys; increased GPT in liver and kidneys; hyperplasia of some gill epithelial cells	1,500	Neskovic et al. 1993
Goldfish, *Carassius auratus*	-	-	48 hr	LC50	>10,000	Nishiuchi and Hashimoto 1967, 1969
Fathead minnow (≤24h), *Pimephales promelas*	97	60	7 days	NOEC (biomass)	≥4,900	Jop 1991b
Fathead minnow (juvenile), *Pimephales promelas*	85%	-	13 days	No effect upon survival or growth	75	Detenbeck et al. 1996
Fathead minnow (larvae), *Pimephales promelas*	85%	-	7	No effect upon survival	75	Detenbeck et al. 1996
Channel catfish, *Ictalurus punctatus*	80%	50	4.5 days (at hatching)	LC50	272	Birge et al. 1979

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Channel catfish, *Ictalurus punctatus*	80%	200	4.5 days (at hatching)	LC50	248	Birge et al. 1979
Channel catfish (sac fry), *Ictalurus punctatus*	80%	50	8.5 days (4 days post-hatch)	LC50	176	Birge et al. 1979
Channel catfish, *Ictalurus punctatus*	80%	200	8.5 days (4 days post-hatch)	LC50	192	Birge et al. 1979
Channel catfish (sac fry), *Ictalurus punctatus*	80%	50	8.5 days (4 days post-hatch)	1% teratic larvae	22.4	Birge et al. 1979
Channel catfish (sac fry), *Ictalurus punctatus*	80%	50	8.5 days (4 days post-hatch)	4% teratic larvae	47.2	Birge et al. 1979
Channel catfish (sac fry), *Ictalurus punctatus*	80%	50	8.5 days (4 days post-hatch)	13% teratic larvae	344	Birge et al. 1979
Channel catfish (sac fry), *Ictalurus punctatus*	80%	50	8.5 days (4 days post-hatch)	69% teratic larvae	3,864	Birge et al. 1979
Channel catfish (sac fry), *Ictalurus punctatus*	80%	50	8.5 days (4 days post-hatch)	100% teratic larvae	37,360	Birge et al. 1979
Channel catfish (sac fry), *Ictalurus punctatus*	80%	200	8.5 days (4 days post-hatch)	1% teratic larvae	26.4	Birge et al. 1979
Channel catfish (sac fry), *Ictalurus punctatus*	80%	200	8.5 days (4 days post-hatch)	4% teratic larvae	43.2	Birge et al. 1979
Channel catfish (sac fry), *Ictalurus punctatus*	80%	200	8.5 days (4 days post-hatch)	16% teratic larvae	336	Birge et al. 1979

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Channel catfish (sac fry), *Ictalurus punctatus*	80%	200	8.5 days (4 days post-hatch)	47% teratic larvae	3,848	Birge et al. 1979
Channel catfish (sac fry), *Ictalurus punctatus*	80%	200	8.5 days (4 days post-hatch)	86% teratic larvae	37,360	Birge et al. 1979
Mosquitofish, *Gambusia affinis*	technical	-	48 hr	no mortality	10,000	Darwazeh and Mulla 1974
Guppy, *Poecilia reticulata*	-	-	48 hr	LC50	38,200	Tscheu-Schluter 1976
Guppy, *Poecilia reticulata*	-	-	72 hr	LC50	31,600	Tscheu-Schluter 1976
Guppy, *Poecilia reticulata*	-	-	96 hr	40% mortality	28,600	Bogacka et al. 1990
Guppy, *Poecilia reticulata*	-	-	96 hr	53.2% mortality	37,200	Bogacka et al. 1990
Mozambique tilapia, *Tilapia mossambica*	-	-	90 days	Decrease in red and white blood cell counts, hemoglobin, packed cell volume, mean corpuscular hemoglobin; decreased whole animal oxygen consumption; increases in mean cell volume, blood volume and blood water content.	1,100	Prasad et al. 1991a
Mozambique tilapia, *Tilapia mossambica*	-	-	30 days	Changes in enzyme activity and levels of amino acids, proteins, ammonia, and urea in brain and liver	1,100	Prasad et al. 1991b

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Mozambique tilapia, *Tilapia mossambica*	-	-	30 days	Increases in lipase activity, free fatty acids, acetoacetate concentration, and total cholesterol in liver and muscle; decreases in total lipids, glycerol and phospholipids in liver and muscle.	1,100	Srinivas et al. 1991
Mozambique tilapia, *Tilapia mossambicus*	-	-	90 days	Increased body weight, percent water, serum Na^+ and serum K^+; decreased serum Ca^{++}, Mg^{++}, and HCO_3^-	1,100	Prasad and Reddy 1994
Bullfrog (embryo and tadpole), *Rana catesbeiana*	80%	113	8 days (4 days post-hatch)	LC1	7.4	Birge et al. 1980
Bullfrog (embryo and tadpole), *Rana catesbeiana*	80%	113	8 days (4 days post-hatch)	LC10	44.9	Birge et al. 1980
Bullfrog (embryo and tadpole), *Rana catesbeiana*	80%	113	8 days (4 days post-hatch)	LC50	410	Birge et al. 1980
Bullfrog (embryo and tadpole), *Rana catesbeiana*	80%	113	4 days (to hatch)	1% teratic surviving larvae	51	Birge et al. 1980
Bullfrog (embryo and tadpole), *Rana catesbeiana*	80%	113	4 days (to hatch)	3% teratic surviving larvae	410	Birge et al. 1980
Bullfrog (embryo and tadpole), *Rana catesbeiana*	80%	113	4 days (to hatch)	7% teratic surviving larvae	6,330	Birge et al. 1980
Bullfrog (embryo and tadpole), *Rana catesbeiana*	80%	113	4 days (to hatch)	22% teratic surviving larvae	14,800	Birge et al. 1980

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Bullfrog (embryo and tadpole), *Rana catesbeiana*	80%	113	4 days (to hatch)	47% teratic surviving larvae	26,400	Birge et al. 1980
Bullfrog (embryo and tadpole), *Rana catesbeiana*	80%	113	4 days (to hatch)	100% teratic surviving larvae	45,800	Birge et al. 1980
Leopard frog (embryo and tadpole), *Rana pipiens*	80%	115	9 days (4 days post-hatch)	LC1	32.6	Birge et al. 1980
Leopard frog (embryo and tadpole), *Rana pipiens*	80%	115	9 days (4 days post-hatch)	LC10	378.9	Birge et al. 1980
Leopard frog (embryo and tadpole), *Rana pipiens*	80%	115	9 days (4 days post-hatch)	LC50	7,680	Birge et al. 1980
Leopard frog (embryo and tadpole), *Rana pipiens*	80%	115	5 days (to hatch)	2% teratic surviving larvae	110	Birge et al. 1980
Leopard frog (embryo and tadpole), *Rana pipiens*	80%	115	5 days (to hatch)	2% teratic surviving larvae	210	Birge et al. 1980
Leopard frog (embryo and tadpole), *Rana pipiens*	80%	115	5 days (to hatch)	5% teratic surviving larvae	1,113	Birge et al. 1980
Leopard frog (embryo and tadpole), *Rana pipiens*	80%	115	5 days (to hatch)	9% teratic surviving larvae	6,540	Birge et al. 1980
Leopard frog (embryo and tadpole), *Rana pipiens*	80%	115	5 days (to hatch)	13% teratic surviving larvae	13,200	Birge et al. 1980
Leopard frog (embryo and tadpole), *Rana pipiens*	80%	115	5 days (to hatch)	46% teratic surviving larvae	48,700	Birge et al. 1980
Leopard frog (tadpole), *Rana pipiens*	85%	-	41 days	No effect upon growth or survival	25	Detenbeck et al. 1996
Pickerel frog (embryo and tadpole), *Rana palustris*	80%	103	8 days (4 days post-hatch)	LC50	17,960	Birge et al. 1980

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Pickerel frog (embryo and tadpole), *Rana palustris*	80%	103	4 days (to hatch)	2% teratic surviving larvae	10,400	Birge et al. 1980
Pickerel frog (embryo and tadpole), *Rana palustris*	80%	103	4 days (to hatch)	5% teratic surviving larvae	20,600	Birge et al. 1980
Pickerel frog (embryo and tadpole), *Rana palustris*	80%	103	4 days (to hatch)	18% teratic surviving larvae	33,900	Birge et al. 1980
American toad (embryo and tadpole), *Bufo americanus*	80%	-	7 days (4 days post-hatch)	LC50	>48,000	Birge et al. 1980
American toad (embryo and tadpole), *Bufo americanus*	80%	-	3 days (to hatch)	2% teratic surviving larvae	490	Birge et al. 1980
American toad (embryo and tadpole), *Bufo americanus*	80%	-	3 days (to hatch)	2% teratic surviving larvae	5,560	Birge et al. 1980
American toad (embryo and tadpole), *Bufo americanus*	80%	-	3 days (to hatch)	3% teratic surviving larvae	10,800	Birge et al. 1980
American toad (embryo and tadpole), *Bufo americanus*	80%	-	3 days (to hatch)	6% teratic surviving larvae	24,800	Birge et al. 1980
American toad (embryo and tadpole), *Bufo americanus*	80%	-	3 days (to hatch)	17% teratic surviving larvae	48,200	Birge et al. 1980
African clawed frog (embryo), *Xenopus laevis*	40.8%	-	96 hr	100% abnormal embryos	8,000	Morgan et al. 1996
African clawed frog (embryo), *Xenopus laevis*	40.8%	-	96 hr	LC50	126,000	Morgan et al. 1996

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
African clawed frog (embryo), *Xenopus laevis*	40.8%	-	96 hr	LOEC (teratogenesis)	1,100	Morgan et al. 1996
Stream mixed algal species	80%	-	1 day to 3 weeks	39-78% reduction in gross productivity	10	Kosinski et al. 1983; Kosinski and Merkle 1984
Experimental stream perphyton community	80%	-	14 days	Severe population density reductions in several species; total destruction of *Cladophora glomerata*	1,000	Kosinski 1984
Stream mixed community	Technical	164-202	30 days	No effect upon macroinvertebrate community structure, periphyton production or biomass, and community P/R ratio	25	Lynch et al. 1985
Experimental laboratory stream community	96.5	-	2 weeks	Decreased diurnal fluctuation and mean values for pH and dissolved oxygen; increased nitrate nitrogen; parameters rapidly returned to control levels when treatment ended	100	Malanchuk and Kollig 1985
Stream mixed algal species	80%	-	3 days	Reduced net primary productivity	100	Moorhead and Kosinski 1986
Stream Aufwuchs community	-	-	12 days	4% biomass reduction at 10°C	24	Krieger et al. 1988

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Stream Aufwuchs community	-	-	12 days	24% biomass reduction; 30% chlorophyll a reduction at 25°C	24	Krieger et al. 1988
Stream Aufwuchs community	-	-	12 days	47% biomass reduction; 40% chlorophyll a reduction at 10°C	134	Krieger et al. 1988
Stream Aufwuchs community	-	-	12 days	31% biomass reduction; 44% chlorophyll a reduction at 25°C	134	Krieger et al. 1988
Natural Stream Periphyton community	98%	-	24 hr	No effect upon algal cell numbers or biomass	77.5	Jurgenson and Hoagland 1990
Natural stream plankton community	Commercial product	-	6 mo	Initial decrease in phytoplankton species (6 wks) followed by a recovery	~0.5	Lakshminarayana et al. 1992
Stream algal and benthic invertebrate community	90%	-	14 days	No effect upon attached algal chlorophyll a concentrations or benthic invertebrate populations	5	Gruessner and Watzin 1996
Artificial stream periphyton community	-	-	30 days	Community photosynthesis inhibited	100	Pearson and Crossland 1996
Pond microcosm, (static system)	98.2%	-	7 days	No effect upon diurnal oxygen production	5.0	Brockway et al. 1984
Pond microcosm, (static system)	98.2%	-	12 days	25-30% decreased oxygen production	50	Brockway et al. 1984

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Pond microcosm, (static system)	98.2%	-	7 days	40-50% decreased diurnal oxygen production	100	Brockway et al. 1984
Pond microcosm, (static system)	98.2%	-	12 days	90% decreased diurnal oxygen production	500	Brockway et al. 1984
Pond microcosm, (static system)	98.2%	-	12 days	100% inhibition of diurnal oxygen production	5,000	Brockway et al. 1984
Freshwater microcosm	-	-	7 wks	No effects upon species composition of phytoplankton, zooplankton or benthic macroinverte-brates; slight decrease in photosynthetic activity	5.1	Van den Brink 1995
Periphyton-dominated microcosm	96.5%	-	1 day	77% decrease in daily net productivity	100	Hamala and Kollig 1985
Periphyton-dominated microcosm	96.5%	-	14 days	~75% decrease in P/R ratio	100	Hamala and Kollig 1985
Phytoplankton, zooplankton and benthos microcosm	-	-	60 days	Reduced ^{14}C uptake/chlorophyll *a* ratio	43.8	Stay et al. 1985
Phytoplankton, zooplankton and benthos microcosm	-	-	25 days	Reduced net primary productivity	~50	Stay et al. 1985

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Pond mesocosm community	-	-	70 days	Changes in population densities of zooplankton (rotifers, crustaceans and insect larvae)	200	Peichl et al. 1984
Pond mesocosm community	-	-	121 days	Changes in phytoplankton community composition; increased rotifer population	10	Peichl et al. 1985
Pond mesocosm community	41%	-	805 days	Reductions in phytoplankton production and biomass, macrophyte, populations, and populations of benthic insect grazers, *Rana catesbiana* tadpoles, grass carp and bluegills	20	deNoyelles et al. 1982, 1989, 1994
Pond mesocosm community	41%	-	4 years with single annual applications	Reduced photosynthesis in 24 hr bioassays, followed by recovery in 20-day bioassays and long-term pond studies	20-500	deNoyelles and Kettle 1985

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Pond mesocosm community	97%	-	9-112 days	Significant reductions of herbivorous benthic insect species richness, abundance, and total insect emergence (89%), shift to earlier emergence for some herbivorous species; destabilization of ecosystem	20[P]	Dewey 1986; Dewey and deNoyelles 1994;
Pond mesocosm community	97%	-	9-112 days	Significant reductions of herbivorous benthic insect species richness, abundance, and total insect emergence (95%), shift to earlier emergence for some herbivorous species; reduced species evenness; destabilization of ecosystem	100[P]	Dewey 1986; Dewey and deNoyelles 1994;

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Pond mesocosm community	97%	-	9-112 days	Significant reductions of herbivorous benthic insect species richness, abundance, and total insect emergence (85%), shift to earlier emergence for some herbivourous species; reduced species evenness; destabilization of ecosystem	500[P]	Dewey 1986; Dewey and de Noyelles 1994;
Pond mesocosm community	40.8%	-	8 wks	Altered macrophyte community species composition; no effects upon primary productivity, total plant biomass, zooplankton or fish	50	Fairchild et al. 1994
Pond mesocosm plankton community	-	-	2 mo	No effect	5	Juttner et al. 1995
Pond mesocosm plankton community	-	-	2 mo	Decreased O_2, pH and conductivity	10	Juttner et al. 1995
Pond mesocosm plankton community	-	-	2 mo	Decreased phytoplankton populations	182	Juttner et al. 1995
Pond mesocosm plankton community	-	-	2 mo	Reduced peak egg ratios in *Daphnia longispina* and elimination of *Polyarthra* sp. rotifers	318	Juttner et al. 1995

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Pond microbial microcosm community	98.6%	~70	21 days	NOEC for concentrations of Mg, Ca and dissolved oxygen	10	Pratt et al. 1988
Pond microbial microcosm community	98.6%	~70	21 days	MATC for concentrations of Mg, Ca and dissolved oxygen	17.9	Pratt et al. 1988
Pond microbial microcosm community	98.6%	~70	21 days	LOEC for concentrations of Mg, Ca and dissolved oxygen	32.0	Pratt et al. 1988
Pond microbial microcosm community	98.6%	~70	21 days	NOEC for protozoan colonization, biomass protein, chlorophyll a, and potassium concentration	110	Pratt et al. 1988
Pond microbial microcosm community	98.6%	~70	21 days	MATC for protozoan colonization, biomass protein, chlorophyll a, and potassium concentration	193	Pratt et al. 1988
Pond microbial microcosm community	98.6%	~70	21 days	LOEC for protozoan colonization, biomass protein, chlorophyll a and potassium concentration	337	Pratt et al. 1988
Phyto- and zooplankton microcosm community	-	-	42 days	No or little effect upon net primary productivity, P/R ratio, and pH	~15	Stay et al. 1989

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Phyto- and zooplankton microcosm community	-	-	42 days	Reduced net primary productivity, P/R ratio, and pH	~84	Stay et al. 1989
Experimental pond community	-	-	39 days after treatment	EC50 (^{14}C uptake)	96	Larsen et al. 1986
Experimental pond community	-	-	43 days after treatment	EC50 (^{14}C uptake)	131	Larsen et al. 1986
Experimental pond community	-	-	101 days after treatment	EC50 (^{14}C uptake)	109	Larsen et al. 1986
Experimental pond community	-	-	177 days after treatment	EC50 (^{14}C uptake)	24	Larsen et al. 1986
Experimental pond community	-	-	249 days after treatment	EC50 (^{14}C uptake)	27	Larsen et al. 1986
Experimental pond community	-	-	259 days after treatment	EC50 (^{14}C uptake)	37	Larsen et al. 1986
Experimental pond community	-	-	373 days after treatment	EC50 (^{14}C uptake)	100	Larsen et al. 1986
Mixed pond community	99.2%	-	4 months	Elimination of *Lemna minor* population	60-120	Gunkel 1983
Mixed pond community	99.2%	-	4 months	Rapid succession of algal species; reduced reproduction rate in *Daphnia pulicaria*	60-120	Gunkel 1983

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Pond mesocosm community	99%	-	2 yr	Decreased green algal species, cell numbers and cladoceran populations; increased cryptomonad cell numbers	20	Neugebauer et al. 1990
Pond mesocosm community	99%	-	2 yr	Decreased green algal species, cell numbers and cladoceran populations; increased cryptomonad cell numbers	100	Neugebauer et al. 1990
Pond mesocosm community	99%	-	2 yr	Decreased green algal species, cell numbers and cladoceran populations; increased cryptomonad cell numbers	300	Neugebauer et al. 1990

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Pond mesocosm community	Reagent grade	-	2 yr	Atrazine applied in May and June each year resulted in decreased abundance of *Endochironomus nigricans* in June, and of total macroinvertebrates in both May and June, followed by recovery in July. Epiphytes were decreased in abundance in June, followed by recovery in July. Detritovore abundance was decreased in May, followed by recovery in June. Generalists were decreased in May and June, followed by recovery in July.	20	Huggins et al. 1994
Pond mesocosm community	Reagent grade	-	2 yr	Results were similar to those at 20 µg/L in May and June. *Caenis* sp. were significantly increased in July. In late July, increases occurred in abundance of *Caenis* sp., total macroinvertebrates, detritovores and generalists.	100	Huggins et al. 1994

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Pond mesocosm community	Reagent grade	-	2 yr	Results were similar to those at 20 and 100 µg/L in May and June. In early July, *Caenis* sp. were significantly reduced in abundance, but not in late July. In late July, the abundance of epiphytes decreased, while the abundance of total macroinvertebrates and generalists increased.	500	Huggins et al. 1994
Mixed algae from pond	-	-	>3 hr	Increased fluorescence rate for photosystem II	10	Ruth 1996
Lake limnocorral community	80%	-	34 days	Reduced periphyton ash-free dry weight	80-140	Herman et al. 1986
Lake limnocorral community	80%	-	9 weeks (2 applications 6 weeks apart)	36-67% reduction in chlorophyll *a*, organic matter, and total periphyton algal biomass	80-140 (first application); ~110-190 (second application)	Herman et al. 1986
Lake limnocorral periphyton community	80%	-	50 days	~50% reduction in ash-free dry weight	80	Hamilton et al. 1987
Lake limnocorral periphyton community	80%	-	230 days	Reductions of ~60% in biomass, ~22% in cell numbers, and ~32% in number of species	80	Hamilton et al. 1987

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Lake limnocorral periphyton community	80%	-	56 days	Reductions of ~50% in chlorophyll a, ~32% in biomass, ~14% in cell numbers, and ~33% in number of species	140	Hamilton et al. 1987
Lake limnocorral periphyton community	80%	-	56 days	Reductions of ~55% in chlorophyll a, ~68% in biomass, ~19% in cell numbers, and ~48% in number of species	1,560	Hamilton et al. 1987
Lake limnocorral community	80%	-	Two exposures 35 days apart	Different phytoplankton species assemblages for up to 114 days after second application; increased Secchi disc readings and decreased levels of dissolved oxygen, chlorophyll, and organic carbon; phytoplankton communities were similar by day 323.	100 (first application); 155 (second application)	Hamilton et al. 1988, 1989
Lake mesocosm plankton community	-	-	18 days	Decreased chlorphyll a, dissolved oxygen, nauplii, *Daphnia*, *Cyclops*; increased particulate organic carbon	1	Lampert et al. 1989

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Lake mesocosm plankton community	-	-	10 days[a/]	Decreased algal photosynthetic production, dissolved oxygen and *Daphnia* population; apparent recoveries after about 25 days	0.1	Lampert et al. 1989
Lake bacterial and algal species in microcosm study	-	-	-	Decreased algal population density and decreased "scope for change in ascendance" of community	250	Genoni 1992
Lake mesocosm community	-	-	20 days	No effect upon tolerance to atrazine by phytoplankton and periphyton communities or upon length of *Cladocera*; minor changes in species composition, POC/PON ratio and chlorophyll concentration	20	Gustavson and Wangberg 1995
Lake mesocosm phytoplankton community	-	-	20 days	EC50	58	Gustavson and Wangberg 1995
Lake mesocosm phytoplankton community	-	-	20 days	EC50	52	Gustavson and Wangberg 1995
Lake mesocosm periphyton community	-	-	20 days	EC50	52	Gustavson and Wangberg 1995
Lake mesocosm periphyton community	-	-	20 days	EC50	54	Gustavson and Wangberg 1995

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Lake phytoplankton	-	-	3 hr	EC50 (carbon assimilation)	100	Brown and Lean 1995
Lake phytoplankton	-	-	3 hr	EC50 (phosphate assimilation)	14,000	Brown and Lean 1995
Lake phytoplankton	-	-	3 hr	EC50 (ammonium assimilation)	>33,000	Brown and Lean 1995
Stream periphyton community	85.5%	-	< 4 hr	LOEC (chlorophyll a)	109	Day 1993
Stream phytoplankton community	-	-	Spring season	Reduction in populations of green algae	40.4 maximum	Caux and Kent 1995
Wetland mesocosm community	85%	-	9-27 days	Decreased periphyton gross productivity; increased dissolved nutrients	15	Detenbeck et al. 1996
			SALTWATER SPECIES			
Green alga, *Chlamydomonas* sp.	-	30[r]	90 min	EC50 (oxygen evolution)	60	Hollister & Walsh, 1973
Green alga, *Chlorococcum* sp.	Technical	30	90 min	EC50 (oxygen evolution)	100	Walsh 1972
Green alga, *Chlorococcum* sp.	80.0%	30	90 min	EC50 (oxygen evolution)	400	Walsh 1972
Green alga, *Chlorococcum* sp.	Technical	30	90 min	EC100 (oxygen evolution)	400	Walsh 1972

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Chlorococcum* sp.	80.0%	30	90 min	EC100 (oxygen evolution)	800	Walsh 1971
Green alga, *Chlorococcum* sp.	Technical	30	10 days	EC50 (growth)	100	Walsh 1972
Green alga, *Chlorococcum* sp.	80.0	30	10 days	EC50 (growth)	100	Walsh 1972
Green alga, *Chlorococcum* sp.	Technical	30	10 days	EC100 (growth)	500	Walsh 1972
Green alga, *Chlorococcum* sp.	80.0%	30	10 days	EC100 (growth)	500	Walsh 1972
Green alga, *Dunaliella tertolecta*	Technical	30	90 min	EC50 (oxygen evolution)	300	Walsh 1972
Green alga, *Dunaliella tertolecta*	80.0%	30	90 min	EC50 (oxygen evolution)	600	Walsh 1972
Green alga, *Dunaliella tertolecta*	Technical	30	90 min	EC100 (oxygen evolution)	700	Walsh 1972
Green alga, *Dunaliella tertolecta*	80.0%	30	90 min	EC100 (oxygen evolution)	1,000	Walsh 1972
Green alga, *Dunaliella tertolecta*	Technical	30	10 days	EC50 (growth)	300	Walsh 1972
Green alga, *Dunaliella tertolecta*	80.0%	30	10 days	EC50 (growth)	400	Walsh 1972
Green alga, *Dunaliella tertolecta*	Technical	30	10 days	EC100 (growth)	1,200	Walsh 1972
Green alga, *Dunaliella tertolecta*	80.0%	30	10 days	EC100 (growth)	1,500	Walsh 1972
Green alga, *Dunaliella tertiolecta*	-	30[r]	90 min	EC50, oxygen evolution	159	Hollister & Walsh, 1973
Green alga, *Dunaliella tertiolecta*	97%	-	5 days	EC50 (cell number)	170	Hughes 1986, 1988

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Dunaliella tertiolecta*	97%	-	5 day exposure, 9 day recovery	NOEC (cell numbers)	< 100	Hughes 1986, 1988
Green alga, *Dunaliella tertiolecta*	97%	-	5 day exposure, 9 day recovery	Algistatic concentration	1,450	Hughes 1986, 1988
Green alga, *Dunaliella tertiolecta*	97%	-	5 day exposure, 9 day recovery	Algicidal concentration	> 3,200	Hughes 1986, 1988
Green alga, *Dunaliella tertiolecta*	-	-	15 min	EC50 (oxygen evolution)	270	Samson and Popovic 1988
Green alga, *Dunaliella tertiolecta*	-	-	15 min	EC50 (complementary area)	37	Samson and Popovic 1988
Green alga, *Dunaliella tertiolecta*	-	-	96 hr	EC50 (cell number)	132	Gaggi et al. 1995
Green alga, *Dunaliella bioculata*	Technical	-	48 hr	35% reduction in growth	216	Felix et al. 1988
Green alga, *Dunaliella bioculata*	Technical	-	48 hr	85% reduction in growth	3,240	Felix et al. 1988
Green alga, *Dunaliella bioculata*	Technical	-	48 hr	100% growth inhibition	21,570	Felix et al. 1988
Green alga, *Platymonas* sp.	-	30	90 min	EC50, oxygen evolution	102	Hollister & Walsh, 1973
Green alga, *Chlorella* sp.	-	30	90 min	EC50, oxygen evolution	143	Hollister & Walsh, 1973
Green alga, *Neochloris* sp.	-	30	90 min	EC50, oxygen evolution	82	Hollister & Walsh, 1973
Green alga, *Chlorococcum* sp.	-	30	90 min	EC50, oxygen evolution	80	Hollister & Walsh, 1973
Green alga, *Nannochloris oculata*	-	15	7 days	21% change in doubling time	50	Kalander et al., 1983; Mayasich et al., 1986

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Nannochloris oculata*	-	15	7 days	11% change in doubling time	50	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	12% change in doubling time	50	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	34% change in doubling time	50	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	35% change in doubling time	50	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	33% change in doubling time	50	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	42% change in doubling time	50	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	35% change in doubling time	50	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	28% change in doubling time	50	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	46% change in doubling time	100	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	35% change in doubling time	100	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	21% change in doubling time	100	Kalander et al., 1983; Mayasich et al., 1986

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Nannochloris oculata*	-	15	7 days	59% change in doubling time	100	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	52% change in doubling time	100	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	47% change in doubling time	100	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	57% change in doubling time	100	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	56% change in doubling time	100	Kalander et al., 1983; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	54% change in doubling time	100	Kalander et al., 9183; Mayasich et al., 1986
Green alga, *Nannochloris oculata*	-	15	7 days	change in doubling time	15	Mayasich et al. 1987
Diatom, *Thalassiosira fluviatilis*	-	20	7 days	Reduced chlorophyll	220	Plumley & Davis, 1980
Diatom, *Thalassiosira fluviatilis*	-	20	7 days	Reduced cell number and photosynthesis	2,200	Plumley & Davis, 1980
Diatom, *Thalassiosira fluviatilis*	-	30	90 min	EC50, oxygen evolution	110	Hollister & Walsh, 1973
Diatom, *Nitzschia sigma*	-	20	7 days	Reduced photosynthesis	220	Plumley & Davis, 1980
Diatom, *Nitzschia sigma*	-	20	7 days	Reduced chlorophyll and cell number	2,200	Plumley & Davis, 1980

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Diatom, *Nitzschia closterium*	-	30	90 min	EC50, oxygen evolution	287	Hollister & Walsh, 1973
Diatom, *Nitzschia* (Ind. 684)	-	30	90 min	EC50, oxygen evolution	434	Hollister & Walsh, 1973
Diatom, *Navicula inserta*	-	30	90 min	EC50, oxygen evolution	460	Hollsiter & Walsh, 1973
Diatom, *Amphora exigua*	-	30	90 min	EC50, oxygen evolution	300	Hollister & Walsh, 1973
Diatom, *Achnanthes brevipes*	-	30	90 min	EC50, oxygen evolution	93	Hollister & Walsh, 1973
Diatom, *Stauroneis amphoroides*	-	30	90 min	EC50, oxygen evolution	348	Hollister & Walsh, 1973
Diatom, *Cyclotella nanna*	-	30	90 min	EC50, oxygen evolution	84	Hollister & Walsh, 1973
Diatom, *Phaeodactylum tricornutum*	-	30	90 min	EC50, oxygen evolution	100	Hollister & Walsh, 1973
Diatom, *Phaeodactylum tricornutum*	-	-	7 days	Limited effect on doubling time	50	Mayasich et al. 1987
Diatom, *Skeletonema costatum*	-	-	48 hr	EC50 (cell numbers)	20	Walsh et al. 1988
Diatom, *Minutocellus polymorphus*	-	-	72 hr	EC50 (cell numbers)	50	Walsh et al. 1988
Chrysophyte, *Monochrysis lutheri*	-	30	90 min	EC50, oxygen evolution	77	Hollister & Walsh, 1973
Diatom, *Isochrysis galbana*	Technical	30	90 min	EC50 (oxygen evolution)	100	Walsh 1972
Diatom, *Isochrysis galbana*	80.0%	30	90 min	EC50 (oxygen evolution)	200	Walsh 1972
Diatom, *Isochrysis galbana*	Technical	30	90 min	EC100 (oxygen evolution)	200	Walsh 1972

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Diatom, *Isochrysis galbana*	80.0%	30	90 min	EC100 (oxygen evolution)	500	Walsh 1972
Diatom, *Isochrysis galbana*	Technical	30	10 days	EC50 (growth)	100	Walsh 1972
Diatom, *Isochrysis galbana*	80.0%	30	10 days	EC50 (growth)	100	Walsh 1972
Diatom, *Isochrysis galbana*	Technical	30	10 days	EC100 (growth)	200	Walsh 1972
Diatom, *Isochrysis galbana*	80.0%	30	10 days	EC100 (growth)	200	Walsh 1972
Diatom, *Isochrysis galbana*	-	30	90 min	EC50, oxygen evolution	100	Hollister & Walsh, 1973
Diatom, *Phaeodactylum tricornutum*	Technical	30	90 min	EC50 (oxygen evolution)	100	Walsh 1972
Diatom, *Phaeodactylum tricornutum*	80.0%	30	90 min	EC50 (oxygen evolution)	200	Walsh 1972
Diatom, *Phaeodactylum tricornutum*	Technical	30	90 min	EC100 (oxygen evolution)	200	Walsh 1972
Diatom, *Phaeodactylum tricornutum*	80.0%	30	90 min	EC100 (oxygen evolution)	600	Walsh 1972
Diatom, *Phaeodactylum tricornutum*	Technical	30	10 days	EC50 (growth)	200	Walsh 1972
Diatom, *Phaeodactylum tricornutum*	80.0%	30	10 days	EC50 (growth)	200	Walsh 1972
Diatom, *Phaeodactylum tricornutum*	Technical	30	10 days	EC100 (growth)	500	Walsh 1972
Diatom, *Phaeodactylum tricornutum*	80.0%	30	10 days	EC100 (growth)	500	Walsh 1972
Red alga, *Porphyridium cruentum*	-	30	90 min	EC50, oxygen evolution	79	Hollister & Walsh, 1973

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Kelp, *Laminaria hyperborea*	-	-	28 days	LOEC growth of new sporophytes	10	Hopkins & Kain, 1971
Kelp, *Laminaria saccharina*	70%	30	2 days	No effect on sexual reproduction	33.2	Thursby & Tagliabue 1990
Kelp, *Laminaria saccharina*	70%	30	2 days	66% reduction in fertilization	72.2	Thursby & Tagliabue 1990
Kelp, *Laminaria hyperborea*	-	-	24 hours	LOEC respiration	>1,000	Hopkins & Kain, 1971
Redheadgrass pondweed, *Potamogeton perfoliatus*	99.7%	10	4 hours	IC50 photosynthesis	80	Jones et al., 1986
Redheadgrass pondweed, *Potamogeton perfoliatus*	-	8-12	2 hours	IC50 photosynthesis	77	Jones & Winchell, 1984
Euraisian watermilfoil, *Myriophyllum spicatum*	-	8-12	2 hours	IC50 photosynthesis	104	Jones & Winchell, 1984
Aquatic vascular plant, *zannichellia palustris*	-	8-12	2 hours	IC50 photosynthesis	91	Jones & Winchell, 1984
Widgeon grass, *Ruppia maritima*	-	8-12	2 hours	IC50 photosynthesis	120	Jones & Winchell, 1984
Vallisneria, *Vallisneria americana*	-	5	47 days	67% reduction in leaf production & 76% reduction in leaf area	12	Cornell & Wu, 1982
Vallisneria, *Vallisneria americana*	-	3	42 days	47% decrease in growth as length, and 48% decrease as dry weight	100	Forney, 1980; Forney & Davis, 1981
Vallisneria, *Vallisneria americana*	-	6	42 days	27% decrease in growth as length, and 30% decrease as dry weight	100	Forney, 1980; Forney & Davis, 1981

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Vallisneria, *Vallisneria americana*	-	3	42 days	27% decreased in growth as length, and 41% decrease as dry weight	320	Forney, 1980; Forney & Davis, 1981
Vallisneria, *Vallisneria americana*	-	6	42 days	32% decrease in growth as length, and 29% decrease as dry weight	320	Forney, 1980; Forney & Davis, 1981
Eelgrass, *Zostera marina*	-	-	24 hours	Reduced net oxygen evolution	100	Kemp et al., 1981
Eelgrass, *Zostera marina*	-	-	24 hours	No net oxygen evolution	1,000	Kemp et al., 1981
Eelgrass, *Zostera marina*	97.2%	14	10 days	100% growth inhibition	1,900	Schwarzschild et al. 1994
Turtlegrass, *Thalassia testudinum*	Technical, 99.7%	30	40 hours	EC50 (photosynthesis)	320	Walsh et al., 1982
Salt-marsh grass, *Spartina alterniflora*	97.1%	-	35 days	Increased peroxidase activity	30	Lytle & Lytle 1998
Salt-march grass, *Spartina alterniflora*	97.1%	-	35 days	No effect upon shoot growth, lipid peroxidation products or chlorophyll production. Enhanced peroxidase activity	3,100	Lytle & Lytle 1988
Salt-marsh rush, *Juncus roemerianus*	97.1%	-	35 days	Reduced chlorphyll *a*; Increased peroxidase activity and lipid peroxidation products	30	Lytle & Lytle 1998

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Salt-marsh rush, *Juncus roemerianus*	97.1%	-	35 days	Reduced shoot growth, chlorophyll *a*, chlorophyll *b*; increased lipid peroxidation products	3,800	Lytle & Lytle 1998
Eastern oyster (juvenile), *Crassostrea virginica*	Technical, 99.7%	28	96 hours	EC50 (shell growth)	>1,000	Butler, 1965; Mayer, 1987
Copepod, *Acartia tonsa*	97.1%	30-34	72 hours	LC50	6,100	McNamara, 1991
Copepod, *Acartia tonsa*	97.1%	30-34	48 hours	LC50	8,400	McNamara, 1991
Copepod, *Acartia tonsa*	97.1%	30-34	24 hours	LC50	15,000	McNamara, 1991
Brown shrimp (juvenile), *Penaeus aztecus*	Technical, 99.7%	30	48 hours	EC50	1,000	Mayer, 1987
Brown shrimp, *Penaeus aztecus*	-	-	24 hours	20% mortality	1,000	Butler, 1965
Brown shrimp, *Penaeus aztecus*	-	-	48 hours	30% mortality	1,000	Butler, 1965
Spot (juvenile), *Leiostomas xanthurus*	Technical, 99.7%	29	48 hours	LC50	>1,000	Butler, 1965; Mayer, 1987
Fiddler crab (field), *Uca pugnax*	80%	-	70 days	No effect on number per m^2 after a single application	1,000,000	Plumley et al., 1980
Fiddler crab (field), *Uca pugnax*	80%	-	70 days	94% reduction in number per m^2 relative to control after a single application	10,000,000	Plumley et al., 1980

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Fiddler crab, *Uca pugnax* (animals collected in August)	80%	20	8 days	25% mortality of large males; 100% mortality of large females; 100% mortality of small males; 75% mortality of small females	100,000	Plumley et al., 1980
Fiddler crab, *Uca pugnax* (animals collected in August 1977)	80%	20	8 days	50% mortality of large males; 100% mortality of large females; 75% mortality of small males, 50% mortality of small females	1,000,000	Plumley et al., 1980
Fiddler crab, *Uca pugnax* (animals collected in November)	80%	20	30 days	No effect on survival of small males	1,000,000	Plumley et al., 1980
Fiddler crab, *Uca pugnax* (animals collected in March)	80%	20	9 days	No effect on survival of small males	1,000,000	Plumley et al., 1980
Fiddler crab, *Uca pugnax* (animals collected in August 1978)	80%	20	9 days	60% mortality	100,000	Plumley et al., 1980
Fiddler crab, *Uca pugnax* (animals collected in August 1978)	80%	20	9 days	90% mortality	180,000	Plumley et al., 1980
Fiddler crab, *Uca pugnax* (animals collected in August 1978)	80%	20	9 days	80% mortality	320,000	Plumley et al., 1980
Fiddler crab, *Uca pugnax* (animals collected in August 1978)	80%	20	9 days	90% mortality	560,000	Plumley et al., 1980

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Fiddler crab, *Uca pugnax* (animals collected in August 1978)	80%	20	9 days	90% mortality	1,000,000	Plumley et al., 1980
Fiddler crab, *Uca pugnax* (animals collected in August 1978)	80%	20	9 days	100% mortality	10,000,000	Plumley et al., 1980
Drift line crab (field), *Sesarma cinereum*	80%	-	70 days	No effect on number per m^2 after a single application	10,000,000	Plumley et al., 1980
Mud crab (field), *Panopeus* sp.	80%	-	70 days	No effect on number per m^2 after a single application	10,000,000	Plumley et al., 1980
Mesocosm, Mixed marine phytoplankton	Residue grade	-	15 days	Reduced pH, particulate carbohydrates, chlorophyll, photosynthesis, primary production; increased dissolved organic phosphorus, dissolved organic nitrogen, and dissolved amino acids	0.12	Bester et al. 1995

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Mesocosm, Mixed marine phytoplankton	Residue grade	-	15 days	Reduced pH, particulate carbohydrates, chlorophyll, photosynthesis, primary production; increased dissolved organic phosphorus, dissolved organic nitrogen, and dissolved amino acids	0.56	Bester et al. 1995
Mesocosm, Mixed marine phytoplankton	Residue grade	-	15 days	Reduced pH, particulate carbohydrates, chlorophyll, photosynthesis, primary production; increased dissolved organic phosphorus, dissolved organic nitrogen, and dissolved amino acids	5.80	Bester et al. 1995

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference

[a] Test was run using a Taub and Dollar medium.
[b] Test was run using an algal assay medium (U.S. EPA 1971).
[c] Only 2.3 to 4.7 percent of this concentration remained on day 7.
[d] Nephelometric determination.
[e] Cultured from sample collected in Osage Spring, Clayton County, Iowa.
[f] Cultured from sample collected in Big Spring, Clayton County, Iowa.
[g] Test performed with an atrazine-sensitive strain.
[h] Test performed with an atrazine-resistant strain
[i] Algae were pre-conditioned for 4 days with 531 µg/L of atrazine.
[j] Colorimetric determination.
[k] Test performed with water from microcosm 30 days after atrazine had been introduced.
[l] Test performed directly with atrazine in water without a microcosm exposure.
[m] EC50 obtained using an algal assay medium.
[n] EC50 obtained using creek water as the test medium.
[o] Animals were fed at 24 hr.
[p] Two single annual applications at nominal concentration indicated.
[q] Atrazine concentrations were below detection after 10 days; however, the study continued for 42 days.
[r] Salinity in g/L.

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