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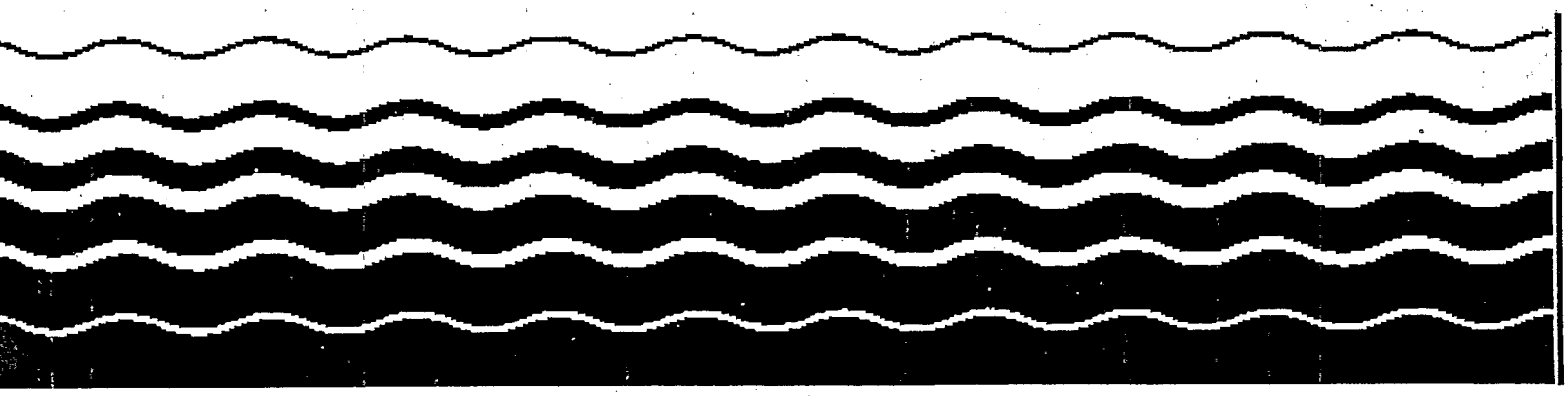

AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR

ATRAZINE

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U.S. ENVIRONMENTAL PROTECTION AGENCY

OFFICE OF WATER
OFFICE OF SCIENCE AND TECHNOLOGY
HEALTH AND ECOLOGICAL CRITERIA DIVISION
WASHINGTON D.C.

NOTICES

This document has been reviewed by the Health and Ecological Criteria Division, Office of Science and Technology, U.S. Environmental Protection Agency, and approved for publication.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

EXECUTIVE SUMMARY

BACKGROUND:

Atrazine is an herbicide that has been used extensively throughout the U.S. for control of weeds in agricultural crops. It is a problem in the aquatic environment because it is toxic to aquatic organisms and is often found in surface water. EPA is developing ambient water quality criteria for atrazine through its authority under Section 304(a) of the Clean Water Act (CWA). These water quality criteria may be used by States and Tribes to establish water quality standards for atrazine.

CRITERIA:

Freshwater:

For atrazine, the criterion to protect freshwater aquatic life from chronic toxic effects is a four-day average of 12 ug/L, not to be exceeded more than once every three years on the average. The criterion to protect freshwater aquatic life from acute toxic effects is a one-hour average of 350 ug/L, not to be exceeded more than once every three years on the average.

Saltwater:

For atrazine, the criterion to protect saltwater aquatic life from chronic toxic effects is a four-day average of 26 ug/L, not to be exceeded more than once every three years on the average. The criterion to protect saltwater aquatic life from acute toxic effects is a one-hour average of 760 ug/L, not to be exceeded more than once every three years on the average.

The criteria for atrazine were developed by the EPA Office of Water (OW) using a large aquatic toxicity data base. Adverse effects of atrazine on survival, growth, and reproduction of aquatic organisms were demonstrated in numerous laboratory studies. In addition, field studies have also demonstrated the toxicity of atrazine to aquatic life.

Concurrent with the publication of these water quality criteria for atrazine, the EPA Office of Pesticide Programs (OPP) is publishing its Preliminary Ecological Fate and Effects Assessment for Atrazine. Both EPA offices shared their aquatic toxicity data bases for atrazine in the development of their respective ecological risk assesssment documents. OW and OPP are currently consulting on their respective ecological risk assessment methodologies. Although there are similarities in the approaches, differences remain. While this consultation is underway, both EPA offices are making their ecological risk assessments for atrazine available to the public and requesting comment on their respective methodologies.

This document provides guidance to States and Tribes authorized to establish water quality standards under the Clean Water Act (CWA) to protect aquatic life from acute and chronic effects of atrazine. Under the CWA, States and Tribes are to establish water quality criteria to protect designated uses. While this document constitutes U.S.EPA's scientific recommendations regarding ambient concentrations of atrazine, this document does not substitute for the CWA or U.S.EPA's regulations; nor is a regulation itself. Thus, it cannot impose legally binding requirements on U.S.EPA, States, Tribes, or the regulated community, and it might not apply to a particular situation based upon the circumstances. State and Tribal decision-makers retain the discretion to adopt approaches on a case-by-case basis that differ from this guidance when appropriate. U.S.EPA may change this guidance in the future.

ACKNOWLEDGMENTS

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Introduction[1]

Atrazine is a 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 173-175°C, a boiling point of 279°C, and solubility in water of 33 mg/L at 25°C (Farm Chemicals Handbook 2000; Hunter et al. 1985). 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·m³/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 in terms of total pounds of herbicide used (Braden et al. 1989; Burridge and Haya 1988; Ciba-Geigy 1994; Council on Environmental Quality 1984; Moxley 1989; Pike 1985; Richards and Baker 1993). Annual domestic usage during the past two decades has been in the general range of 30 to 40 million kilograms applied to approximately 70 million acres of farm land in the U.S. (U.S. EPA 2000). It is also commonly used in other countries (Bester and Huhnerfuss 1993; Bester et al. 1995; Caux and Kent 1995; Galassi et al. 1992, 1993; Lode et al. 1994). Atrazine is also used in combination with other herbicides including alachlor,

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

ametryne, linuron, paraquat, propachlor, amitrole, and cyanazine (Farm Chemicals Handbook 2000).

With this magnitude of application, atrazine has commonly been detected in surface waters of agricultural watersheds where it has been used. Due to its relative mobility from soil, atrazine surface water concentrations are highest in field runoff, with concentration peaks generally following early major storm events that occur within a few weeks of application (Glotfelty et al. 1984; Muir et al. 1978; Triplett et al. 1978; Wauchope 1978; Wauchope and Leonard 1980). Concentrations in the low mg/L range may be encountered in edge-of-field run-off (Hall et al. 1972; Kadoum and Mock 1978; Klaine et al. 1988; Roberts et al. 1979). 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 (Frank and Sirons 1979; Frank et al. 1979; Richards and Baker 1993; Richard et al. 1975; Roberts et al. 1979; Wu 1981). 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 from 5 to 70 μg/L (Ciba-Geigy 1992a,b,c,d, 1994; Frank and Sirons 1979; Frank et al. 1979, 1982; Illinois State Water Survey 1990; Muir et al. 1978; Richards and Baker 1993; Roberts et al. 1979). Factors that strongly and positively correlate with the release of atrazine from soil include sediment organic carbon, landscape position, and tillage (Novak 1999).

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 from April to June, followed by a rapid decrease from June to 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 at lower levels and several weeks later than in Ohio (Bodo 1991). Nonetheless, atrazine concentrations in Ontario have regularly exceeded 2 μg/L, which is 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 (Ciba-Geigy 1992a; Illinois State Water Survey 1990), in Iowa (Ciba-Geigy 1994), and in other midwestern states (Ciba-Geigy 1992c). In large rivers such as the Mississippi, Missouri and Ohio Rivers, peak concentrations have most commonly occurred in June, with mean levels of less than 5.0 μg/L during the spring period (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 μg/L to 4.7 μg/L (Pereira and Hostetler 1993).

Atrazine residues in Illinois lakes tended to be lower than those in the streams (with less pronounced peak values), however, 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 1992e). Here, the maximum observed concentration in a tributary was 14.6 μg/L, and only three out of 600 samples analyzed between 1976 and 1991 exceeded 3.0 μg/L. The highest observed maxima in the 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 1992c).

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 1981; Wu et al. 1980). 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 direct input rather than a result of atmospheric wet 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 percent loss of atrazine occurred in 3.2 days (Kosinski 1984; Moorhead and Kosinski 1986). Lay et al. (1984) reported an 82 percent loss in 5 days and a 95 percent 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 (Jones et al. 1982; Kemp et al. 1982a).

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 percent in 120 days and 0 percent in 85 days in two separate 0.49 hectare pond applications (Klaassen and Kadoum 1979), and a loss of only 40-50 percent in pond water over a period of more than 5 months (Gunkel 1983). In two months time, approximately 25-30 percent of individual 20 and 500 $\mu g/L$ 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. 1994a).

The above information indicates that the persistence of atrazine in water is 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. For example, Comber (1999) determined that significant hydrolysis of atrazine occurs only at pH values of 4 or less, while photolysis was initiated only by wavelengths below 300 nm at higher pH (pH 6 to 8). Based on this author's experiments, the aquatic half-life of atrazine in sunny upland waters was predicted to be 6 days, but in low land rivers with higher pH (7 to 8.5), the half-life would be in the order of months rather than days. The opposite is true for groundwater where the half-life would be in the order of years due to exceedingly slow rates of hydrolysis.

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 et al. (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 anaerobically (Behki et al. 1993; Radosevich et al. 1995, 1996). Some soil fungi also can degrade atrazine (Donnelly et al. 1993). 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.

Seybold et al. (1999) recently examined the fate of atrazine (^{14}C-labeled) from two undisturbed sediments over a 2-year period. The atrazine was released from the sediment into the water column primarily through diffusion from the pore water. The amount of atrazine released was affected by sediment type and temperature. More atrazine residue was released into the water column at 5°C than at 24°C. However, degradation of the atrazine in sediment was high; less than 2 percent of extractable atrazine and metabolites

remained after 2 years. The authors concluded that the accumulation and later release of atrazine is greatest at cold water temperatures and in sediments with low adsorption capacity.

The major atrazine degradate in aquatic systems is hydroxyatrazine (U.S. EPA 2000). Others include deethylatrazine, deisopropylatrazine, and diaminoatrazine. The degradation products of atrazine were found to be less toxic to algae (Stratton 1984)[11] and submerged aquatic plants (Jones and Winchell 1984) then the parent compound. Equivalent studies of atrazine degradate toxicity to aquatic animals is sparse. Results from mammalian studies indicate that some atrazine degradates may be more toxic than parent compound (U.S. EPA 2000).

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; Dewey 1986; Herman et al. 1986; Kosinski and Merkle 1984; Pratt et al. 1988). On the other hand, the mode of toxic action toward aquatic animals has not been documented, probably because atrazine is not considered acutely toxic to these species. Recent evidence implicates atrazine as an indirect endocrine disruptor (Dodson et al. 1999; Petit et al. 1997) that may act by stimulating the activity of the aromatase enzyme that converts testosterone to estrogen (Sanderson et al. 2000). Other investigators have demonstrated that atrazine causes induction of xenobiotic metabolizing systems (Miota et al. 1999), and enhances the toxicity of organophosphorous insecticides to aquatic invertebrates (Belden and Lydy 2000; Pape-Lindstrom and Lydy 1997).

Several reviews exist on atrazine and its environmental impact (CCREM 1989; deNoyelles et al. 1994; Eisler 1989; Huber 1993, 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.

Comprehension 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 1985) are necessary to understand the following text, tables, and calculations. Results of intermediate calculations such as recalculated LC50 values and Species Mean Acute Values are given to four significant figures to prevent roundoff error in subsequent calculations, not to reflect the precision of values. The criteria presented herein are the Agency's best estimate of maximum concentrations of the chemical of concern to protect most aquatic organisms or their uses from any unacceptable short- or long-term effects. 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 1991). The latest comprehensive literature search for this document was conducted in November, 1999. 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 49,000 µg/L for the cladoceran, *Daphnia magna* (Putt 1991). 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 (*Ceriodaphnia dubia*) had a Species Mean Acute Value (SMAV) of >12,120 µg/L (Jop 1991a; Oris et al. 1991). The remaining invertebrate species tested, a snail (*Physa* sp.) and an annelid (*Lumbriculus variegatus*), had LC50 values in excess of 34,100 and 37,100 µg/L, respectively (Brooke 1990).

The rainbow trout (*Oncorhynchus mykiss*) was the most sensitive freshwater vertebrate species tested, with an LC50 of 5,300 µg/L (Beliles and Scott 1965). The goldfish, Carassius auratus, was 11.32 times less sensitive to atrazine (Table 1). The fathead minnow (*Pimephales promelas*) had a SMAV of 20,000 µg/L (Dionne 1992), while the LC50 for the brown trout (*Salmo trutta*) was 27,000 µg/L (Grande et al. 1994). The SMAVs for the remaining vertebrate species, all fishes, were 6,300; >8,000, >10,000, >10,000, and >18,000 µg/L for the brook trout, *Salvelinus fontinalis* (Macek et al. 1976); bluegill,

Lepomis macrochirus (Beliles and Scott 1965; 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 in the cases of the fathead minnow and bluegill sunfish, where other test results were also available.

Freshwater Genus Mean Acute Values were identical to the SMAVs in all cases with the exception of *Oncorhynchus* where the two species tested had different SMAVs. Three of the four most sensitive freshwater genera to atrazine are invertebrates. The freshwater Final Acute Value for atrazine was calculated to be 702.4 µg/L using the procedure described in the Guidelines and the Genus Mean Acute Values for invertebrates and fish in Table 3. The freshwater Final Acute Value is lower than all available freshwater Species Mean Acute Values (Figure 1).

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 saltwater Species Mean Acute Values range from 2,324 µg/L for mysids, *Americamysis bahia* (formerly *Mysidopsis bahia*), to >30,000 µg/L for the eastern oyster, *Crassostrea virginica*. The copepod, *Acartia tonsa*, had similar LC50 values resulting from 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 percent). A possible explanation is that the measured values from the static renewal tests were conducted with 70 percent technical grade atrazine, while the flow-through test used 97.1 percent atrazine. The other 30 percent 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. LC50 values for the copepod, *Eurytemora affinis*, were 500, 2,600 and 13,200 µg/L at salinities of 5, 15 and 25 g/kg, respectively (Hall et al. 1994a,b). The resultant SMAV was 2,579 µg/L. The opposite trend was observed for the sheepshead minnow; the LC50 values were 16,200, 2,300 and 2,000 µg/L at salinities of 5, 15 and 25 g/kg, respectively, for larval fish (Hall et al. 1994a,b). Two other LC50 values of 13,000 and >16,000 µg/L for sheepshead minnow was derived from the flow-through concentration measured test by Machado (1994b) and Ward and Ballantine (1985). However, because the former LC50 values were from a more sensitive life-stage, an SMAV of 4,208 µg/L has been calculated for this species.

Saltwater 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. Three of the four most sensitive saltwater genera to atrazine are crustaceans. The saltwater Final Acute Value for atrazine, 1,519 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 (Figure 2).

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 2a. Freshwater tests have been completed with three invertebrate and four 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 3,536 µg/L. An accompanying acute toxicity test resulted in an LC50 of >30,000 µg/L (Oris et al. 1991). The resultant acute-chronic ratio was >8.484.

In another 7-day life cycle exposure with *Ceriodaphnia dubia* (Jop 1991b), 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 (Jop 1991a) resulted in an acute-chronic ratio of >2.829. Therefore, the species mean acute-chronic ratio is >4.899 (Table 3).

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 young 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 187.1 µg/L. A corresponding acute value of 6,900 µg/L (Macek et al. 1976) yielded an acute-chronic ratio of 36.88.

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 159.1 µg/L. A corresponding acute value of 720 µg/L (Macek et al. 1976) yielded an acute-chronic ratio of 4.525 for *Chironomus tentans*.

Rainbow trout (*Oncorhynchus mykiss*) were exposed to atrazine in an early-life stage test (ELS) conducted in reconstituted water with a hardness of 50 mg/L as calcium carbonate (Whale et al. 1994). The ELS test was divided into 3 main stages: (I) immediately post-fertilization to hatching (30-day duration), (II) post-hatch to swim up (28-day duration), (III) post-swim up to

3 months old (28-day duration), for a total exposure of 86 days. Mean measured concentrations (mean ± SD) were <10 (water control), <10 (solvent control), 36 ± 12, 130 ± 50, 410 ± 170, 1,100 ± 660, and 3,800 ± 2,200 µg/L, respectively. Significant mortalities (58.8 percent) occurred in the highest atrazine exposure during stage I and II of the test although no other dose response relationships could be defined. Significant decrease in fish wet weight was observed in concentrations of 1,100 and 3,800 µg/L compared to the solvent control, although fry exposed to 1,100 µg/L did show signs of a recovery in wet weight toward the end of the stage III exposure. Statistical analysis of the dry weights of these same fish samples showed that a significant decrease in weight occurred only in fish exposed to 3,800 µg/L atrazine. Because of the recovery in growth at the 1,100 µg/L atrazine concentration, the chronic limits in this study were set at 1,100 and 3,800 µg/L, resulting in a chronic value of 2,045 µg/L. An accompanying acute value is not available for this species, therefore, an acute-chronic ratio cannot be calculated.

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[11]. 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 88.32 µg/L. A corresponding acute value of 6,300 µg/L (Macek et al. 1976) yielded an acute-chronic ratio of 71.33 for brook trout.

Fathead minnows (*P. 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 the hatchability, survival or 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 hours 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 430.5 μg/L. A corresponding acute value of 15,000 μg/L from Macek et al. (1976) yielded an acute-chronic ratio of 34.84.

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, first generation 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. Second generation 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 first and second generation larval hatching and growth. This resulted in a chronic value of 339.1 μg/L. An accompanying acute value of 20,000 μg/L (Dionne 1992) yielded an acute-chronic ratio of 58.98.

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 217.9 µg/L. A corresponding acute value of >8,000 µg/L (Macek et al. 1976) yielded an acute-chronic ratio of >36.71.

The acute values for *D. magna*, *C. tentans*, *S. fontinalis*, *P. promelas* and *L. 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 three 8-day life cycle tests with the copepod, *Eurytemora affinis*, a 28-day life cycle test with the mysid, *Americamysis bahia*, and an early life-stage test (28-day) with the sheepshead minnow, *Cyprinodon variegatus* (Table 2a). Survival was the most sensitive endpoint in the 8-day chronic tests with *E. affinis*. Tests were performed at salinity levels of 5, 15 and 25 g/kg. At a salinity of 5 g/kg, survival was significantly reduced to 37 percent at the 17,500 µg/L concentration, while at the next lower concentration of 12,250 µg/L it was similar to controls at 71 percent (Hall et al. 1995). The chronic value was 14,640 µg/L. At a salinity of 15 g/kg, the

chronic limits were 17,500 and 25,000 µg/L, and the chronic value was 20,920 µg/L. Sensitivity appeared greater at a salinity of 25 g/kg, with chronic limits of 4,200 and 6,000 µg/L, and a chronic value of 5,020 µg/L. Only at this highest salinity level was the acute value greater than the chronic value. The resultant Acute-Chronic Ratio of 2.629, determined at a salinity of 25 g/kg (13,200 µg/L ÷ 5,020 µg/L), 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, 30, and 20 percent at 190, 290 and 470 µg/L, respectively. No statistically significant effect was observed for survival at concentrations ≤80 µg/L. Reproduction did not occur at 470 µg/L, but no adverse effects on reproduction were observed at all lower concentrations. The chronic value for mysids, based on survival, is 123.3 µg/L. The acute value, as determined by the same authors, is 1,000 µg/L and the resulting acute-chronic ratio is 8.110 (Table 2b).

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 in any of the 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 the sheepshead minnow, as determined by the same authors, is a "greater than" value (>16,000 µg/L). Therefore, the resulting acute-chronic value is >6.294.

The range of species mean acute-chronic ratios for both freshwater and saltwater differ by more than a factor of 10 (Table 2b), and are not related to rank order of acute sensitivity (Table 3). For both freshwater and

saltwater, separate fish and invertebrate chronic values were calculated using separate fish and invertebrate Acute-Chronic Ratios (Table 3). Acute-Chronic Ratios with greater than values were not used for these calculations. The freshwater Fish Chronic Value of 12.35 µg/L is the quotient of the Final Acute Value (702.4 µg/L) and the Fish Final Acute-Chronic Ratio (56.86). Likewise, the Invertebrate Chronic Value of 90.95 µg/L is the quotient of the Final Acute Value (702.4 µg/L) and the Invertebrate Final Acute-Chronic Ratio (7.723). The Final freshwater Chronic Value is 12.35 µg/L, the lesser of the two chronic values.

The saltwater Fish Chronic Value of 26.71 µg/L is the quotient of the Final Acute Value (1,519 µg/L) and the Fish Final Acute-Chronic Ratio (56.86). Likewise, the Invertebrate Chronic Value of 196.7 µg/L is the quotient of the Final Acute Value (1,519 µg/L) and the Invertebrate Final Acute-Chronic Ratio (7.723). The Final Saltwater Chronic Value is 26.71 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 µg/L, after 7 days of exposure to 21 µg/L, and after 10 days of exposure to 10.2 µg/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 values for pheophytin a and chlorophyll a content were 20 and 150 µg/L, respectively. Using 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 (1991a) 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, respectively, whereas, EC90 values at 4 and 5 days were 190 and 120 µg/L, respectively (Hoberg 1991a, 1993a).

A 7-day exposure of the duckweed, *Lemna gibba*, to atrazine 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 (Hoberg 1993b), using frond number as an endpoint, the EC10, EC50 and EC90 values were 6.2, 37, and 220 µg/L, respectively, after 14 days of exposure. Using frond biomass, the EC10, EC50 and EC90 values were 12, 45 and 170 µg/L, respectively. In the second study (Hoberg 1993c), the EC10, EC50 and EC90 values 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.

Exposure of a different species of 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. In another study using *L. minor* (Kirby and Sheahan 1994), 10-day exposures to atrazine yielded EC50 values that were comparable to those found for *L. gibba* by Hoberg (1993b,c). EC50 values of 56, 60 and 62 µg/L were obtained based upon frond number, fresh weight and chlorophyll content, respectively.

Elodea (*Elodea canadensis*) was exposed to atrazine both in the absence and presence of sediment (University of Mississippi 1990). In the absence of sediment, LOEC values of 10 and 100 µg/L were observed, based upon mature frond production and biomass, respectively. With sediment present, the biomass LOEC was also 100 µg/L. Biomass EC50 values 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 sensitivities of saltwater plants to atrazine is available for five phytoplankton species and four vascular plant species, representing eight genera (Table 4). Although the phytoplankton test results do not meet the minimum requirement of a four-day exposure, they are included here to show that their sensitivity to atrazine is similar to vascular plants. 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 EC50 values 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 IC50 values for final biomass and photosynthesis between 25 and 117 µg/L, with the biomass endpoint being more sensitive in both species (Kemp et al. 1982b, 1983, 1985). The sago pondweed, *Potamogeton pectinatus*, was tested (Hall et al. 1997) for atrazine toxicity for 28 days at three salinities (1, 6, and 12 g/kg). Dry weight was the most sensitive endpoint with chronic values of 21.2, 21.2 and 10.6 µg/L at salinities of 1, 6, and 12 g/kg salinity, respectively. A two-way ANOVA yielded a chronic value of 5.3 µg/L of atrazine. Four separate 21-day exposures of the seagrass, *Zostera marina*, resulted in LC50 values 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

The data available according to the Guidelines concerning the bioaccumulation of atrazine are included in Table 5. Only freshwater data are available. 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 µg/kg of atrazine in muscle tissue, resulting in a bioconcentration factor (BCF) of <0.27. Fathead minnows exposed to atrazine at 210 µg/L for 301 days had less than 1,700 µg/kg of atrazine in pooled samples of eviscerated carcasses, for a BCF of <8.1. Bluegills exposed to 94 µg/L for 546 days also contained less than 200 µg/kg in their muscle tissue, for a BCF of <2.1.

Dionne (1992) exposed fathead minnows to atrazine for up to 274 days using ^{14}C-labeled atrazine and measuring the radiolabel in fish tissue. The values obtained represent maximum possible BCFs. Regardless of the life-stage or exposure duration, maximum BCFs were less than or equal to 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. These test results are presented in Table 6. 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. Below is a summary of their results.

At the lowest levels of biological organization, mixed nitrifying bacteria were unaffected regarding ammonium oxidation at 28-day exposures up to 2,000 µg/L of atrazine (Gadkari 1988), and cell growth in the bacterium, *Pseudomonas putida*, was not inhibited following a 16-hour exposure at 10,000 µg/L (Bringmann and Kuhn 1976, 1977). Progressing phylogenetically, Rohwer and Fluckiger (1979) obtained a 14-day growth LOEC of 2,160 µg/L for *Anabaena*

cylindrica, while Stratton (1984) obtained a 12 to 14-day EC50 of 1,200 µg/L in terms of cell number. The latter EC50 value was approximately 5 to 7 times higher than the 24-hour EC50 values based on ^{14}C uptake of 253, 178 and 182 µg/L as reported by Larsen et al. (1986) for this same species (Table 6). The other species of cyanobacteria tested by Stratton (1984), *Anabaena inaequalis* and *Anabaena variabilis*, had highly different EC50 values of 30 and 4,000 µg/L after 14 days. *A. inaequalis* and *Pseudoanabaena* sp. exhibited reduced photosynthetic uptake of ^{14}C in the amounts of 65 and 91 percent, respectively, following a 22-hour exposure to 2,667 µg/L of atrazine (Peterson et al. 1994).

A number of tests have been performed with the cyanobacterium, *Anabaena flos-aquae*. Hughes (1986) and Hughes et al. (1986, 1988) reported an EC50 based on cell number 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). At this concentration of atrazine, chlorophyll a content was initially reduced but recovered with time. Using this parameter, the 3-day EC50 was 58 µg/L, while the 7-day EC50 was 766 µg/L (Abou-Waly 1991b). *A. flos-aquae* had a 4-day EC50 based on chlorophyll a that exceeded 3,000 µg/L in a study by Fairchild et al. (1998).

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*, while Peterson et al. (1994) reported that photosynthetic ^{14}C uptake was highly reduced (84-96 percent) in *M. aeruginosa* following a 22-hour exposure to 2,667 µg/L of atrazine. A 4-day

EC50 of 90 µg/L was reported for an unidentified species of *Microcystis* based on biomass (Fairchild et al. 1998).

Toxicity studies of atrazine toward several other species of cyanobacteria have been reported. Peterson et al. (1994) found that *Aphanizomenon flos-aquae* and *Oscillatoria* sp. exhibited highly reduced photosynthetic uptake of ^{14}C (97 and 87 percent, respectively) from a 22-hour exposure to 2,667 µg/L of atrazine. The latter is consistent with the lowest complete inhibition of growth reported for *Oscillatoria* cf. *chalybea* after 6 days of exposure to 2,160 µg/L atrazine (Schrader et al. 1997). A 31-day exposure of *Plectonema boryanum* to 10,000 µg/L of atrazine resulted in a 69 percent decrease in cell numbers (Mallison and Cannon 1984), whereas, 5-day exposures of *Synechococcus leopolensis* yielded an EC50 of 130 µg/L (Kallqvist and Romstad 1994).

The green alga, *Ankistrodesmus braunii*, had an 11-day EC50 of 60 µg/L (Burrell et al. 1985). Similarly, ^{14}C uptake EC50 values of 72 and 61 µg/L resulted from 24-hour exposures of *Ankistrodesmus* sp. to atrazine (Larsen et al. 1986). The green alga, *Chlamydomonas geitleri* Ettl, had a slightly higher EC50 of 311 µg/L based on CO_2 fixation after a 1-hour exposure (Francois and Robinson 1990). Similarly, a growth-based EC50 of 330 µg/L was obtained for *Chlamydomonas noctigama* after 3 days of atrazine exposure (Kallqvist and Romstad 1994).

The green alga, *Chlamydomonas reinhardtii*, appears more sensitive to atrazine, exhibiting approximately a 32 percent inhibition of photosynthesis in an 8-hour exposure to 10 µg/L (Valentine and Bingham 1976), and EC50 values based on reduction in photosynthetic activity (^{14}C uptake) in 24-hour exposures of 19 to 48 µg/L of atrazine (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-hour exposure to 49.6 µg/L resulted in a 13 percent reduction of chlorophyll (Hiranpradit and Foy 1992), and Fairchild et al. (1998) obtained a 96-hour chlorophyll-based EC50 of 176 µg/L for this same species.

Foy and Hiranpradit (1977) exposed an unknown *Chlamydomonas* sp. to various concentrations of atrazine for 72 to 96 hours. Concentrations of 50 to 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. (1994a) obtained a 4-day EC50 based on biomass of 176 µg/L to a different species of *Chlamydomonas*.

Chlorella fusca cell reproduction was reduced and an EC50 of 26 µg/L was calculated following a 24-hour exposure to atrazine (Altenburger et al. 1990). Similarly, Faust et al. (1993) obtained a 24-hour EC50 of 15 µg/L for this species, and Kotrikla et al. (1997) report 14-day EC50 values based on growth inhibition of 53.91 (exponential growth phase) and 75.73 µg/L (stationary growth phase). In contrast, *Chlorella kessleri* exhibited 30 percent growth inhibition following a 72-hour exposure at a concentration of 1,078 µg/L (El-Sheekh et al. 1994), while *C. pyrenoidosa* had 70 to 95 percent reduced growth following 2-week exposures to atrazine concentrations ranging from 500 to 10,000 µg/L (Virmani et al. 1975). Photosynthesis in this species was inhibited by approximately 64 percent following an 8-hour exposure to 100 µg/L atrazine (Valentine and Bingham 1976). Stratton (1984) obtained an EC50 of 300 µg/L following a 12- to 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-Murua et al. 1985), while a 110-hour 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 less than 50-minute exposure to 125 µg/L (Hannan 1995).

The green alga, *Chlorella vulgaris,* had 24-hour EC50 values of 325, 305 and 293 µg/L in three separate tests based upon ^{14}C uptake (Larsen et al. 1986). Similarly, a 30-minute EC50 value of 305 µg/L based on decreased oxygen evolution was obtained for the same species by Van der Heever and Grobbelaar (1997). Following 7 days of exposure to 250 to 5,000 µg/L (only 2.3 to 4.7 percent remained on day 7), dry weights of *C. vulgaris* were reduced from 31 to 62 percent (Veber et al. 1981). This same species had an EC50 of 94 µg/L based upon chlorophyll concentration after a 96-hour exposure (Fairchild et al. 1998). Reduced growth was initially observed for *C. vulgaris* exposed for 12 days to 10 µg/L, although signs of recovery were evident by the end of the exposure (Berard et al. 1999).

In an undefined species of *Chlorella*, a 72- to 96-hour 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). In that same study, higher exposures generally resulted in greater adverse effects. More recently, a 2- to 3-day atrazine exposure of 21.6 µg/L reduced the growth rate of one *Chlorella* sp. by 55 percent (Hersh and Crumpton 1987), and another study using *Chlorella* sp. exhibited very rapid responses to atrazine with EC50 values of 35 to 41 µg/L based upon photosynthetic oxygen evolution following a 2-minute atrazine exposure (Hersh and Crumpton 1989). Fairchild et al. (1994a) reported a 4-day biomass-based EC50 of 92 µg/L in yet another study using an unidentified species of the genus *Chlorella*.

Virmani et al. (1975) observed 75 and 92 percent reductions in growth of a much less sensitive species of green algae, *Chlorococcum hypnosporum*,

following 2-week exposures to 5,000 and 10,000 µg/L atrazine, respectively. Similarly, a high test concentration (2,157 µg/L) was necessary to inhibit calcification in *Gloetaenium loitlesbergarianum* in a 96-hour test (Prasad and Chowdary 1981). Short exposures (2 minutes) to *Franceia* sp. yielded EC50 values between 430 and 774 µg/L, measured as photosynthetic oxygen evolution (Hersh and Crumpton 1989).

In three tests with the green alga, *Scenedesmus obliquus*, the 24-hour EC50 values for ^{14}C uptake were between 38 and 57 µg/L (Larsen et al. 1986). The green alga, *Scenedesmus quadricauda*, exhibited photosynthesis inhibition of approximately 42 percent after 8 hours at an atrazine exposure of 10 µg/L (Valentine and Bingham 1976). Bringmann and Kuhn (1977, 1978a,b) found that 30 µg/L caused the onset of cell multiplication inhibition after 8 days of atrazine exposure to this species. *S. quadricauda* exhibited a 12- to 14-day EC50 of 100 µg/L based on cell number (Stratton 1984). Bogacka et al. (1990) studied photosynthesis reductions in *S. quadricauda* at various concentrations after 8 days of atrazine exposure. These authors observed a gradation from 4.5 percent reduction at 4 µg/L to a 99.3 percent reduction at 337 µg/L. Similarly, photosynthetic ^{14}C uptake was highly inhibited (96 percent) after 22 horrs at 2,667 µg/L of atrazine (Peterson et al. 1994). This species had a 96-hour EC50 of 169 µg/L, based upon chlorophyll concentration (Fairchild et al. 1998).

In this same genera of algae, *Scenedesmus subspicatus* had a 4-day EC50 of 110 µg/L (Geyer et al. 1985), and Schafer et al. (1994) found that 37 µg/L of atrazine inhibited the effective photosynthetic rate of this species by 57.4 percent within 24 hours. This latter apparent effect concentration was corroborated by Kirby and Sheahan (1994) who reported a 2-day EC50 of 21 µg/L based on cell numbers, as well as Zagorc-Koncan (1996) who reported a 24-hour

EC50 value of 25 µg/L based on net assimilation and inhibition. Reinhold et al. (1994) observed a 50 percent reduction in dry mass at 21.5 µg/L within 24 hours, and Behra et al. (1999) reported a 60-day NOEC based on growth and photosynthetic oxygen evolution for this species of 20 µg/L.

Exposure of an unidentified species of *Scenedesmus* for 72 to 96 hours at 50 µg/L resulted in 60.2 percent growth inhibition (Foy and Hiranpradit 1977), and increased concentrations resulted in increased growth inhibition. Fairchild et al. (1994a) obtained a 4-day EC50 based on biomass of 169 µg/L.

The green alga, *Selenastrum capricornutum*, exhibited a significant reduction in cell numbers following a 5-day exposure to 54 µg/L of atrazine (Parrish 1978). In this study, chlorophyll a reduction increased as concentrations increased from 32 and 200 µg/L. The minimum algistatic concentration was determined to be 200 µg/L. A similar 5-day LOEC for *S. capricornutum* growth of 220 µg/L was recently reported by Schrader et al. (1998). Interestingly, 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). The lowest complete inhibition concentration of growth after a 6-day exposure was 2,160 µg/L (Schrader et al. 1997).

There are a number of additional EC50 values from exposures of *S. capricornutum* to atrazine (Table 6). Larsen et al. (1986) obtained 24-hour EC50 values of 53, 34 and 42 µg/L based upon ^{14}C uptake. In a couple of 21-day exposures (Turbak et al. 1986), biomass-based EC50 values of 58.7 and 410 µg/L were obtained using algal assay media and creek water for test media, respectively. Likewise, EC50 values were 69.7 and 854 µg/L, respectively, using these two media in 24-hour tests that measured photosynthetic oxygen evolution. Roberts et al. (1990) reported 5-day EC50 values of 100 and 95 µg/L based on cell numbers, and an EC50 of 50 µg/L based on cell numbers was

reported in a 4-day exposure by Versteeg (1990). Similarly, El Jay et al. (1997) found the 4-day IC50 values based on chlorophyll a content to be 80 µg/L. 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). EC50 values 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 for chlorophyll content, while Kallqvist and Romstad (1994) obtained 3-day growth-based EC50 values of 200 and 110 µg/L. Photosynthetic ^{14}C uptake was almost completely inhibited (99 percent) within 22 hours at an exposure of 2,667 µg/L (Peterson et al. 1994). A 96-hour EC50 of 147 µg/L was reported by Gaggi et al. (1995) for chlorophyll a content. Additional cell number-based EC50 values reported for 72- to 96-hour exposures include 118.2 µg/L (Radetski et al. 1995), 359 µg/L (Van der Heever and Grobbelaar 1996), 200 and 220 µg/L (Abdel-Hamid 1996), and 26 µg/L (Caux et al. 1996). Van der Heever and Grobbelaar (1997, 1998) expanded on their 1996 study and reported a 30-minute EC50 value based on decreased oxygen evolution of 222 µg/L (1997) and a 4-hour EC50 value based on chlorophyll a fluorescence of 232 µg/L (1998). Benhra et al. (1997) reported an EC50 of 164.3 µg/L based on growth inhibition and Fairchild et al. (1997) reported a biomass-based EC50 of 235 µg/L.

Two tests with *Stigeoclonium tenue* yielded 24-hour EC50 values based on ^{14}C uptake of 127 and 224 µg/L, while a test with *Ulothrix subconstricta* yielded an EC50 of only 88 µg/L (Larsen et al. 1986).

Several diatom species have been tested for their sensitivities to atrazine. Chlorophyll a content in the benthic diatom, *Craticula cuspidata*, was significantly reduced after 12 days exposure to 83 µg/L atrazine immediately following 67 days in 1 µg/L atrazine (Nelson et al. 1999).

Cyclotella meneghiniana yielded 7-minute EC50 values based upon photosynthesis between 99 and 243 µg/L (Millie and Hersh 1987), while a 22-hour exposure to 2,667 µg/L of atrazine inhibited photosynthetic ^{14}C uptake by 97 percent (Peterson et al. 1994). A 6-day growth-based EC50 of 430 µg/L was obtained for an unidentified species of *Cyclotella* by Kallqvist and Romstad (1994). Hughes (1986) and Hughes et al. (1986, 1988) determined several endpoints in 5-day exposures of *Navicula pelliculosa* to atrazine, including a 5-day EC50 of 60 µg/L based on cell numbers. Using a 9-day recovery period following the 5-day exposure, they determined algistatic and algicidal concentrations of 1,710 and >3,200 µg/L, respectively. Likewise, photosynthesis was almost completely inhibited (99 percent) in *Nitzschia* sp. by a 22-hour exposure to 2,667 µg/L of atrazine (Peterson et al. 1994). The cryptomonad, *Cryptomonas pyrinoidifera*, which also appears to be somewhat less sensitive to atrazine, had a 6-day EC50 based on growth 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 of 50 to 250 µg/L (Beaumont et al. 1976,a,b, 1978). Peterson et al. (1994), on the other hand, observed that growth was inhibited 95 percent by a 7-day exposure to 2,667 µg/L. Four-day EC50 values for *L. minor* based on biomass and frond production were 153 and 92 µg/L, respectively (Fairchild et al. 1997, 1998). Biochemical and ultrastructural changes in the chloroplasts of *Lemna minor* were observed in 15-day exposures of 100 and 1000 µg/L of atrazine (Grenier et al. 1979) as well as an exposure of 248 µg/L (Grenier et al. 1987, 1989; Simard et al. 1990) for 15, 10 and 2 days, respectively. This is very close to the EC50 of 170 µg/L for frond production obtained when Hughes (1986) and Hughes et al. (1986, 1988) exposed a different species of duckweed, *Lemna gibba*, to atrazine for 5 days. 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). Wild celery, *Vallisneria americana*, exhibited reduced leaf growth and whole plant biomass at an exposure of 8 µg/L and reduced over-wintering success of tubers at 4 µg/L (Cohn 1985). A 42-day test using this species resulted in an EC50 based on total leaf length of 163 µg/L (Davis 1981; Forney and Davis 1981). A 14-day EC50 based on wet weight of 22 µg/L was reported for coontail, *Ceratophyllum* sp. (Fairchild et al. 1998), and reduced stem elongation occurred within 6 to 8 days at 50 µg/L (Detenbeck et al. 1996). These authors also found that cattails, *Typha latifolia*, were unaffected at 25 µg/L atrazine after 19 days. The Eurasian watermilfoil, *Myriophyllum heterophyllum*, had a 14-day wet weight-based EC50 of 132 µg/L (Fairchild et al. 1998) while *Myriophyllum spicatum* had a 28-day EC50 based on length of 1,104 µg/L (Davis 1981; Forney and Davis 1981). This species also exhibited a 30 percent increase in net photosynthetic rate at 10 µg/L after 24 hours (Hoffmann and Winkler 1990), and a 50 percent reduction in branch number at 3,700 µg/L after 5 days (Bird 1993). Sago pondweed, *Potamogeton pectinatus*, on the other hand, had reduced biomass after 28 days at 100 µg/L (Fleming et al. 1991), and bushy pondweed, *Najas* sp., had a 14-day wet weight-based EC50 of 24 µg/L (Fairchild et al. 1998). A 14-day biomass-based EC50 of <38 µg/L was reported for *Egeria* sp. (Fairchild et al. 1994a).

The exposure of *Elodea canadensis* to atrazine for 21 and 28 days resulted in EC50 values based on length of 109 and 80 µg/L, respectively (Davis 1981; Forney and Davis 1981). In a 20-day exposure to 10 µg/L of

atrazine, Hoffmann and Winkler (1990) found that the dark respiration rate of this species exceeded the net photosynthetic rate, while Detenbeck et al. (1996) reported that growth was unaffected after 19 days at 75 µg/L. Fairchild et al. (1998) reported a 14-day EC50 of 21 µg/L for *E. canadensis* based upon wet weight.

Three species of water moss (*Fontinalis antipyretica*, *Fontinalis hypnoides* and *Fontinalis squamosa*) were tested by Hoffman and Winkler (1990). While *F. squamosa* and *F. antipyretica* were affected in their photosynthetic production at 10 µg/L after 24 hours and 20 days, respectively, *F. hypnoides* exhibited a much greater reduction (90 percent) in net photosynthesis within 24-hours at an exposure of only 2 µg/L. Conversely, 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 after 30 days.

The protozoan, *Acanthamoeba castellanii*, had population decreases of from 5 to 40 percent when exposed for 6 days to atrazine at concentrations from 100 to 10,000 µg/L (Prescott et al. 1977). Photosynthesis was inhibited by about 11 percent in *Euglena gracilis* at 10 µg/L after 8 hours, and exhibited increasingly greater inhibition at higher concentrations (Valentine and Bingham 1976). Two species of protozoans, *Colpidium campylum* and *Tetrahymena pyriformis*, had 24-hour EC50 values of >50,000 (Roberts et al. 1990) and 118,500 µg/L (Huber et al. 1991), respectively. Schafer et al. (1994) reported a 48-hour EC50 of 96,000 µg/L for *T. pyriformis*.

Relatively high concentrations were required to produce notably adverse responses in representatives from higher animal phyla. A concentration of 5,000 µg/L reduced the budding rate in *Hydra viridis* after 21 days (Benson and Boush 1983). The rotifer, *Brachionus calyciflorus*, had a 24-hour LC50 of 7,840 µg/L (Crisinel et al. 1994). Two species of leeches, *Glossiphonia*

complanata and *Helobdella stagnalis*, had LC50 values of 6,300 and 9,900 µg/L, respectively, after a 27- to 28-day exposure (Streit and Peter 1978). After 21 weeks, 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 24- and 48-hour LC50 values were greater than 60,000 µg/L for both larval and juvenile mussels, *Anadonta imbecilis* (Johnson et al. 1993).

The anostracan crustacean, *Streptocephalus texanus*, had a 24-hour LC50 of >30,000 µg/L (Crisinel et al. 1994). The cladoceran, *Ceriodaphnia dubia*, exhibited maximum acceptable toxicant concentrations (MATCs) of 7,100 and 14,100 µg/L in two 4-day tests (Oris et al. 1991). A 26-hour LC50 of 3,600 µg/L was reported for *Daphnia magna* (Frear and Boyd 1967). In 48-hour exposures of *Daphnia 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* after 21 days at 2,000 µg/L (Kaushik et al. 1985). After 96 hours of exposure, Bogacka et al. (1990) observed a 30 percent mortality in *D. magna* at 16,900 µg/L, and a 60 percent mortality at 48,300 µg/L. Johnson et al. (1993) reported a 48-hour LC50 of 9,400 µg/L, but the animals were fed at 24 hours. Crisinel et al. (1994) obtained a 24-hour EC50 of >30,000 µg/L, while Detenbeck et al. (1996) observed a significant decrease in the survival of these invertebrates after 48 hours of exposure at 25 µg/L, but not at 50 µg/L. Nishiuchi and Hashimoto (1967, 1969) found the 3-hour LC50 to be greater than 40,000 µg/L for *Daphnia pulex*. Exposures of *D. pulex* for 28 to approximately 70 days resulted in decreased survival and reproduction at concentrations ranging from 1,000 and 20,000 µg/L atrazine, with reproduction

affected more 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 after 10 minutes (Pott 1980). Bowman et al. (1981) reported an 18-hour LC50 for *D. pulex* of approximately 700 µg/L. Conversely, the 3-hour LC50 was in excess of 40,000 µg/L for the cladoceran, *Moina macrocopa* (Nishiuchi and Hashimoto 1967, 1969), and a concentration of 1,000 µg/L was shown to cause 40 percent mortality and reduced population growth after 4 to 6 weeks (Shcherban 1972a,b).

The amphipod, *Gammarus fasciatus*, had a 48-hour LC50 of 5,700 µg/L (Macek et al. 1976). Similarly, exposure of *Hyalella azteca* for 18 hours resulted in an LC50 of 2,000 µg/L (Bowman et al. 1981). For the midge, *Chironomus riparius*, a 10-day exposure to atrazine yielded an LC50 of 18,900 µg/L (Taylor et al. 1991), while a 96-hour exposure of *C. tentans* in a fed test had less than 50 percent mortality at the high concentration of 28,000 µg/L (McNamara 1991b). The 18-hour LC50 for the white dotted mosquito, *Culex restuans*, is considerably higher at approximately 60,000 µg/L (Bowman et al. 1981).

Rainbow trout, *Oncorhynchus mykiss*, embryos and sac fry exposed continuously for 23 (embryos at hatching) and 27 (sac fry, 4 days post-hatch) days had LC50 values 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-hour LC50 of 5,660 µg/L. Changes in the ultrastructure of trout renal corpuscles and tubules were observed following 28-day exposures to 5 to 10 µg/L of atrazine (Fischer-Scherl et al. 1991). Similarly, 28-day exposures resulted in slight ultrastructural changes in trout renal corpuscles at 5 µg/L, 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). Exposure to 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 within 5 weeks in *O. mykiss* in the proximal tubules at 12.4 μg/L, and in both the proximal and distal tubules at 24.0 μg/L. The most sensitive indicator of biological effect exhibited by a salmonid was the reduction in milt and plasma levels of 17,20 β-dihydroxy-4-pregnen-3-one in Atlantic salmon, *Salmo salar*, parr exposed for 5 days to 0.04 μg/L atrazine (Moore and Waring 1998). In the same study, a 30-minute exposure to 2.0 μg/L reduced olfactory response of mature male parr to a female pheromone.

The 48-hour LC50 for the goldfish, *Carassius auratus*, was >10,000 μg/L (Nishiuchi and Hashimoto 1967, 1969), although Saglio and Trijasse (1998) observed reduced burst swimming performance in goldfish after a 24-hour exposure to 0.5 μg/L. The 48-hour LC50 for the common carp, *Cyprinus carpio*, was also >10,000 μg/L (Nishiuchi and Hashimoto 1967, 1969). Short-term exposures of from 4 to 24 hours to lesser concentrations between 100 and 500 μg/L resulted in increased serum cortisol and serum glucose (Hanke et al. 1983). Serum acetylcholinesterase first increased and then decreased with time of exposure. Changes were also noted in gill ATPase activity. Longer exposures of 72-hour duration to 1,000 μg/L and 100 μg/L of atrazine also yielded decreased liver glycogen (Hanke et al. 1983), and decreased liver and muscle glycogen as well as serum protein and cholesterol (Gluth and Hanke 1984, 1985), respectively. Juvenile carp yielded a 48-hour LC50 of 16,100

µg/L (Pluta 1989), and a 96-hour LC50, in which the fish were fed, of 18,800 µg/L (Neskovic et al. 1993). It was noted in the latter study that 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). Conversely, no effects on gill, liver, and histopathology were observed at this same concentration (1,500 µg/L) in a study by Poleksic et al. (1997).

Jop (1991c) reported the "no observed effect concentration" (NOEC) to be in excess of 4,900 µg/L for fathead minnows, *P. promelas*, exposed to atrazine for 7 days. Also, survival and growth were shown to be unaffected in fathead minnows exposed to 75 µg/L for 13 days (Detenbeck et al. 1996). On the other hand, channel catfish (*Ictalurus punctatus*) embryos and sac fry had LC50 values between 176 and 272 µg/L after exposures of either 4.5 (embryos at hatch) or 8.5 (sac fry, 4 days post-hatch) days (Birge et al. 1979). Concentrations of approximately 340 µg/L caused an incidence of 13 to 16 percent teratic larvae, while concentrations of approximately 3,850 µg/L resulted in 47 to 69 percent teratic larvae.

Mosquitofish (*Gambusia affinis*) survival was unaffected in a 48-hour exposure to 10,000 µg/L (Darwazeh and Mulla 1974), and LC50 values as high as 38,200 and 31,600 µg/L were reported for the guppy (*Poecilia reticulata*) after exposures of 48 and 72 hours, respectively (Tscheu-Schluter 1976). These data are consistent with results reported by Bogacka et al. (1990), in which the authors reported mortalities of 40 and 53.2 percent after exposing guppies for 96 hours to 28,600 and 37,200 µg/L, respectively.

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). A 90-day exposure 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), the results of which are quite different between species (Table 6). LC50 values for continuous exposure of embryos and larvae through 4 days post-hatch were 410 µg/L for the bullfrog (*Rana catesbeiana*), 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*). In most of these species, 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. pipiens* tadpoles were unaffected after 41 days of exposure to 25 µg/L (Detenbeck et al. 1996). A 96-hour exposure of the African clawed frog (*Xenopus laevis*) embryos to 8,000 µg/L resulted in 100 percent abnormal embryos (Morgan et al. 1996). The lowest observed effect concentration (LOEC; teratogenesis) in the study was 1,100 µg/L. This concentration is more than an order of magnitude higher than that which delayed development and retarded the growth in the tiger salamander, *Ambystoma tigrium*, after 86 days of exposure (Larson et al. 1998).

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 and Merkle 1984; Kosinski et al. 1985). 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. Similarly, Moorhead and Kosinski (1986) observed reduced net primary productivity at 100 µg/L in an assemblage of mixed stream algal species. By contrast, in a mixed stream community, no effects were observed upon stream macroinvertebrate community structure, periphyton production or biomass, or 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, after which time the atrazine was removed 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, but nitrate nitrogen levels increased. Following the cessation of atrazine treatment, there was a rapid recovery for each of these parameters back to control levels.

Biomass reductions were also noted in a stream aufwuchs community exposed to 24 or 134 µg/L of atrazine for 12 days (Krieger et al. 1988), although a 24-hour 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 as low as 0.5 µg/L for 6 months resulted in an initial decrease in phytoplankton species followed by a recovery (Lakshminarayana et al. 1992). Gruessner and Watzin (1996), however, did not observe any effects of atrazine on a stream community of attached algae and benthic invertebrates at a concentration of 5 µg/L when exposed for 14 days. 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 to 30 percent reduction in diurnal oxygen production, while 7- to 12-day exposures at 100 to 5,000 µg/L further decreased oxygen production. Berard et al. (1999) observed seasonal and species-dependent effects in a lake microcosm plankton community after 10 to 21 days of exposure to 10 µg/L atrazine. During the experiment, growth was generally stimulated for Chryptophytes and Chrysophytes, but inhibited in *Chlorella vulgaris*.

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 et al. 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 to 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.

Peichl et al. (1984) observed changes in the population densities of zooplankton in a pond mesocosm study after 70 days of exposure to 200 µg/L of atrazine. In a later study (Peichl et al. 1985), the authors observed changes in the phytoplankton community after 121 days of exposure to only 10 µg/L. 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 (*R. catesbeiana*) tadpoles, grass carp (*Ctenopharyngodon idella*) that had been introduced, and in 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-hour) 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 experimental ponds used in Kansas 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 the lowest exposure of 20 µg/L. Abundance of the herbivorous, non-predatory insects was 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. EC50 values 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 for 2 years 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 in May and June with 20 μg/L of atrazine for two years, there was decreased abundance of *Endochironomus nigricans* in June and of total macroinvertebrates 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 hour) of pond algae to 10 μg/L of atrazine was observed to increase the rate of fluorescence 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 μg/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 two atrazine applications 6 weeks apart, which resulted in measured concentrations of approximately 80 to 140 μg/L after the first application and 110 to 190 μg/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. 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 eutrophic lake, Lampert et al. (1989) observed decreased photosynthesis and decreased populations of certain zooplankters at atrazine concentrations of 0.1 and 1.0 $\mu g/L$. At 0.1 $\mu g/L$, populations of *Daphnia* sp. were severely reduced within 15 days, and oxygen concentrations were reduced after 10 days. At 1.0 $\mu g/L$, concentrations of chlorophyll *a* and oxygen were reduced after 18 days as were populations of *Daphnia*, *Cyclops*, and *Bosmina* species, and nauplii larvae. At 0.1 $\mu g/L$, 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 $\mu g/L$. 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. EC50 values 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 hours) 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 hours) to 109 μg/L of atrazine (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 μg/L. Detenbeck et al. (1996) observed a decrease in the gross productivity of a wetland mesocosm community after 9 to 27 days of exposure 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 Berard et al. (1999), Kosinski and Merkle (1984), Kosinski et al. (1985), Lakshminarayana et al. (1992), Lampert et al. (1989), and Peichl et al. (1984, 1985) 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 µg/L or greater.

In summary, cyanobacteria had EC50 values for various exposure durations of 30 µg/L or greater, while EC50 values for green algae, diatoms and cryptomonads were ≥15 µg/L. Among macrophytes, duckweed had a minimal 4-day EC50 of 92 µg/L. Wild rice was affected at 50 µg/L, and wild celery had reduced growth at 8 µg/L. Several rooted vascular plants (i.e., coontail, bushy pondweed, egeria, and elodea) had 14-day EC50 values between 21 and <38 µg/L, while that for a water milfoil was 132 µg/L. Two species of water moss (*Fontinalis* sp.) exhibited reduced photosynthetic activity at 10 µg/L, and one species was affected at 2 µg/L. EC50/LC50 values for protozoans, coelenterates, annelids, molluscs and rotifers were ≥6,300 µg/L. Various crustaceans had LC50 values ≥5,700 µg/L. The most sensitive endpoints among fish were rainbow trout plasma protein and kidney ultrastructural changes at atrazine exposures of 3 and 3.5 µg/L, respectively. The lowest LC50 values in fish were 176-272 µg/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 µg/L. In most aquatic ecosystem studies, reductions in algal or vascular plant biomass were observed at concentrations ≥15 µg/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 µg/L). From these freshwater Other Data, most of the effect levels of possible biological

significance appear to be ≥15 µg/L. This concentration is greater than the freshwater Final Chronic Value, 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 based on differing endpoints (e.g., oxygen evolution or growth) for various green algal species ranged from 37 µg/L to 600 µg/L (Gaggi et al. 1995; Hollister and Walsh 1973; Hughes 1986; Hughes et al. 1986, 1988; Samson and Popovic 1988; Walsh 1972). A 48-hour exposure of the green alga, *Dunaliella bioculata*, to 216 µg/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*, at concentrations of 50 and 100 µg/L 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 µg/L changed the doubling time in *N. oculata* (Mayasich et al. 1987).

Diatom species were similar to green algae in terms of their sensitivities to atrazine. EC50 values for exposures of various durations were generally between 20 and 460 µg/L (Hollister and Walsh 1973; Walsh 1972; Walsh et al. 1988). Plumley and Davis (1980) observed reduced photosynthesis in *Nitzschia sigma* and reduced chlorophyll in *Thalassiosira fluviatilis* in 7-day exposures to 220 µg/L. Mayasich et al. (1987) reported a limited effect on doubling time to *Phaeodactylum tricornutum* in a 7-day exposure to 50 µg/L of atrazine.

The red alga, *Porphyridium cruentum*, had an EC50 based on oxygen evolution of 79 µg/L when exposed for 90 minutes (Hollister and Walsh 1973), and the kelp, *Laminaria hyperborea*, had a 24-hour LOEC value for respiration

of >1,000 µg/L (Hopkins and Kain 1971). The 28-day LOEC for this species based on growth of new sporophytes was 10 µg/L. It was shown in another species of kelp, *Laminaria saccharina*, that a 2-day exposure to ≥72.2 µg/L of atrazine was sufficient to significantly reduce sexual reproduction, but no effect was detected at 33.2 µg/L (Thursby and Tagliabue 1990).

Inhibition concentrations of 77 to 120 µg/L for a 50 percent effect on photosynthesis by vascular plants in short-term (2- to 4-hour) exposures to atrazine (Jones and Winchell 1984; Jones et al. 1986) were similar to the effects upon growth and photosynthesis in longer exposures with several other species (Table 4). Studies involving *Vallisneria americana* at low salinities for 42 to 47 days resulted in reduced leaf production in terms of length, leaf area, and dry weight for concentrations ranging from 12 to 320 µg/L of atrazine (Correll and Wu 1982; Forney 1980; Forney and Davis 1981). Eelgrass, *Zostera marina*, had reduced oxygen evolution at 100 µg/L, and complete inhibition of photosynthesis and growth at 1,000 (Kemp et al. 1982a) and 1,900 µg/L of atrazine (Schwarzschild et al. 1994). Walsh et al. (1982) report a 40-hour EC50 of 320 µg/L for the turtlegrass, *Thalassia testudinum*. The emergent salt-marsh rush, *Juncus roemerianus*, exhibited effects indicative of stress after a 35-day exposure to 30 µg/L, while the salt-marsh grass, *Spartina alterniflora*, only exhibited enhanced peroxidase activity at a concentration as high as 3,100 µg/L for the same length of time (Lytle and Lytle 1998).

The three LC50 values for the copepod, *Acartia tonsa*, at 24, 48 and 72 hours showed that the sensitivity to atrazine increased with increasing duration of exposure (McNamara 1991b; also see Table 1). The 96-hour EC50 in the juvenile Eastern oyster, *Crassostrea virginica*, as well as the 48-hour LC50 for the juvenile spot, *Leiostomas santhurus*, were both ≥1,000 µg/L, while

the brown shrimp, *Penaeus aztecus*, had a 48-hour EC50 of 1,000 µg/L (Butler 1964; Mayer 1987). 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). However, there was 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. Two other species of crabs, *Sesarma cinereum* and *Panopeus* sp., were also insensitive to very high levels of atrazine (Plumley et al. 1980).

The acute and chronic effects of atrazine on an estuarine microbial community were recently examined by DeLorenzo et al. (1999a,b). Exposure for 9 days to 40 µg/L of atrazine in dilute seawater (7-25 g/kg) inhibited the phototrophic component - chlorophyll a, carbon assimilation, biovolume, and caused changes in species composition (DeLorenzo et al. 1999a). The same effects were observed in full strength seawater at an atrazine concentration of 47 µg/L, but within 24 hours (DeLorenzo et al. 1999b). An earlier mesocosm study of a mixed assemblage of marine phytoplankton species demonstrated reduced photosynthesis and primary production at concentrations of 0.12 and 0.56 µg/L atrazine at 15 days (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 (e.g., Alazemi et al. 1996; Biagianti-Risbourg and Bastide 1995; Diaz et al. 1998; Forget et al. 1998; Görge and Nagel 1990; Gunkel and Kausch 1976; Gzhetotskii et al. 1977; Hussein et al. 1996; Juhnke and Luedemann 1978; Kirby et al. 1998; Lewis et al. 1993; L'Haridon et al. 1993; Nagel 1992; Pantani et al. 1997; Portmann 1972; Prasad et al. 1990, 1995; Steinberg et al. 1995). Results were not used if the duration of the exposure was not specified or was unclear (e.g., Hopkins and Kain 1968; Portmann 1972; Rojickova-Padrtova and Marsalek 1999; Tellenbach et al. 1983), or if the procedures or test materials were not adequately described or translated (e.g. Braginskii and Migal 1973; Delistraty 1999; Kross et al. 1992; Shcherban 1973; Tang et al. 1998a,b; Wenzel et al. 1997).

The acute toxicity data of Bathe et al. (1973, 1975) were not used due to an insufficient number of test organisms. High control moralities occurred in tests reported by Dodson et al. (1999), as well as in a chronic study with *Gammarus fasciatus* (Macek et al. 1976). Studies published only as abstracts of presentations were not used (e.g., Fairchild et al. 1994b; Palmstrom and Krieger 1983; Zora and Paladino 1986). Secondary observations reported in a review were not used (e.g., Giddings and Hall 1998; Hurlbert 1975; Hutchinson et al. 1998; Lange et al. 1998; Mercurio 1998). Similarly, papers by Birge et al. (1983), Fairchild et al. (Manuscript), Mark and Solbe (1998), and Pratt et al. (1993, 1997) were not used, as the data they 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 or emulsifiable concentrate and atrazine comprised less than 80 percent of its weight (e.g., Antychowicz et al. 1979; Carder and Hoagland 1998; Clements et al. 1997; Hartman and Martin 1985; Hiltibran 1967; Howe et al. 1998; Lin et al. 1999; Pavlov 1976; Rojickova-Padrtova and Marsalek 1999; Semov and Iosifov 1973; Sreenivas and Rana 1991, 1994; Walker 1964), if atrazine was a component of a pesticide mixture (e.g., Britson and Threlkeld 1998; Crain et al. 1998; Guasch and Sabater 1998; Guasch et al. 1997, 1998; Hartgers et al. 1998; Lowcock et al. 1997; Ort et al. 1994; Pollehne et al. 1999; Reeder et al. 1998; Vanderpoorten 1999), if atrazine was dosed in the diet (e.g., Cossarini-Dunier et al. 1988), or if the concentration of solvent used in atrazine stock preparation exceeded 0.5 ml/L (e.g., Cheney et al. 1997; Crain et al. 1997, 1999; Tang et al. 1997); the latter representing a value below which neither acetone nor ethanol are toxic to algae (e.g., El Jay 1996; Stratton and Corke 1981), but where DMSO and atrazine may interact additively (El Jay 1996).

The results from Langan and Hoagland (1996) were not used because the tests were conducted in distilled water without addition of the appropriate salts. Toxicity tests by Schmitz et al. (1994) and Tubbing et al. (1993) 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 (e.g., Spazier et al. 1992). Effects data were not used if the atrazine exposure was part of a soil mixture (e.g., Johnson et al. 1999; Jones and Estes 1984; Miller and Doxtader 1995; Ruth 1997). McBride and Richards (1975) exposed excised tissue, and Petit et al. (1997) exposed cell cultures.

A study of atrazine accumulation by Bohm 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 (e.g., Davis et al. 1979; Jones et al. 1982; McEnerney and Davis 1979; Neumann et al. 1987; Pillai et al. 1977, 1979; Weete et al. 1980), or atrazine was not detected in tissue (e.g., Harris et al. 1998). Uptake and accumulation from exposures in flasks or microcosms were not used if ^{14}C only was measured and not atrazine itself (e.g., Huckins et al. 1986; Isensee 1976, 1987; Kearney et al. 1977; Mailhot 1987).

Biochemical studies of resistant strains of mutated algae (e.g., Boura-Halfon et al. 1997; Forster et al. 1997; Ottmeier et al. 1991) and results from *in vitro* genotoxicity and mutagenicity tests (e.g., Ruiz and Marzin 1997) were not used. A study of atrazine effects upon promutagen activation by *Selenastrum capricornutum* (e.g., Sauser and Klaine 1990) and alteration in allele and genotype frequencies of the oyster, *Crassostrea gigas* (e.g., Moraga and Tanguy 2000) were also not used.

Summary

Atrazine is not highly toxic to aquatic animals on an acute basis. SMAVs for eight freshwater invertebrate species ranged from 720 µg/L for a midge, *Chironomus tentans*, to 49,000 for *Daphnia magna*. SMAVs for nine fish species ranged from 5,300 µg/L for the rainbow trout, *Oncorhynchus mykiss*, to 60,000 µg/L for the goldfish, *Carassius auratus* (Figure 1). Genus Mean Acute Values for atrazine are available for nine genera of saltwater animals and

range from 2,324 to >30,000 µg/L; a factor of approximately 12.9 (Figure 2). Genus Mean Acute values for the four most sensitive genera (three species of crustaceans and one fish) differed by a factor of approximately 2.5.

Chronic effects of atrazine exposure to aquatic animals have been studied with seven freshwater species, three of which are invertebrates and four of which are fish (Figure 3). In three tests with *Ceriodaphnia dubia*, chronic values were 3,536, 3,536, 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 187.1 µg/L was derived, and a corresponding acute-chronic ratio of 36.88. 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 159.1 µg/L was calculated, and a corresponding acute-chronic ratio of 4.525 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 88.32 µg/L and an acute-chronic ratio of 71.33 were calculated. In two life-cycle tests with the fathead minnow, *Pimephales promelas*, the chronic limits were set in the first test at 213 and 870 µg/L based upon no adverse effects observed in a chronic exposure at 213 µg/L and 25 percent mortality in 3- to 5-day old fry at 870 µg/L. The chronic value was 430.5 µg/L and the acute-chronic ratio was 34.84. In the second test, chronic limits were 250 and 460 µg/L, based upon growth of larval fish, resulting in a chronic value of 339.1 µg/L and an acute-chronic ratio of 58.98. The acute-chronic ratio for this species, 45.33, was calculated as the geometric mean of these two values. 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 217.9 µg/L. Since

the acute value was a "greater than" value, the acute-chronic ratio was >36.71.

Chronic values are available for three species of saltwater organisms. The chronic values for *Eurytemora affinis* ranged from 5,020 to 20,920 µg/L, based on survival. The chronic value for *Americamysis bahia* was 123.3 µg/L, also based on survival. The chronic value for *Cyprinodon variegatus* was 2,542 µg/L, based on mortality of juveniles. The resultant acute-chronic ratio for *E. affinis* was 2.629, while the acute-chronic ratios for *A. bahia* and *C. variegatus* were 8.110 and >6.294, respectively.

Effect concentrations for freshwater and saltwater plants are lower than the acute and chronic values for aquatic animals (Figures 4 and 5). Atrazine toxicity to aquatic plants, both algae and macrophytes, commonly occurs at concentrations of 10 µg/L and above, with several reports of toxicity to specific plant taxa at concentrations below 10 µg/L (primarily freshwater plant species). 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 freshwater 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 EC50 values for these species would be considerably higher. The lowest reported EC50 value for a freshwater vascular plant species, *Lemna gibba*, was 37 µg/L in a 14-day exposure, using wet weight as an endpoint (Figure 4).

Conversely, the lowest EC50 based on growth for a saltwater green algae species, *Neochloris* sp., was 82 µg/L, while the equivalent value for a saltwater vascular plant species, *Myriophyllum spicatum*, was 25 µg/L. A Final Plant Value was not determined, as there were no tests meeting the requirements stated in the Guidelines (Stephan et al. 1985).

Atrazine has a limited tendency to accumulate in tissues of aquatic animals. BCFs ranged from <0.27 to a maximum of 8.5 in three species of freshwater fish. There are no BCFs available for saltwater species.

Aquatic ecosystem structural and functional parameters have most frequently been observed to be adversely affected by atrazine concentrations of 10 μg/L and above (Figures 4 and 5). However, in a few studies (saltwater), 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, mainly a result of decreased availability of shelter and plant matter for food.

The effects data presented above indicate that criteria which adequately protect aquatic animals and their uses will probably also protect aquatic plants and their uses. The national criteria are determined on the basis of atrazine toxicity to aquatic animals. The Criterion Maximum Concentrations for fresh water (351.2 μg/L) and salt water (759.5 μg/L) are one-half of the respective Final Acute Values (702.4 and 1,519 μg/L, respectively). These values are based on Table 1 acute toxicity values for all invertebrate and vertebrate species. The Criterion Continuous Concentrations for fresh water (12.35 μg/L) and salt water (26.71 μg/L) are based on the Final Chronic Values for fish. These were calculated by dividing the Final Fish Acute-Chronic Ratio (56.86) 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 for fresh water and salt water because 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 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 12.35 μg/L more than once every three years on the average, and if the one-hour average concentration does not exceed 351.2 μg/L more than once every three years on the average. The four-day average of 12.35 μg/L for the protection of freshwater animals should also be protective of most freshwater plants.

The procedures described in the Guidelines 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 26.71 μg/L more than once every three years on the average, and if the one-hour average concentration does not exceed 759.5 μg/L more than once every three years on the average. The four-day average of 26.71 μg/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 1983a) 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 1983a,b, 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 the U.S. EPA in deriving numeric criteria that are scientifically 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 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).

Figure 1. Ranked Summary of Atrazine GMAVs

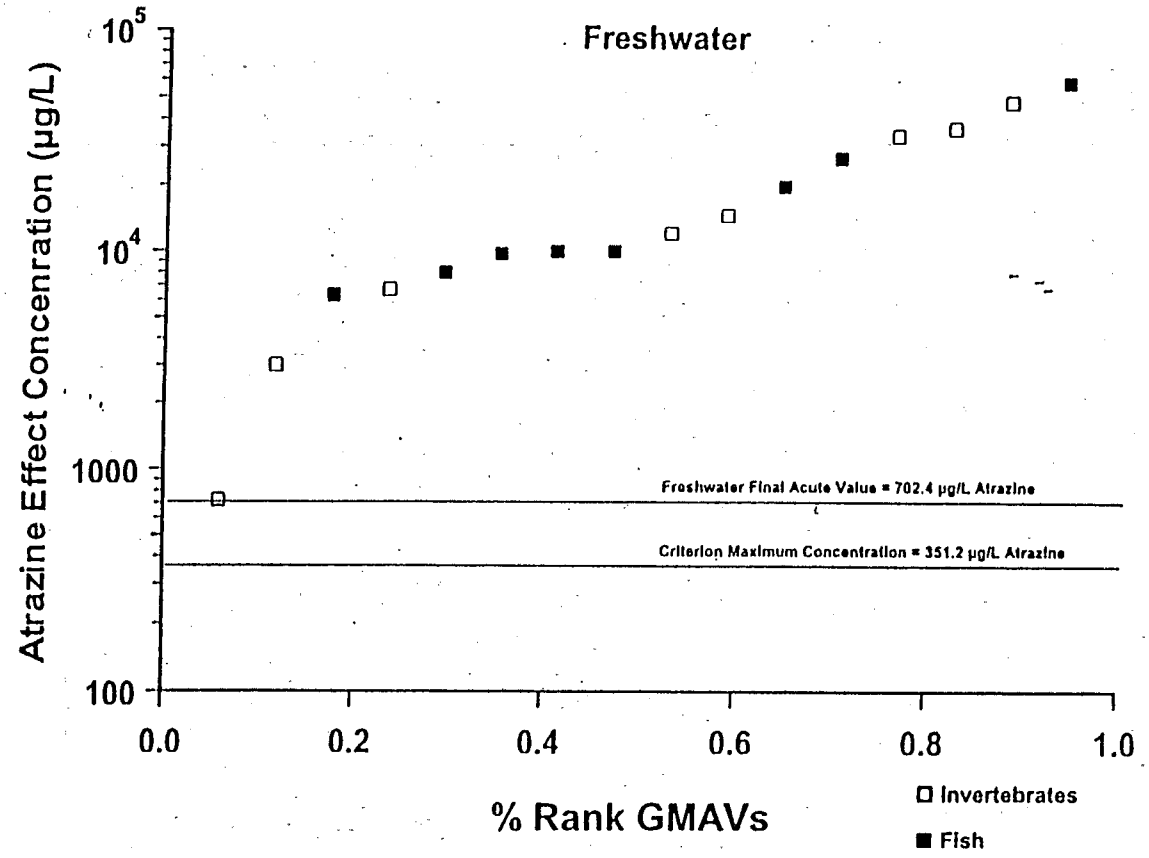

Figure 2. Ranked Summary of Atrazine GMAVs

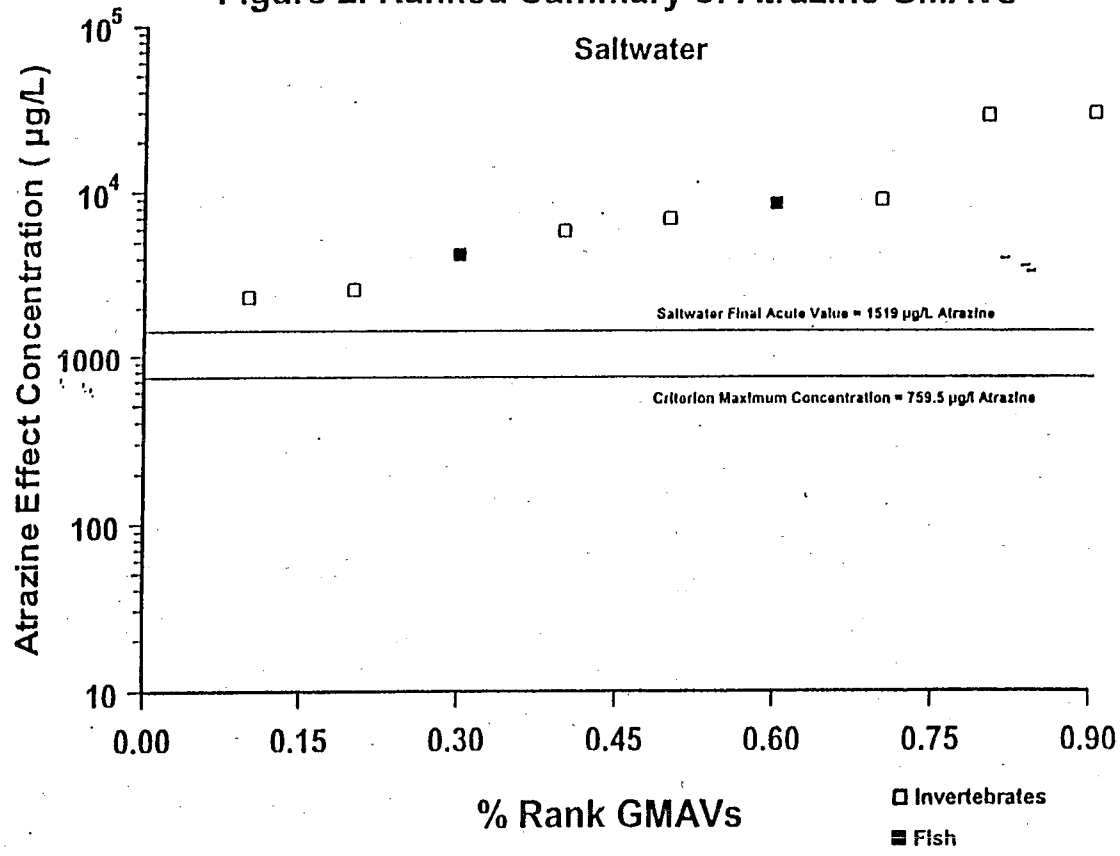

Figure 3. Chronic Toxicity of Atrazine to Aquatic Animals

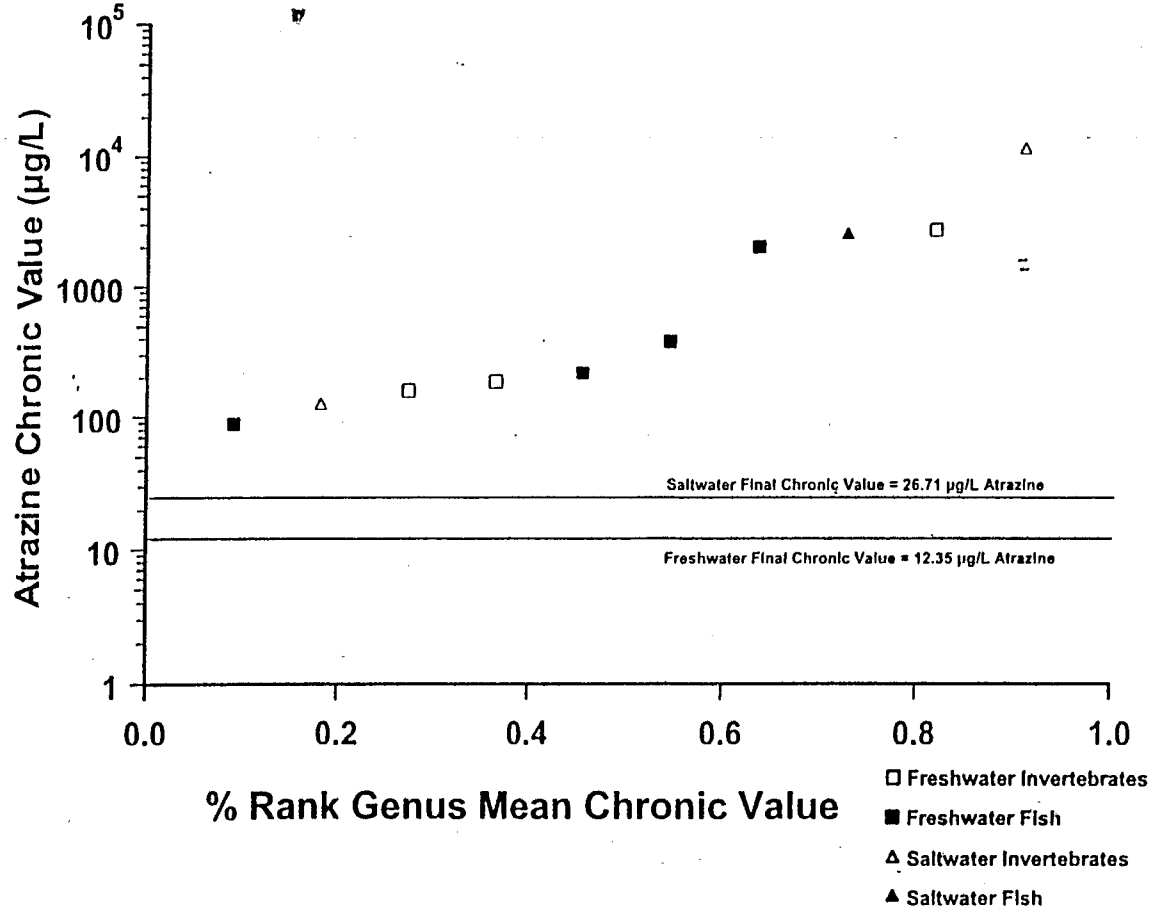

Figure 4. Ranked Summary of Test Values for Freshwater Plants.

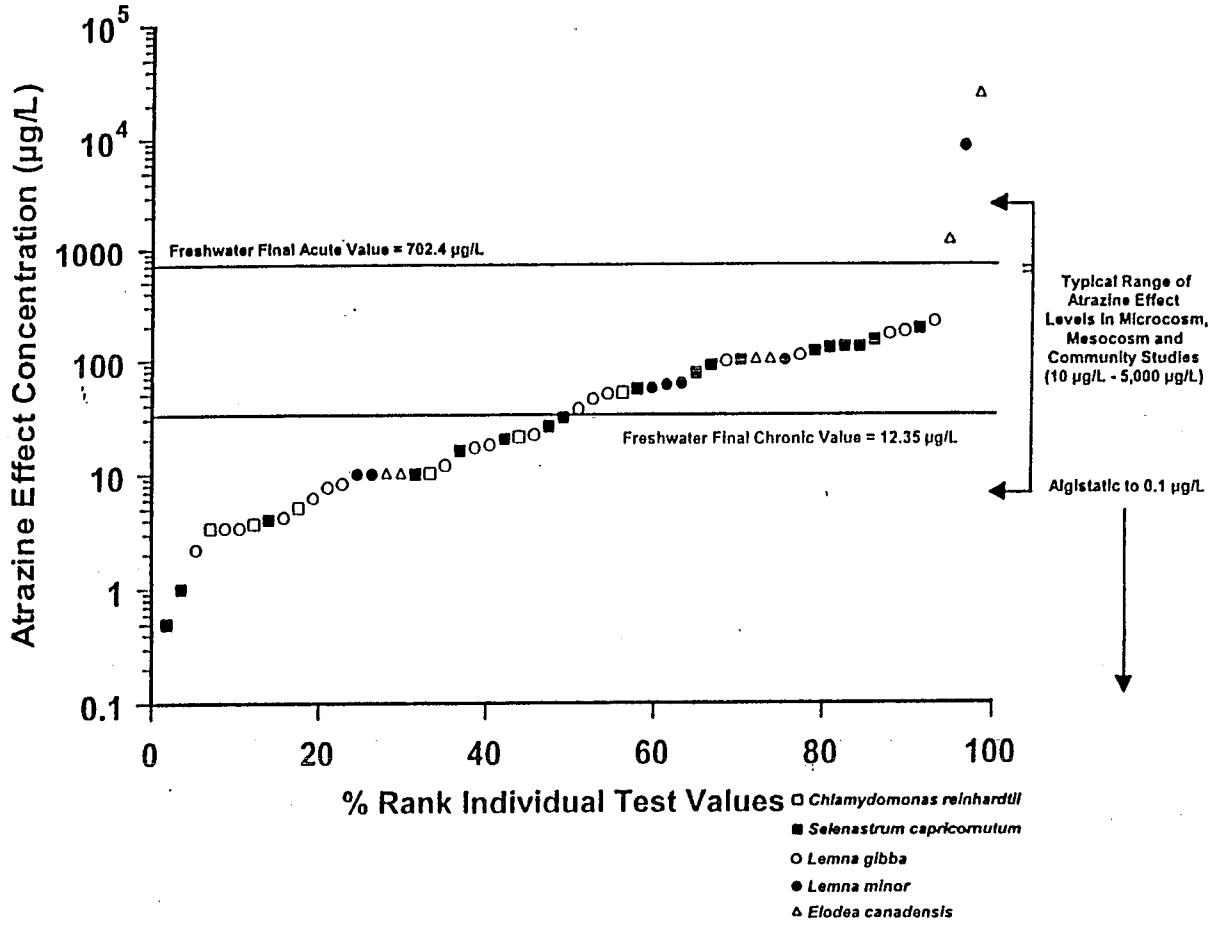

Figure 5. Ranked Summary of Test Values for Saltwater Plants.

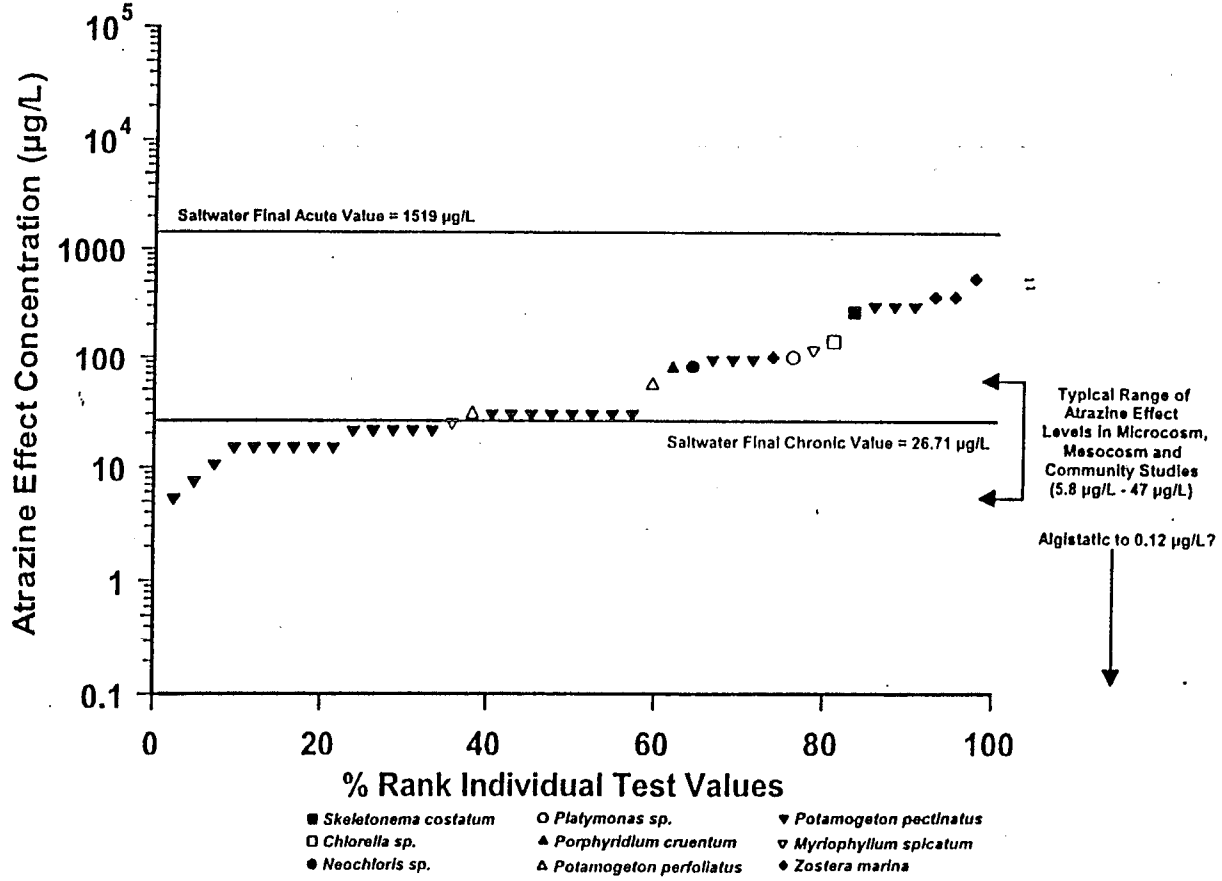

Table 1. Acute Toxicity of Atrazine to Aquatic Animals

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 (<24 hr), *Ceriodaphnia dubia*	S,M	97%	52	>4,900	-	Jop 1991a
Cladoceran (<12 hr), *Ceriodaphnia dubia*	S,M	>99%	57.1	>30,000	>12,120	Oris et al. 1991
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 (4th instar), *Chironomus tentans*	S,U	99%	80-100	>20,000[c]	-	Pape-Lindstrom and Lydy 1997
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
Rainbow trout (juvenile), *Oncorhynchus mykiss*	S,U	98.8%	43	5,300	5,300	Belliles and Scott 1965
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)[b]	Species mean Acute Value (µg/L)	References
Goldfish (juvenile), *Carassius auratus*	S,U	98.8%	43	60,000	60,000	Belliles and Scott 1965
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 1991d
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*	S,U	98.8%	43	24,000	-	Belliles and Scott 1965
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

Species	Method[a]	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)[b]	Species mean Acute Value (µg/L)	References
			SALTWATER SPECIES			
Eastern oyster (embryo/larval), *Crassostrea virginica*	S,U	97.4%	16	>30,000	>30,000	Ward and Ballantine 1985
Copepod (nauplius), *Eurytemora affinis*	S,M	97.1%	5	500	-	Hall et al. 1994a,b
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
Copepod (adult), *Acartia clausii*	R,U	70%	6	7,925	7,925	Thursby et al. 1990

Table 1 (Continued)

Species	Method[a]	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)[b]	Species mean Acute Value (µg/L)	References
Copepod (adult), *Acartia tonsa*	R,M	70%	31-32	210.1	-	Thursby et al. 1990
Copepod (adult), *Acartia tonsa*	R,M	70%	31	91.73	-	Thursby et al. 1990
Copepod (adult), *Acartia tonsa*	F,M	97.1%	30-34	4,300	4,300	McNamara 1991a
Mysid, *Americamysis bahia*	F,M	97.4%	20	1,000	-	Ward and Ballantine 1985
Mysid, *Americamysis bahia*	F,M	97.1%	32	5,400	2,324	Machado 1994
Pink shrimp, *Penaeus duorarum*[d]	S,U	97.4%	26	6,900	6,900	Ward and Ballantine 1985
Grass shrimp, *Palaemonetes pugio*[d]	S,U	97.4%	26	9,000	9,000	Ward and Ballantine 1985
Fiddler crab, *Uca pugilator*[d]	S,U	97.4%	26	>29,000	>29,000	Ward and 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	4,208	Hall et al. 1994a,b
Sheepshead minnow, *Cyprinodon variegatus*	F,M	97.4%	13	>16,000[c]	-	Ward and Ballantine 1985
Sheepshead minnow, *Cyprinodon variegatus*	F,M	97.1%	32	13,000[c]	-	Machado 1994b
Spot, *Leiostomus xanthurus*[d]	S,U	97.4%	12	8,500	8,500	Ward and Ballantine 1985

[a] S = static; R = renewal; F = flow-through; M = measured; U = unmeasured.
[b] Results are expressed as atrazine, not as the chemical.
[c] Not used in calculations because data are available for a more sensitive life stage.
[d] Test organisms collected from the field.

Table 2a. Chronic Toxicity of Atrazine to Aquatic Animals

Species	Test[a]	Chemical	Hardness (mg/L as $CaCO_3$)	Chronic Limits ($\mu g/L$)[b]	Chronic Value ($\mu g/L$)	References
			FRESHWATER SPECIES			
Cladoceran, *Ceriodaphnia dubia*	LC	>99%	57.1	2,500-5,000	3,536	Oris et al. 1991
Cladoceran, *Ceriodaphnia dubia*	LC	>99%	57.1	2,500-5,000	3,536	Oris et al. 1991
Cladoceran, *Ceriodaphnia dubia*	LC	97%	52	1,200-2,500	1,732	Jop 1991b
Cladoceran, *Daphnia magna*	LC	94%	32.2	140-250	187.1	Macek et al. 1976
Midge, *Chironomus tentans*	LC	94%	43.0	110-230	159.1	Macek et al. 1976
Rainbow trout *Oncorhynchus mykiss*	ELS	Technical	50.0	1,100-3,800	2,045	Whale et al. 1994
Brook trout, *Salvelinus fontinalis*	LC	94%	35.7	65-120	88.32	Macek et al. 1976
Fathead minnow, *Pimephales promelas*	LC	94%	36.2	213-870	430.5	Macek et al. 1976
Fathead minnow, *Pimephales promelas*	LC	97.1%	24-36	250-460	339.1	Dionne 1992
Bluegill, *Lepomis macrochirus*	LC	94%	33.9	95-500	217.9	Macek et al. 1976

Species	Test[a]	Chemical	Salinity (g/kg)	Chronic Limits ($\mu g/L$)[b]	Chronic Value ($\mu g/L$)	References
			SALTWATER SPECIES			
Copepod, *Eurytemora affinis*	LC	97.1%	5	12,250-17,500	14,640	Hall et al. 1995
Copepod, *Eurytemora affinis*	LC	97.1%	15	17,500-25,000	20,920	Hall et al. 1995
Copepod, *Eurytemora affinis*	LC	97.1%	25	4,200-6,000	5,020	Hall et al. 1995

Table 2a (Continued)

Species	Test[a]	Chemical	Salinity (g/kg)	Chronic Limits (µg/L)[b]	Chronic Value (µg/L)	References
Mysid, *Americamysis bahia*	LC	97.4%	20	80-190	123.3	Ward and Ballantine 1985
Sheepshead minnow, *Cyprinodon variegatus*	ELS	97.4%	13	1,900-3,400	2,542	Ward and Ballantine 1985

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

Table 2b. Acute-Chronic Ratios

Species	Hardness (mg/L as $CaCO_3$)	Acute Value (µg/L)[a]	Chronic Value (µg/L)	Ratio	Reference
Cladoceran, *Ceriodaphnia dubia*	57.1	>30,000	3,536	>8.484	Oris et al. 1991
Cladoceran, *Ceriodaphnia dubia*	52	>4,900	1,732	>2.829	Jop 1991a,b
Cladoceran, *Daphnia magna*	32.2	6,900	187.1	36.88	Macek et al. 1976
Midge, *Chironomus tentans*	43.0	720	159.1	4.525	Macek et al. 1976
Brook trout, *Salvelinus fontinalis*	35.7	6,300	88.32	71.33	Macek et al. 1976
Fathead minnow, *Pimephales promelas*	36.2	15,000	430.5	34.84	Macek et al. 1976
Fathead minnow, *Pimephales promelas*	24-36	20,000	339.1	58.98	Dionne 1992
Bluegill, *Lepomis macrochirus*	33.9	>8,000	217.9	>36.71	Macek et al. 1976
Copepod, *Eurytemora affinis*	5[b]	500	14,640	0.0342	Hall et al. 1994a,b; 1995
Copepod, *Eurytemora affinis*	15[b]	2,600	20,920	0.1243	Hall et al. 1994a,b; 1995
Copepod, *Eurytemora affinis*	25[b]	13,200	5,020	2.629	Hall et al. 1994a,b; 1995
Mysid, *Americamysis bahia*	20[b]	1,000	123.3	8.110	Ward and Ballantine 1985
Sheepshead minnow, *Cyprinodon variegatus*	13[b]	>16,000	2,542	>6.294	Ward and Ballantine 1985

[a] From Table 1.
[b] Salinity expressed as g/kg.

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		
16	60,000	Goldfish, *Carassius auratus*	60,000	-
15	49,000	Cladoceran, *Daphnia magna*	49,000	36.88
14	>37,100	Annelid, *Lumbriculus variegatus*	>37,100	-
13	>34,100	Snail, *Physa* sp.	>34,100	-
12	27,000	Brown trout, *Salmo trutta*	27,000	-
11	20,000	Fathead minnow, *Pimephales promelas*	20,000	45.33
10	14,700	Amphipod, *Hyalella azteca*	14,700	-
9	>12,120	Cladoceran *Ceriodaphnia dubia*	>12,120	>4.899
8	>10,000	Channel catfish, *Ictalurus punctatus*	>10,000	-
7	>10,000	Largemouth bass, *Micropterus salmoides*	>10,000	-
6	9,767	Coho salmon, *Oncorhynchus kisutch*	>18,000	-
	-	Rainbow Trout, *Oncorhynchus mykiss*	5300	-
5	>8,000	Bluegill, *Lepomis macrochirus*	>8,000	>36.71
4	6,700	Stonefly, *Acroneuria* sp.	6,700	-
3	6,300	Brook trout, *Salvelinus fontinalis*	6,300	71.33

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	4.525
		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	-
		Copepod, *Acartia tonsa*	4,300	-
3	4,208	Sheepshead minnow, *Cyprinodon variegatus*	4,208	>6.294
2	2,579	Copepod, *Eurytemora affinis*	2,579	2.629
1	2,324	Mysid, *Americamysis bahia*	2,324	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 2b.

Table 3 (continued)

Fresh Water

Final Acute Value = 702.4 µg/L

Criterion Maximum Concentration = (702.4 µg/L)/2 = 351.2 µg/L

Final Fish Acute-Chronic Ratio = 56.86

Fish Chronic Value = 12.35 µg/L

Final Invertebrate Acute-Chronic Ratio = 7.723

Invertebrate Chronic Value = 90.95 µg/L

Salt Water

Final Acute Value = 1519 µg/L

Criterion Maximum Concentration = (1519 µg/L)/2 = 759.5 µg/L

Final Fish Acute-Chronic Ratio = 56.86

Fish Chronic Value = 26.71 µg/L

Final Invertebrate Acute-Chronic Ratio = 7.723

Invertebrate Chronic Value = 196.7 µg/L

Table 4. Toxicity of Atrazine to Aquatic Plants

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)*	Reference
			FRESHWATER SPECIES			
Green alga, *Chlamydomonas reinhardtii*	-	-	4	EC50 (cell number)	51	Schafer et al. 1993
Green alga, *Chlamydomonas reinhardtii*	-	-	7	EC50 (cell number)	21	Schafer et al. 1993
Green alga, *Chlamydomonas reinhardtii*	-	-	10	EC50 (cell number)	10.2	Schafer et al. 1993
Green alga, *Chlamydomonas reinhardtii*	-	-	4	NOEC (growth inhibition)	3.4	Schafer et al. 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	7	NOEC (growth inhibition)	5.1	Schafer et al. 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	10	NOEC (growth inhibition)	3.7	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 (chlorophyll a, pheophytin a)	10	Univ. of Mississippi 1990
Green alga, *Selenastrum capricornutum*	-	-	4	LOEC (cell density, biomass)	1.0	Univ. of Mississippi 1990
Green alga, *Selenastrum capricornutum*	-	-	4	LOEC (chlorophylla, 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

Table 4 (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)*	Reference
Green alga, *Selenastrum capricornutum*	97.0%	-	4	NOEC (cell number)	76	Hoberg 1991a
Green alga, *Selenastrum capricornutum*	97.0%	-	4	LOEC (cell number)	130	Hoberg 1991a
Green alga, *Selenastrum capricornutum*	97.0%	-	4	EC10 (cell number)	90	Hoberg 1991a
Green alga, *Selenastrum capricornutum*	97.0%	-	4	EC50 (cell number)	130	Hoberg 1991a
Green alga, *Selenastrum capricornutum*	97.0%	-	4	EC90 (cell number)	190	Hoberg 1991a
Green alga, *Selenastrum capricornutum*	97.1%	-	5	NOEC (cell number)	16	Hoberg 1993a
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 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

Table 4 (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)[a]	Reference
Duckweed, *Lemna gibba*	97.1%	-	14	EC10 (frond biomass)	12	Hoberg 1993b
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	LOEC (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*	-	-	14	NOEC (biomass)	10	Univ. of Mississippi 1990

Table 4 (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)[a]	Reference
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 minor*	98%	-	10	EC50 (frond number)	56	Kirby and Sheahan 1994
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	EC50 (biomass)	25,400[d]	Univ. of Mississippi 1990

Species	Chemical	Salinity g/kg	Duration (days)	Effect	Concentration (µg/L)[a]	Reference
			SALTWATER SPECIES			
Diatom, *Skeletonema costatum*	-	30	2	EC50 (growth)	265	Walsh 1983

Table 4 (Continued)

Species	Chemical	Salinity g/kg	Duration (days)	Effect	Concentration (µg/L)*	Reference
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
Green alga, *Platymonas sp.*	99.7%	30	3	EC50 (growth)	100	Mayer 1987
Red alga, *Porphyridium cruentum*	99.7%	30	3	EC50 (growth)	79	Mayer 1987
Redheadgrass pondweed, *Potamogeton perfoliatus*	96.4%	9	28	IC50 (photosynthesis)	55	Kemp et al. 1982b, 1983; Kemp et al. 1985
Redheadgrass pondweed, *Potamogeton perfoliatus*	96.4%	9	35	IC50 (final biomass)	30	Kemp et al. 1982b, 1983; Kemp et al. 1985
Sago pondweed, *Potamogeton pectinatus*	97.1%	1	28	NOEC (Dry weight)	15	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	1	28	NOEC (Wet weight)	15	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	1	28	NOEC (Rhizome tip Mass)	30	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	1	28	LOEC (Dry weight)	30	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	1	28	LOEC (Wet weight)	30	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	1	28	LOEC (Rhizome tip Mass)	300	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	1	28	Chronic value (Dry weight)	21.2	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	1	28	Chronic value (Wet weight)	21.1	Hall et al. 1997

Table 4 (Continued)

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

Table 4 (Continued)

Species	Chemical	Salinity g/kg	Duration (days)	Effect	Concentration (µg/L)[a]	Reference
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	LOEC (Wet weight)	30	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	LOEC (Rhizome tip mass)	300	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Chronic value (Dry weight)	10.6	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Chronic value (Wet weight)	21.2	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	12	28	Chronic value (Rhizome tip mass)	94.9	Hall et al. 1997
Sago pondweed, *Potamogeton pectinatus*	97.1%	1-12	28	Chronic value (Dry weight)	5.3	Hall et al. 1997
Eurasian water milfoil, *Myriophyllum spicatum*	96.4%	9	28	IC50 (photosynthesis)	117	Kemp et al. 1982b, 1983; Kemp et al. 1985
Eurasian water milfoil, *Myriophyllum spicatum*	96.4%	9	35	IC50 (final biomass)	25	Kemp et al. 1982b, 1983; Kemp et al. 1985
Eelgrass, *Zostera marina*	-	22	21	LC50	540	Delistraty and Hershner 1984
Eelgrass, *Zostera marina*	-	20	21	LC50	100	Delistraty and Hershner, 1984
Eelgrass, *Zostera marina*	-	20	21	LC50	365	Delistraty and Hershner, 1984
Eelgrass, *Zostera marina*	-	19	21	LC50	367	Delistraty and 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.

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, *Anabaena cylindrica*	-	-	14 days	LOEC (growth)	2,160	Rohwer and Fluckiger 1979
Cyanobacterium, *Anabaena cylindrica*	-	-	19 hr	LOEC (nitrogenase activity)	2,160	Rohwer and Fluckiger 1979
Cyanobacterium, *Anabaena cylindrica*	-	-	1 hr	LOEC (O_2 production)	21,600	Rohwer and Fluckiger 1979
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, *Anabaena 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; Hughes et al. 1986, 1988

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Cyanobacterium, *Anabaena flos-aquae*	97%	-	5 day exposure, 9 day recovery	NOEC (cell number)	<100	Hughes 1986; Hughes et al. 1986, 1988
Cyanobacterium, *Anabaena flos-aquae*	97%	-	5 day exposure, 9 day recovery	Algistatic concentration	4,970	Hughes 1986; Hughes et al. 1986, 1988
Cyanobacterium, *Anabaena flos-aquae*	97%	-	5 day exposure, 9 day recovery	Algicidal concentration	>3,200	Hughes 1986; Hughes et al. 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
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-Waly et al. 1991b
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	5 days	EC50 (chlorophyll *a*)	469	Abou-Waly et al. 1991b
Cyanobacterium, *Anabaena flos-aquae*	99.9%	-	7 days	EC50 (chlorophyll *a*)	766	Abou-Waly et al. 1991b

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Cyanobacterium, *Anabaena flos-aquae*	92.2%	-	4 days	EC50 (chlorophyll a)	>3,000	Fairchild et al. 1998
Cyanobacterium, *Anabaena inaequalis*	>95%	-	12-14 days	EC50 (cell number)	30	Stratton 1984
Cyanobacterium, *Anabaena inaequalis*	Technical or analytical	-	22 hr	65% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994
Cyanobacterium, *Anabaena variabilis*	>95%	-	12-14 days	EC50 (cell number)	4,000	Stratton 1984
Cyanobacterium, *Aphanizomenon flos-aquae*	Technical or analytical	-	22 hr	97% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994
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, *Oscillatoria* cf. *chalybea*	99.7%	-	6 days	Lowest complete inhibition conc.	2160	Schrader et al. 1997
Cyanobacterium, *Oscillatoria* cf. *chalybea*	99.7%	-	5 days	LOEC (growth)	220	Schrader at al 1998
Cyanobacterium, *Oscillatoria* sp.	Technical or analytical	-	22 hr	87% 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, *Pseudoanabaena* sp.	Technical or analytical	-	22 hr	91% inhibition of photosynthesis (^{14}C uptake)	2,667	Peterson et al. 1994
Cyanobacterium, *Synechococcus leopolensis*	-	-	5 days	EC50 (growth)	130	Kallqvist and Romstad 1994
Cyanobacterium, *Synechococcus leopolensis*	-	-	5 days	EC50 (microplate method)	130	Kallqvist and Romstad 1994
Green alga, *Ankistrodesmus braunii*	99.9%	-	11 days	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, *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[c]	Francois and Robinson 1990

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Chlamydomonas moewssi*	95%	-	14 days	EC50 (growth inhibition)	1384 (exponential growth phase)	Kotrikla et al. 1997
Green alga, *Chlamydomonas moewssi*	95%	-	14 days	EC50 (growth inhibition)	1181 (stationary growth phase)	Kotrikla et al. 1997
Green alga, *Chlamydomonas noctigama*	-	-	72 hr	EC50 (growth)	330	Kallqvist and Romstad 1994
Green alga, *Chlamydomonas reinhardtii*	-	-	8 hr	~32% inhibition of photosynthesis	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*[d]	-	-	1-2 days	Growth rate reduced by 100%	216	Hersh and Crumpton 1987
Green alga, *Chlamydomonas reinhardtii*[e]	-	-	1-2 days	Growth rate reduced by 13%	21.6	Hersh and Crumpton 1987
Green alga, *Chlamydononas reinhardtii*[d]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	45	Hersh and Crumpton 1989

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Chlamydomonas reinhardtii*[a]	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
Green alga, *Chlamydomonas reinhardtii*	92.2%	-	96 hr	EC50 (chlorophyll)	176	Fairchild et al. 1998
Green alga, *Chlamydomonas* sp.	-	-	72-96 hr	36.2%[f] and 84.9%[g] growth inhibition; 12.8% reduction in chlorophyll	50-52	Foy and Hiranpradit 1977
Green alga, *Chlamydomonas* sp.	-	-	72-96 hr	64.1%[f] and 93.3%[g] growth inhibition; 32.4% reduction in chlorophyll	100-104	Foy and Hiranpradit 1977
Green alga, *Chlamydomonas* sp.	-	-	72-96 hr	77.5%[f] and 96.6%[g] growth inhibition; 49.9% reduction in chlorophyll	200-208	Foy and Hiranpradit 1977
Green alga, *Chlamydomonas* sp.	-	-	72-96 hr	76.6%[f] and 100%[g] growth inhibition; 84.2% reduction in chlorophyll	400-416	Foy and Hiranpradit 1977
Green alga, *Chlamydomonas* sp.	-	-	72-96 hr	78.6% growth inhibition[f]; 90.5% reduction in chlorophyll	832	Foy and Hiranpradit 1977

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Chlamydomonas* sp.	-	-	4 days	EC50 (biomass)	176	Fairchild et al. 1994a
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
Green alga, *Chlorella fusca*	95%	-	14 days	EC50 (growth inhibition)	53.91 (exponential growth phase)	Kotrikla et al. 1997
Green alga, *Chlorella fusca*	95%	-	14 days	EC50 (growth inhibition)	75.73 (stationary growth phase)	Kotrikla et al. 1997
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 pyrenoidosa*	-	-	2 wk	70% reduced growth	500	Virmani et al. 1975
Green alga, *Chlorella pyrenoidosa*	-	-	2 wk	95% reduced growth	2,500	Virmani et al. 1975
Green alga, *Chlorella pyrenoidosa*	-	-	2 wk	92% reduced growth	10,000	Virmani et al. 1975

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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-Murua et al. 1985
Green alga, *Chlorella pyrenoidosa*	-	-	10 days	65% growth inhibition; 70% reduction in chlorophyll a	107.8	Gonzalez-Murua 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
Green alga, *Chlorella vulgaris*	-	-	7 days	31.0% reduction in dry wt.	250[b]	Veber et al. 1981
Green alga, *Chlorella vulgaris*	-	-	7 days	43.6% reduction in dry wt.	500[b]	Veber et al. 1981
Green alga, *Chlorella vulgaris*	-	-	7 days	56.4% reduction in dry wt.	2,500[b]	Veber et al. 1981
Green alga, *Chlorella vulgaris*	-	-	7 days	61.8% reduction in dry wt.	5,000[b]	Veber et al. 1981

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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*	-	-	30 min	EC50 (Decrease in oxygen evolution)	305	Van der Heever and Grobbelaar 1997
Green alga, *Chlorella vulgaris*	92.2%	-	96 hr	EC50 (chlorophyll)	94	Fairchild et al. 1998
Green alga, *Chlorella vulgaris*	98%	-	12 days	Reduced growth, but showed signs of recovery	10	Berard et al 1999
Green alga, *Chlorella* sp.	-	-	72-96 hr	31.0% growth inhibition[f]; 38.8% reduction in chlorophyll	52	Foy and Hiranpradit 1977
Green alga, *Chlorella* sp.	-	-	72-96 hr	45.3% growth inhibition[f]; 30.3% reduction in chlorophyll	104	Foy and Hiranpradit 1977
Green alga, *Chlorella* sp.	-	-	72-96 hr	52.3% growth inhibition[f]; 83.7% reduction in chlorophyll	208	Foy and Hiranpradit 1977
Green alga, *Chlorella* sp.	-	-	72-96 hr	59.2% growth inhibition[f]; 93.5% reduction in chlorophyll	416	Foy and Hiranpradit 1977

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Chlorella* sp.	-	-	72-96 hr	53.7% growth inhibition[f]; 95.4% reduction in chlorophyll	832	Foy and Hiranpradit 1977
Green alga, *Chlorella* sp.	-	-	1-2 days	Growth rate reduced by 86%	216	Hersh and Crumpton 1987
Green alga, *Chlorella* sp.	-	-	2-3 days	Growth rate reduced by 55%	21.6	Hersh and Crumpton 1987
Green alga, *Chlorella* sp.	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	36	Hersh and Crumpton 1989
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. 1994a
Green alga, *Chlorococcum hypnosporum*	-	-	2 wk	75% reduced growth	5,000	Virmani et al. 1975
Green alga, *Chlorococcum hypnosporum*	-	-	2 wk	92% reduced growth	10,000	Vermani et al. 1975
Green alga, *Franceia* sp.[f]	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	466	Hersh and Crumpton 1989
Green alga, *Franceia* sp.	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	774	Hersh and Crumpton 1989

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Franceia* sp.	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	710	Hersh and Crumpton 1989
Green alga, *Franceia* sp.	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	430	Hersh and Crumpton 1989
Green alga, *Franceia* sp.	94%	-	2 min	EC50 (photosynthetic oxygen evolution)	720	Hersh and Crumpton 1989
Green alga, *Gloetaenium loitlesbergarianum*	-	-	96 hr	inhibition of calcification	2,157	Prasad and Chowdary 1981
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
Green alga, *Scenedesmus quadricauda*	-	-	8 hr	~42% inhibition of photosynthesis	10	Valentine and Bingham 1976
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

Table 6 (continued)

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

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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 subspicatus*	-	-	24 hr	EC50 (net assimilation inhibition)	25	Zagorc-Koncan 1996
Green alga, *Scenedesmus subspicatus*	-	-	72 hr	EC50 (growth inhibition)	200	Zagorc-Koncan 1996
Green alga, *Scenedesmus subspicatus*	99%	-	60 days	NOEC (growth and photosynthetic oxygen evolution)	20	Behra et al. 1999
Green alga, *Scenedesmus* sp.	-	-	72-96 hr	60.2% growth inhibition[g]	50	Foy and Hiranpradit 1977
Green alga, *Scenedesmus* sp.	-	-	72-96 hr	72.4% growth inhibition[g]	100	Foy and Hiranpradit 1977
Green alga, *Scenedesmus* sp.	-	-	72-96 hr	81.6% growth inhibition[g]	200	Foy and Hiranpradit 1977
Green alga, *Scenedesmus* sp.	-	-	72-96 hr	84.7% growth inhibition[g]	400	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.	-	-	72-96 hr	83.7% growth inhibition[g]	800	Foy and Hiranpradit 1977
Green alga, *Scenedesmus* sp.	-	-	4 days	EC50 (biomass)	169	Fairchild et al. 1994a
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[i]	Johnson 1986
Green alga, *Selenastrum capricornutum*	85.5%	47	7 days	36.2% decreased biomass	1,000[i]	Johnson 1986
Green alga, *Selenastrum capricornutum*	85.5%	47	7 days	75.9% decreased biomass	1,000[i]	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

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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[k]	Turbak et al. 1986
Green alga, *Selenastrum capricornutum*	80%	-	24 hr	EC50 (O_2 evolution)	854[l]	Turbak et al. 1986
Green alga, *Selenastrum capricornutum*	-	-	5 days	EC50 (cell number)	100	Roberts et al. 1990
Green alga, *Selenastrum capricornutum*	-	-	5 days	EC50 (cell number)	95	Roberts et al. 1990
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-Waly et al. 1991b
Green alga, *Selenastrum capricornutum*	99.9%	-	5 days	EC50 (chlorophyll a)	218	Abou-Waly et al. 1991b
Green alga, *Selenastrum capricornutum*	99.9%	-	7 days	EC50 (chlorophyll a)	214	Abou-Waly 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*	-	-	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
Green alga, *Selenastrum capricornutum*	-	-	72 hr	EC50 (chlorophyll a - fluorometric measurement)	960	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*	-	-	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*	-	-	96 hr	LC50	26	Caux et al. 1996
Green alga, *Selenastrum capricornutum*	-	-	96 hr	EC50 (cell numbers)	26	Caux et al. 1996
Green alga, *Selenastrum capricornutum*	-	-	30 min	EC50 (decrease in oxygen evolution)	222	Van der Heever and Grobbelaar 1997
Green alga, *Selenastrum capricornutum*	-	-	72 hr	EC50 (growth inhibition)	164.3	Benhra et al. 1997
Green alga, *Selenastrum capricornutum*	-	-	72 hr	EC50 (growth inhibition)	92.9 (Cryoalgotox)	Benhra et al. 1997
Green alga, *Selenastrum capricornutum*	-	-	4 days	I50 (chlorophyll a)	80	El Jay et al. 1997
Green alga, *Selenastrum capricornutum*	Technical grade	-	96 hr	NOEC (biomass)	75	Fairchild et al. 1997
Green alga, *Selenastrum capricornutum*	Technical grade	-	96 hr	LOEC (biomass)	150	Fairchild et al. 1997
Green alga, *Selenastrum capricornutum*	Technical grade	-	96 hr	EC50 (biomass)	235	Fairchild et al. 1997
Green alga, *Selenastrum capricornutum*	99.7%	-	6 days	Lowest Complete Inhibition Concentration (growth)	2160	Schrader et al. 1997

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Selenastrum capricornutum*	-	-	4 hr	EC50 (chlorophyll a fluorescence)	232	Van der Heever and Grobbelaar 1998
Green alga, *Selenastrum capricornutum*	ACS	-	≥3 days	EC50 (growth)	164	Mayer et al. 1998
Green alga, *Selenastrum capricornutum*	99.7%	-	5 days	LOEC (growth)	220	Schrader et al 1998
Green alga, *Stigeoclonium tenue*	-	-	24 hr	EC50 (^{14}C uptake)	127*	Larsen et al. 1986
Green alga, *Stigeoclonium tenue*	-	-	24 hr	EC50 (^{14}C uptake)	224*	Larsen et al. 1986
Green alga, *Ulothrix subconstricta*	-	-	24 hr	EC50 (^{14}C uptake)	88*	Larsen et al. 1986
Benthic diatom, *Craticula cuspidata*	98%	-	67 days chronic, 12 days acute	LOEC (chlorophyll a)	83	Nelson et al. 1999
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* (Minnesota race)	-	-	7 min	EC50 (photosynthesis)	243	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; Hughes et al. 1986, 1988

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Diatom, *Navicula pelliculosa*	97%	-	5 day exposure, 9 day recovery	NOEC	<100	Hughes 1986; Hughes et al. 1986, 1988
Diatom, *Navicula pelliculosa*	97%	-	5 day exposure, 9 day recovery	Algistatic concentration	1,710	Hughes 1986; Hughes et al. 1986, 1988
Diatom, *Navicula pelliculosa*	97%	-	5 day exposure, 9 day recovery	Algicidal concentration	>3,200	Hughes 1986; Hughes et al. 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 gibba*	97%	-	5 days	EC50 (frond production)	170	Hughes 1986; Hughes et al. 1986, 1988
Duckweed, *Lemna gibba*	97%	-	5 day exposure 9 day recovery	NOEC (frond production)	<100	Hughes 1986; Hughes et al. 1986, 1988
Duckweed, *Lemna gibba*	97%	-	5 day exposure 9 day recovery	Phytostatic concentration	1,720	Hughes 1986; Hughes et al. 1986, 1988
Duckweed, *Lemna gibba*	97%	-	5 day exposure 9 day recovery	Phytocidal concentration	>3,200	Hughes 1986; Hughes et al. 1986, 1988

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Duckweed, *Lemna minor*	-	-	20 days	No effect upon growth; increased soluble protein content; increased photosynthesis and respiration	20	Beaumont et al. 1976a,b
Duckweed, *Lemna minor*	-	-	20 days	-12% reduced growth; increased water and soluble protein content; increased photosynthesis and respiration	50	Beaumont et al. 1976a,b, 1978
Duckweed, *Lemna minor*	-	-	20 days	-23% reduced growth; increased water and soluble protein content; increased photosynthesis and respiration	100	Beaumont et al. 1976a,b, 1978
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

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 monogalatosyldi a-cyl-glycerol percentage	100	Grenier et al. 1979
Duckweed, *Lemna minor*	-	-	15 days	Increased total fatty acid and α-linolenic acid content; decreased linoleic acid content; increased monoga-lactosyldiacyl-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
Duckweed, *Lemna minor*	-	-	2 days	Changes in chloroplast ultrastructure; increased chlorophyll content	248	Simard et al. 1990

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Duckweed, *Lemna minor*	Technical or analytical	-	7 days	95% inhibition of growth	2,667	Peterson et al. 1994
Duckweed, *Lemna minor*	Technical	-	96 hr	NOEC (biomass)	75	Fairchild et al. 1997
Duckweed, *Lemna minor*	Technical	-	96 hr	LOEC (biomass)	150	Fairchild et al. 1997
Duckweed, *Lemna minor*	Technical	-	96 hr	EC50 (biomass)	153	Fairchild et al. 1997
Duckweed, *Lemna minor*	92.2%	-	4 days	EC50 (frond production)	92	Fairchild et al. 1998
Wild rice, *Zizania aquatica*	85%	-	83 days	Visibly senescent; 75% reduction in chlorophyll a in leaves	50	Detenbeck et al. 1996
Wild celery, *Vallisneria americana*	-	-	42 days	EC50 (total leaf length)	163	Davis 1981; Forney and Davis 1981
Wild celery, *Vallisneria americana*	-	-	-	Reduced leaf growth and whole plant biomass	8	Cohn 1985
Wild celery, *Vallisneria americana*	-	-	-	Reduced tuber over-wintering success	4	Cohn 1985
Coontail, *Ceratophyllum dermersum*	85%	-	6-8 days	Reduced stem elongation	50	Detenbeck et al. 1996
Coontail, *Ceratophyllum sp.*	92.2%	-	14 days	EC50 (wet weight)	22	Fairchild et al. 1998
Cattail, *Typha latifolia*	85%	-	19 days	No effect upon growth	25	Detenbeck et al. 1996

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Watermilfoil, *Myriophyllum heterophyllum*	92.2%	-	14 days	EC50 (wet weight)	132	Fairchild et al. 1998
Watermilfoil, *Myriophyllum spicatum*	-	-	28 days	EC50 (length)	1,104	Davis 1981; Forney and Davis 1981
Watermilfoil, *Myriophyllum spicatum*	-	-	24 hr	30% increase in net photosynthetic rate	10	Hoffmann and Winkler 1990
Watermilfoil, *Myriophyllum spicatum*	-	-	5 days	50% reduction in branch number	3,700	Bird 1993
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. 1994a
Elodea, *Elodea canadensis*	-	-	28 days	EC50 (length)	80	Davis 1981; Forney and Davis 1981
Elodea, *Elodea canadensis*	-	-	21 days	EC50 (length)	109	Davis 1981; 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	Datenbeck et al. 1996
Elodea, *Elodea canadensis*	92.2%	-	14 days	EC50 (wet weight)	21	Fairchild et al. 1998

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Water moss, *Fontinalis antipyretica*	-	-	20 days	Dark respiration rate exceeded net photosynthesis rate	10	Hoffmann and Winkler 1990
Water moss, *Fontinalis hypnoides*	-	-	24 hr	90% reduction in net photosynthesis	2	Hoffmann and Winkler 1990
Water moss, *Fontinalis squamosa*	-	-	24 hr	20% reduction in net photosynthesis	10	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
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, *Colpidium campylum*	-	-	24 hr	EC50 (cell number)	>50,000	Roberts et al. 1990
Protozoa, *Euglena gracilis*	-	-	8 hr	~11% 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
Protozoa, *Euglena gracilis*	-	-	8 hr	-28% inhibition of photosynthesis	100	Valentine and Bingham 1976
Protozoa, *Euglena gracilis*	-	-	8 hr	-83% inhibition of photosynthesis	1,000	Valentine and Bingham 1976
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
Rotifer, *Brachionus calyciflorus*	-	-	24 hr	LC50	7,840	Crisinel et al. 1994
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 wk	No effect upon growth, fecundity or glycogen metabolism	125	Baturo et al. 1995
Snail, *Lymnaea palustris*	97.8%	-	12 wk	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
Mussel (1-2 d 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

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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, *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, *Daphnia magna*	97.3%	40-50	48 hr	LC50	9,400*	Johnson et al. 1993
Cladoceran, *Daphnia magna*	-	-	24 hr	EC50	>30,000	Crisinel et al. 1994
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

Table 6 (continued)

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

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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, *Daphnia pulex*	98%	-	18 hr	LC50	~700	Bowman et al 1981
Cladoceran (adult), *Moina macrocopa*	-	-	3 hr	LC50	>40,000	Nishiuchi and Hashimoto 1967, 1969
Cladoceran, *Moina macrocopa*	-	-	4-6 wk	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
Amphipod (approx 2nd instar), *Hyalella azteca*	98%	-	18 hr	LC50	2,000	Bowman et al. 1981
White dotted mosquito, *Culex restuans*	98%	-	18 hr	LC50	~60,000	Bowman et al. 1981
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 1991b
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), *Oncorhynchus mykiss*	80%	50	27 days (4 days post-hatch)	62% teratic larvae	4,020	Birge et al. 1979
Rainbow trout (sac fry), *Oncorhynchus 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
Rainbow trout (juvenile), *Oncorhynchus mykiss*	99.3%	-	48 hr	LC50	5,660	Pluta 1989

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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. 1994b

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Rainbow trout (juvenile), *Oncorhynchus mykiss*	≥98%	-	10 days	Reduced plasma protein	50	Davies et al. 1994b
Rainbow trout (juvenile), *Oncorhynchus mykiss*	99%	380	5 wk	Ultrastructural alterations in kidney proximal tubules	12.4	Oulmi et al. 1995
Rainbow trout (juvenile), *Oncorhynchus mykiss*	99%	380	5 wk	Ultrastructural alterations in kidney proximal and distal tubules	24.0	Oulmi et al. 1995
Atlantic salmon (parr), *Salmo salar*	-	-	30 min	Reduced olfactory response to female pheromone	2.0	Moore and Waring 1998
Atlantic salmon (parr), *Salmo salar*	-	-	5 days	Reduction in milt and plasma 17,20 βP levels	0.04	Moore and Waring 1998
Goldfish, *Carassius auratus*	-	-	48 hr	LC50	>10,000	Nishiuchi and Hashimoto 1967, 1969
Goldfish (6-9 g), *Carassius auratus*	97.9%	-	24 hr (10 min flowing)	Burst swimming	0.5 (0.1 test dripping)	Saglio and Trijasse 1998
Common carp, *Cyprinus carpio*	-	-	48 hr	LC50	>10,000	Nishiuchi and Hashimoto 1967, 1969
Common carp (30-50 g), *Cyprinus carpio*	-	-	12 hr	~125% increased serum cortisol	100	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	24 hr	~300% increased serum cortisol	100	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	6 hr	~40% increased serum cortisol	500	Hanke et al. 1983

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Common carp (30-50 g), *Cyprinus carpio*	-	-	12 hr	~60% increased serum cortisol	500	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	24 hr	~250% increased serum cortisol	500	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	12 hr	~60% increased serum glucose	100	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	24 hr	~35% increased serum glucose	100	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	6 hr	~15% increased serum glucose	500	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	12 hr	~40% increased serum glucose	500	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	24 hr	~70% increased serum glucose	500	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	72 hr	~180% increased serum glucose; ~40% decreased liver glycogen	1,000	Hanke et al. 1983
Common carp (30-50 g), *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 (30-50 g), *Cyprinus carpio*	-	-	6 hr	~10% increase in gill total ATPase; ~30% decrease in gill Na-K dependent ATPase	100	Hanke et al. 1983

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Common carp (30-50 g), *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 (30-50 g), *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 (30-50 g), *Cyprinus carpio*	-	-	4 hr	-60% increase in serum AChE	100	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	6 hr	-15% increase in serum AChE	100	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	12 hr	-35% increase in serum AChE	100	Hanke et al. 1983
Common carp (30-50 g), *Cyprinus carpio*	-	-	24 hr	-25% decrease in serum AChE	100	Hanke et al. 1983
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	Naskovic et al. 1993

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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
Common carp (50 - 60 g), *Cyprinus carpio*	94%	-	14 days	NOEC (gill, liver, and kidney histopathology)	1,500	Poleksic et al. 1997
Fathead minnow (≤24h), *Pimephales promelas*	97	60	7 days	NOEC (biomass)	≥4,900	Jop 1991c
Fathead minnow (larvae), *Pimephales promelas*	85%	-	7	No effect upon survival	75	Detenbeck et al. 1996
Fathead minnow (juvenile), *Pimephales promelas*	85%	-	13 days	No effect upon survival or growth	75	Detenbeck et al. 1996
Channel catfish (embryo), *Ictalurus punctatus*	80%	50	4.5 days (at hatching)	LC50	272	Birge et al. 1979
Channel catfish (embryo), *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 (sac fry), *Ictalurus punctatus*	80%	200	8.5 days (4 days post-hatch)	LC50	192	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%	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
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

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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	Decreased red and white blood cell counts, hemoglobin, packed cell volume, mean corpuscular hemoglobin; decreased whole animal oxygen consumption; increased mean cell volume, blood volume and blood water content	1,100	Prasad et al. 1991a
Mozambique tilapia, *Tilapia mossambica*	-	-	30 days	Changed 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	Increased lipase activity, free fatty acids, acetoacetate concentration, and total cholesterol in liver and muscle; decreased 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

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)	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
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

Table 6 (continued)

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

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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
African clawed frog (embryo), *Xenopus laevis*	40.8%	-	96 hr	LOEC (teratogenesis)	1,100	Morgan et al. 1996
Tiger salamander, *Ambystoma tigrinum*	-	333	86 days	Stimulated plasma thyroxine; delayed development - retarded growth	82	Larson et al. 1998
Stream mixed algal species	80%	-	1 day to 3 wk	39-78% reduction in gross productivity	10	Kosinski et al. 1985; Kosinski and Merkle 1984
Stream mixed algal species	80%	-	3 days	Reduced net primary productivity	100	Moorhead and Kosinski 1986
Experimental stream periphyton community	80%	-	14 days	Severe population density reductions in several species; total destruction of *Cladophora glomerata*	1,000	Kosinski 1984

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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 wk	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 aufwuchs community	-	-	12 days	4% biomass reduction at 10°C	24	Krieger et al. 1988
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

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
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	Bröckway et al. 1984
Pond microcosm, (static system)	98.2%	-	12 days	25-30% decreased oxygen production	50	Brockway et al. 1984
Pond microcosm, (static system)	98.2%	-	7 days	40-50% decreased diurnal oxygen production	100	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%	-	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
Lake microcosm plankton community	98%	-	10-21 days	Seasonal and species-dependent effects; growth generally stimulated for Chryptophytes and Chrysophytes, but inhibited in *Chlorella vulgaris*	10	Berard et al. 1999
Freshwater microcosm	-	-	7 wk	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/chloroph yll a ratio	43.8	Stay et al. 1985

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Phytoplankton, zooplankton and benthos microcosm	-	-	25 days	Reduced net primary productivity	~50	Stay et al. 1985
Pond mesocosm community	-	-	70 days	Changed population densities of zooplankton (rotifers, crustaceans and insect larvae)	200	Peichl et al. 1984
Pond mesocosm community	-	-	121 days	Changed phytoplankton community composition; increased rotifer population	10	Peichl et al. 1985
Pond mesocosm community	41%	-	805 days	Reduced 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 yr 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 ($\mu g/L$)	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[a]	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[a]	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*	Dewey 1986; Dewey and de Noyelles 1994
Pond mesocosm community	40.8%	-	8 wk	Altered macrophyte community species composition; no effects upon primary productivity, total plant biomass, zooplankton or fish	50	Fairchild et al. 1994a
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

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Pond mesocosm plankton community	-	-	2 mo	Reduced peak egg ratios in *Daphnia longispina* and elimination of *Polyarthra* sp. rotifers	318	Juttner et al. 1995
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

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	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
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

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Experimental pond community	-	-	373 days after treatment	EC50 (^{14}C uptake)	100	Larsen et al. 1986
Mixed pond community	99.2%	-	4 mo	Elimination of *Lemna minor* population	60-120	Gunkel 1983
Mixed pond community	99.2%	-	4 mo	Rapid succession of algal species; reduced reproduction rate in *Daphnia pulicaria*	60-120	Gunkel 1983
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: decreased abundance of *Endochironomus nigricans* in June and of total macroinvertebrates in both May and June, followed by recovery in July; epiphytes decreased in abundance in June, followed by recovery in July; detritovore abundance decreased in May, followed by recovery in June; generalists decreased in May and June, followed by recovery in July	20	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 similar to those at 20 µg/L in May and June; *Caenis* sp. significantly increased in July; also increased abundance of *Caenis* sp., total macroinverte-brates, detrito-vores and generalists in late July	100	Huggins et al. 1994
Pond mesocosm community	Reagent grade	-	2 yr	Results similar to those at 20 and 100 µg/L in May and June: *Caenis* sp. were significantly reduced in abund- ance in early July but not in late July; the abundance of epi- phytes decreased, while the abund- ance of total macroinverte-brates and generalists increased in late July	500	Huggins et al. 1994
Mixed algae from pond	-	-	>3 hr	Increased fluorescence rate for photosystem II	10	Ruth 1996

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Lake limnocorral community	80%	-	34 days	Reduced periphyton ash-free dry weight	80-140	Herman et al. 1986
Lake limnocorral community	80%	-	9 wk (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
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

Table 6 (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)	Reference
Lake limnocorral community	80%	-	Two exposures 35 days apart	Different phytoplankton species assemblages for up to 114 days after second applica- tion; increased Secchi disc readings and decreased levels of dissolved oxygen, chlorophyll, and organic carbon; phyto- plankton communities were similar by day 323.	100 (1st applic.) 155 (2nd applic.)	Hamilton et al. 1988, 1989
Lake mesocosm plankton community	-	-	18 days	Decreased chlorphyll a, dissolved oxygen, nauplii, *Daphnia*, *Cyclops*; increased particulate organ- ic carbon	1	Lampert et al. 1989
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

Table 6 (continued)

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

Table 6 (continued)

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

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
			SALTWATER SPECIES			
Green alga, *Chlamydomonas* sp.	-	30	90 min	EC50 (oxygen evolution)	60	Hollister and Walsh 1973
Green alga, *Chlorella* sp.	-	30	90 min	EC50 (oxygen evolution	143	Hollister and 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

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Chlorococcum* sp.	Technical	30	90 min	EC100 (oxygen evolution)	400	Walsh 1972
Green alga, *Chlorococcum* sp.	80.0%	30	90 min	EC100 (oxygen evolution)	800	Walsh 1972
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, *Chlorococcum* sp.	-	30	90 min	EC50 (oxygen evolution)	80	Hollister and Walsh 1973
Green alga, *Dunaliella tertiolecta*	Technical	30	90 min	EC50 (oxygen evolution)	300	Walsh 1972
Green alga, *Dunaliella tertiolecta*	80.0%	30	90 min	EC50 (oxygen evolution)	600	Walsh 1972
Green alga, *Dunaliella tertiolecta*	Technical	30	90 min	EC100 (oxygen evolution)	700	Walsh 1972
Green alga, *Dunaliella tertiolecta*	80.0%	30	90 min	EC100 (oxygen evolution)	1,000	Walsh 1972
Green alga, *Dunaliella tertiolecta*	Technical	30	10 days	EC50 (growth)	300	Walsh 1972

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Dunaliella tertiolecta*	80.0%	30	10 days	EC50 (growth)	400	Walsh 1972
Green alga, *Dunaliella tertiolecta*	Technical	30	10 days	EC100 (growth)	1,200	Walsh 1972
Green alga, *Dunaliella tertiolecta*	80.0%	30	10 days	EC100 (growth)	1,500	Walsh 1972
Green alga, *Dunaliella tertiolecta*	-	30	90 min	EC50 (oxygen evolution)	159	Hollister and Walsh 1973
Green alga, *Dunaliella tertiolecta*	97%	-	5 days	EC50 (cell number)	170	Hughes 1986; Hughes et al. 1986, 1988
Green alga, *Dunaliella tertiolecta*	97%	-	5 day exposure, 9 day recovery	NOEC (cell numbers)	< 100	Hughes 1986; Hughes et al. 1986, 1988
Green alga, *Dunaliella tertiolecta*	97%	-	5 day exposure, 9 day recovery	Algistatic concentration	1,450	Hughes 1986; Hughes et al. 1986, 1988
Green alga, *Dunaliella tertiolecta*	97%	-	5 day exposure, 9 day recovery	Algicidal concentration	>3,200	Hughes 1986; Hughes et al. 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

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Dunaliella bioculata*	Technical	-	48 hr	35% reduction in growth	216	Pelix et al. 1988
Green alga, *Dunaliella bioculata*	Technical	-	48 hr	85% reduction in growth	3,240	Pelix et al. 1988
Green alga, *Dunaliella bioculata*	Technical	-	48 hr	100% growth inhibition	21,570	Pelix et al. 1988
Green alga, *Nannochloris oculata*	-	15	7 days	21% change in doubling time	50	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	11% change in doubling time	50	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	12% change in doubling time	50	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	34% change in doubling time	50	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	35% change in doubling time	50	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	33% change in doubling time	50	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	42% change in doubling time	50	Karlander et al. 1983; Mayasich et al. 1986

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Nannochloris oculata*	-	15	7 days	35% change in doubling time	50	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	28% change in doubling time	50	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	46% change in doubling time	100	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15.	7 days	35% change in doubling time	100	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	21% change in doubling time	100	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	59% change in doubling time	100	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	52% change in doubling time	100	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	47% change in doubling time	100	Karlander et al. 1983; Mayasich et al. 1986

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
Green alga, *Nannochloris oculata*	-	15	7 days	57% change in doubling time	100	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	56% change in doubling time	100	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	54% change in doubling time	100	Karlander et al. 1983; Mayasich et al. 1986
Green alga, *Nannochloris oculata*	-	15	7 days	change in doubling time	15	Mayasich et al. 1987
Green alga, *Neochloris* sp.	-	30	90 min	EC50 (oxygen evolution)	82	Hollister and Walsh 1973
Green alga, *Platymonas* sp.	-	30	90 min	EC50 (oxygen evolution)	102	Hollister and Walsh 1973
Diatom, *Achnanthes brevipes*	-	30	90 min	EC50 (oxygen evolution)	93	Hollister and Walsh 1973
Diatom, *Amphora exigua*	-	30	90 min	EC50 (oxygen evolution)	300	Hollister and Walsh 1973
Diatom, *Cyclotella nanna*	-	30	90 min	EC50 (oxygen evolution)	84	Hollister and Walsh 1973
Diatom, *Isochrysis galbana*	Technical	30	90 min	EC50 (oxygen evolution)	100	Walsh 1972

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
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
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 and Walsh 1973
Diatom, *Minutocellus polymorphus*	-	-	72 hr	EC50 (cell numbers)	50	Walsh et al. 1988
Diatom, *Monochrysis lutheri*	-	30	90 min	EC50 (oxygen evolution)	77	Hollister and Walsh 1973
Diatom, *Navicula inserta*	-	30	90 min	EC50 (oxygen evolution)	460	Hollister and Walsh 1973
Diatom, *Nitzschia closterium*	-	30	90 min	EC50 (oxygen evolution)	287	Hollister and Walsh 1973

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
Diatom, *Nitzschia* (Ind. 684)	-	30	90 min	EC50 (oxygen evolution)	434	Hollister and Walsh 1973
Diatom, *Nitzschia sigma*	-	20	7 days	Reduced photosynthesis	220	Plumley and Davis 1980
Diatom, *Nitzschia sigma*	-	20	7 days	Reduced chlorophyll and cell number	2,200	Plumley and Davis 1980
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
Diatom, *Phaeodactylum tricornutum*	-	30	90 min	EC50 (oxygen evolution)	100	Hollister and Walsh 1973

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
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, *Stauroneis amphoroides*	-	30	90 min	EC50 (oxygen evolution)	348	Hollister and Walsh 1973
Diatom, *Thalassiosira fluviatilis*	-	20	7 days	Reduced chlorophyll	220	Plumley and Davis 1980
Diatom, *Thalassiosira fluviatilis*	-	20	7 days	Reduced cell number and photosynthesis	2,200	Plumley and Davis 1980
Diatom, *Thalassiosira fluviatilis*	-	30	90 min	EC50 (oxygen evolution)	110	Hollister and Walsh 1973
Red alga, *Porphyridium cruentum*	-	30	90 min	EC50 (oxygen evolution)	79	Hollister and Walsh 1973
Kelp, *Laminaria hyperborea*	-	-	28 days	LOEC (growth of new sporophytes)	10	Hopkins and Kain 1971
Kelp, *Laminaria hyperborea*	-	-	24 hr	LOEC (respiration)	>1,000	Hopkins and Kain 1971
Kelp, *Laminaria saccharina*	70%	30	2 days	No effect on sexual reproduction	33.2	Thursby and Tagliabue 1990
Kelp, *Laminaria saccharina*	70%	30	2 days	66% reduction in fertilization	72.2	Thursby and Tagliabue 1990
Redheadgrass pondweed, *Potamogeton perfoliatus*	-	8-12	2 hr	IC50 (photosynthesis)	77	Jones and Winchell 1984
Redheadgrass pondweed, *Potamogeton perfoliatus*	99.7%	10	4 hr	IC50 (photosynthesis)	80	Jones et al. 1986

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
Euraisian watermilfoil, *Myriophyllum spicatum*	-	8-12	2 hr	IC50 (photosynthesis)	104	Jones and Winchell 1984
Aquatic vascular plant, *zannichellia palustris*	-	8-12	2 hr	IC50 (photosynthesis)	91	Jones and Winchell 1984
Widgeon grass, *Ruppia maritima*	-	8-12	2 hr	IC50 (photosynthesis)	120	Jones and Winchell 1984
Vallisneria, *Vallisneria americana*	-	3	42 days	47% decrease in growth as length, and 48% decrease as dry weight	100	Forney 1980; Forney and Davis 1981
Vallisneria, *Vallisneria americana*	-	6	42 days	27% decrease in growth as length, and 30% decrease as dry weight	100	Forney 1980; Forney and Davis 1981
Vallisneria, *Vallisneria americana*	-	3	42 days	27% decreased in growth as length, and 41% decrease as dry weight	320	Forney 1980; Forney and Davis 1981
Vallisneria, *Vallisneria americana*	-	6	42 days	32% decrease in growth as length, and 29% decrease as dry weight	320	Forney 1980; Forney and Davis 1981
Vallisneria, *Vallisneria americana*	-	5	47 days	67% reduction in leaf production & 76% reduction in leaf area	12	Correll and Wu 1982
Eelgrass, *Zostera marina*	-	-	24 hr	Reduced net oxygen evolution	100	Kemp et al. 1982a
Eelgrass, *Zostera marina*	-	-	24 hr	No net oxygen evolution	1,000	Kemp et al. 1982a

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
Eelgrass, *Zostera marina*	97.2%	14	10 days	100% growth inhibition	1,900	Schwarzchild et al. 1994
Turtlegrass, *Thalassia testudinum*	Technical 99.7%	30	40 hr	EC50 (photosynthesis)	320	Walsh et al. 1982
Salt-marsh grass, *Spartina alterniflora*	97.1%	-	35 days	Increased peroxidase activity	30	Lytle and 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 and Lytle 1988
Salt-marsh rush, *Juncus roemerianus*	97.1%	-	35 days	Reduced chlorphyll a; Increased peroxidase activity and lipid peroxidation products	30	Lytle and Lytle 1998
Salt-marsh rush, *Juncus roemerianus*	97.1%	-	35 days	Reduced shoot growth, chlorophyll a, chlorophyll b; increased lipid peroxidation products	3,800	Lytle and Lytle 1998
Eastern oyster (juvenile), *Crassostrea virginica*	Technical 99.7%	28	96 hr	EC50 (shell growth)	>1,000	Butler 1964; Mayer 1987
Copepod, *Acartia tonsa*	97.1%	30-34	72 hr	LC50	6,100	McNamara 1991b

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
Copepod, *Acartia tonsa*	97.1%	30-34	48 hr	LC50	8,400	McNamara 1991b
Copepod, *Acartia tonsa*	97.1%	30-34	24 hr	LC50	15,000	McNamara 1991b
Brown shrimp (juvenile), *Penaeus aztecus*	Technical 99.7%	30	48 hr	EC50	1,000	Mayer 1987
Brown shrimp, *Penaeus aztecus*	-	-	24 hr	20% mortality	1,000	Butler 1964
Brown shrimp, *Penaeus aztecus*	-	-	48 hr	30% mortality	1,000	Butler 1964
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
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
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	Salinity (g/kg)	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

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)	Reference
Fiddler crab, *Uca pugnax* (animals collected in August 1978)	80%	20	9 days	90% mortality	560,000	Plumley et al. 1980
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
Spot (juvenile), *Leiostomas santhurus*	Technical 99.7%	29	48 hr	LC50	>1,000	Butler 1964; Mayer 1987
Estuarine microbial community	-	7-25	9 days	Effects on phototrophic component - chlorophyll a, carbon assimilation, biovolume, and changes in species composition	40	DeLorenzo et al. 1999a
Estuarine microbial community	97%	-	24 hr	Effects on phototrophic component - chlorophyll a, carbon assimilation, and biovolume	47	DeLorenzo et al. 1999b

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	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	0.12	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	0.56	Bester et al. 1995

Table 6 (continued)

Species	Chemical	Salinity (g/kg)	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	5.80	Bester et al. 1995

[a] Test was run using a Taub and Dollar (1964) medium.
[b] Test was run using an algal assay medium (U.S. EPA 1971).
[c] Algae were pre-conditioned for 4 days with 531 µg/L of atrazine.
[d] Test performed with an atrazine-sensitive strain.
[e] Test performed with an atrazine-resistant strain
[f] Nephelometric determination.
[g] Colorimetric determination.
[h] Only 2.3 to 4.7 percent of this concentration remained on day 7.
[i] Test performed with water from microcosm 30 days after atrazine had been introduced.
[j] Test performed directly with atrazine in water without a microcosm exposure.
[k] EC50 obtained using an algal assay medium.
[l] EC50 obtained using creek water as the test medium.
[m] Animals were fed at 24 hr.
[n] Two single annual applications at nominal concentration indicated.
[o] Atrazine concentrations were below detection after 10 days; however, the study continued for 42 days.

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