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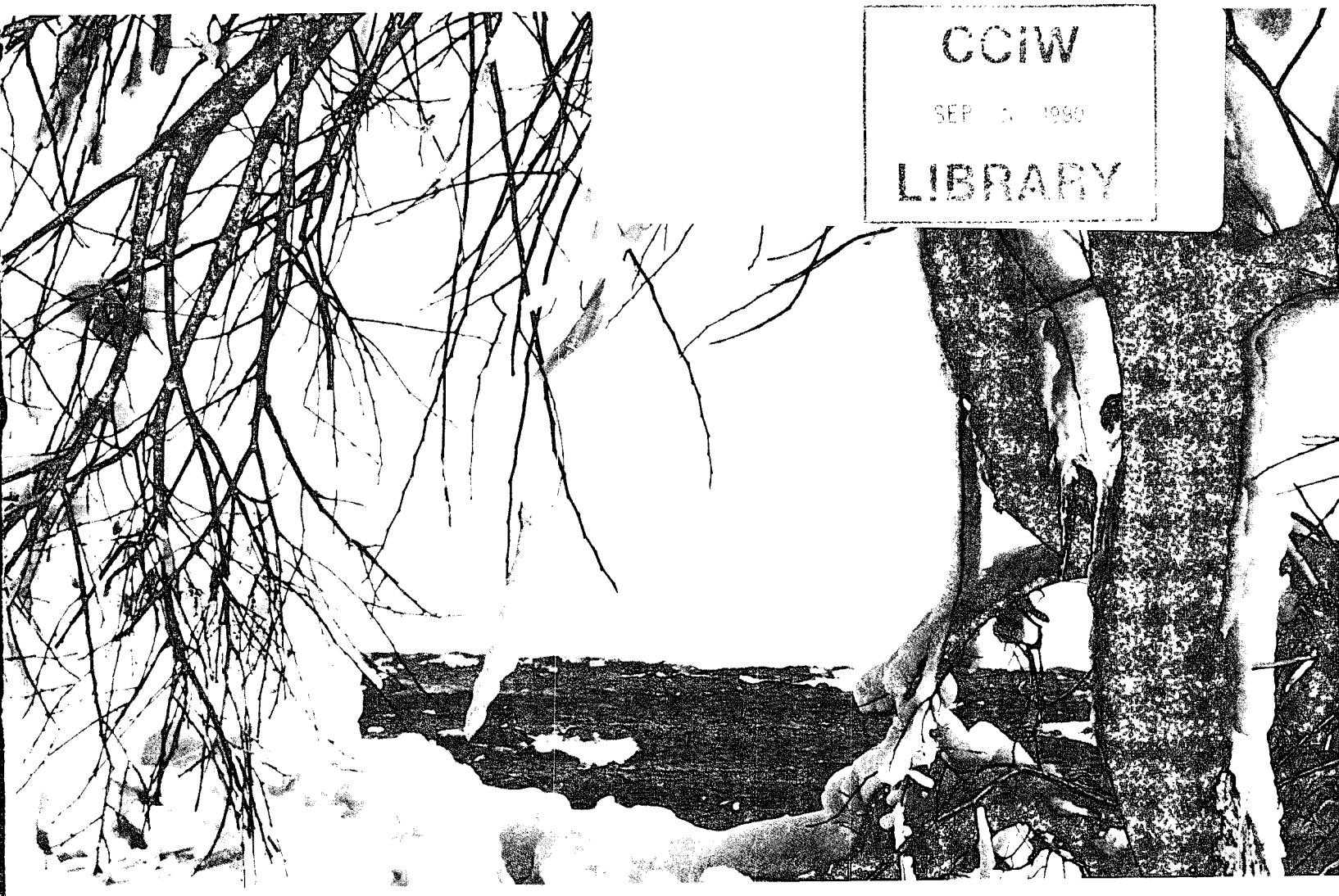
SCIENTIFIC SERIES
168



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Canadian Water Quality Guidelines for Atrazine

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SCIENTIFIC SERIES NO. 168

INLAND WATERS DIRECTORATE
WATER QUALITY BRANCH
OTTAWA, ONTARIO, 1990

(Disponible en français sur demande)

Published by authority of
the Minister of the Environment

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Cat. No. En 36-502/168E
ISBN 0-662-18038-0

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Abstract

A literature review was conducted on the uses, fate, and effects of atrazine on raw water for drinking water supply, freshwater aquatic life, agricultural water uses, recreational water quality and aesthetics, and industrial water supplies. The information is summarized in this publication. From it, water quality guidelines for the protection of specific water uses are recommended.

Résumé

On a examiné la documentation relative aux utilisations, au devenir et aux effets de l'atrazine sur l'eau naturelle utilisée comme eau potable non traitée, sur la vie aquatique en eau douce, sur l'utilisation de l'eau pour l'agriculture, sur la qualité de l'eau pour les loisirs et l'esthétique, ainsi que sur les approvisionnements en eau pour l'industrie. Ces renseignements sont résumés dans cette publication. À partir de cette étude, des lignes directrices sur la qualité de l'eau sont recommandées pour la protection d'utilisations particulières de l'eau.

Canadian Water Quality Guidelines for Atrazine

D.M. Trotter, A. Baril, M.P. Wong, and R.A. Kent

SOURCES, OCCURRENCE, AND CHARACTERISTICS

Uses and Production

Atrazine, which is the common name for 6-chloro-$\underline{N}^2$-ethyl-$\underline{N}^4$-isopropyl-1,3,5-triazine-2,4-diamine (IUPAC) or 2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine (C.A.), is a white crystalline compound with a molecular weight of 215.7 and a molecular formula of $C_8H_{14}ClN_5$. The structural formula of atrazine is shown in Figure 1. The

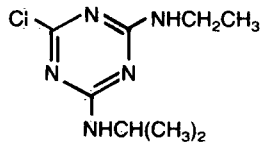

Figure 1. Structural formula for atrazine.

Chemical Abstracts Service Registry Number for atrazine is 1912-24-9. Other synonymous names for atrazine and its various commercial formulations are AAtrex^R, Atazinax, Atranex, Atratol A, Candex, Cekuzina-T, Fenamin, Gesaprim, Inakor, Primatol A, Primaze, Radazin, Vectal, Zeasin, and AAtrex-9-0 (Thomson, 1979; Worthing and Walker, 1983; Weed Science Society of America, 1983).

Atrazine is a selective pre- and postemergence herbicide widely used on agricultural crops including corn, sorghum, sugarcane, and pineapples for the control of annual broadleaf and grassy weeds (Weed Science Society of America, 1983). Other uses include treatment of turf and asparagus, as well as forestry applications. In Canada, there are currently 24 companies marketing 4 domestic and 63 commercial products containing atrazine. Domestic uses include the control of algae in aquariums and ornamental ponds and application as a soil sterilant around driveways, patios, and fencelines. Commercial uses include the control of weeds, mostly grassy types, in corn production and application as a soil sterilant on noncroplands, such as airfields, parking lots, and industrial sites (Environment Canada/Agriculture Canada, 1987).

Atrazine was first introduced in Canada about 1960 to control weeds in corn production. At present, atrazine represents one of the most widely used pesticides in Canada (Environment Canada/Agriculture Canada, 1987). A survey of the amount of pesticides sold to Quebec farmers in 1982 revealed that triazines and triazoles, which include atrazine, were the largest group of pesticides sold, for a total of 570.8 t. Individual pesticides were not quantified in this survey (Environment Canada/Ministère de l'Environnement du Quebec, 1984). In Ontario, a total of 1 729 680 kg of the active ingredient was used in agriculture and on roadsides in 1983. This was the most heavily used pesticide in Ontario that year (McGee, 1984). By 1988, atrazine had dropped to the second most heavily used pesticide in Onario with a total of 1 045 110 kg used that year (Moxley, 1989). The quantities of formulated atrazine herbicide and technical atrazine imported into Canada are shown in Table 1.

Depending on the crop or the intended use, atrazine may be applied as a pre-plant, preemergence, or postemergence herbicide. Rates of 1 to 4 kg-ai·ha^{-1} (ai = active ingredient) are usually recommended. Higher dosages are applied when atrazine is used as a nonselective herbicide. Atrazine is found in liquid, wettable powder, emulsion, and granular formulations.

The principal mode of action of atrazine appears to be the blockage of photosynthesis. Atrazine has been documented to be a potent inhibitor of the Hill reaction and its associated noncyclic photophosphorylation (Ashton and Crafts, 1973; Moreland, 1980). More recent findings suggest that the site of atrazine action in chloroplasts may be the apoprotein of the secondary electron acceptor in photosystem II (Gardner, 1981).

Table 1. Statistics Canada Import Data for Atrazine[1]

Year	1981	1982	1983	1984	1985
Atrazine formulation (tonnes)	2088	1719	2307	3248	5428
Atrazine technical (tonnes)	469	736	407	563	307

[1] From Statistics Canada, 1986.

Note:
Generally, but not always, Statistics Canada records the imports of formulated pesticides and bulk or technical pesticides. Readers should be cautioned about the accuracy of the data. There are two points to remember:

1. The quantities refer to the mass of the product (i.e., not the active ingredient) and likely include solvents and additives (e.g., surfactants). Secondary pesticide active ingredients may also be included.

2. There are often several categories under which a product could be classified. For example, there may be a specific formulated pesticide category, a more general pesticide category (based on the chemical or functional similarity of a group of pesticides), or an even more general chemical or product category, which may include nonpesticides. Therefore, a single category may not reflect the total importation of a particular pesticide.

Physical and Chemical Characteristics

The physical and chemical properties of atrazine are summarized in Table 2. Its solubility in water at 27°C has been reported as 33 $mg \cdot L^{-1}$ (Weed Science Society of America, 1983), but an aqueous solubility of 30 $mg \cdot L^{-1}$ at 20°C has also been widely published (Burkhard and Guth, 1981). Atrazine is stable in slightly acidic or basic aqueous solutions, but is hydrolyzed to hydroxy derivates by alkali or mineral acids (Windholtz et al., 1983).

Table 2: Physical and Chemical Properties of Atrazine

Chemical formula:	$C_8H_{14}ClN_5$[1]
Molecular weight:	215.7[1]
Physical state:	White, crystalline solid [2]
Henry's law constant:	2.45×10^{-7}[3]
Melting point:	173-175°C[2]
Vapour pressure:	3×10^{-7} mm Hg at 20°C[4] 6.9×10^{-6} mm Hg at 25°C[3]
Sediment-water distribution coefficient:	149-163[3]
Octanol water partition coefficient (K_{ow}):	223.9[5] 426.6[6] 3468.0[7] 512.9[3]
Solubility:	
water	70 mg/L at 25°C[4] 33 mg/L at 27°C[2]
ether	12 000 mg/L at 27°C[2]
chloroform	52 000 mg/L at 27°C[2]
methanol	18 000 mg/L at 27°C[2]
Elemental analysis:	C, 44.55%; H, 6.54%; Cl, 16.44%; N, 32.47%[1]
Half-life in soils:	20-48[3]

[1] Windholtz et al., 1983.
[2] Weed Science Society of America, 1983.
[3] Huckins et al., 1986.
[4] Verschueren, 1983.
[5] Metcalfe and Lu, 1977.
[6] Veith et al., 1979.
[7] Chiou et al., 1977.

The n-octanol/water partition coefficient of atrazine estimated by Chiou et al. (1977) was 3468 (log K_{OW} = 3.54). Metcalfe and Lu (1977) and Veith et al. (1979) published log K_{OW} values of 2.35 and 2.63, respectively.

Atrazine in the Environment

Atrazine is usually surface-applied as a pre-emergence spray to cultivated soils. Upon application, atrazine distributes or partitions among the various compartments of the environment in accordance with its physical-chemical properties and environmental conditions. The various processes governing the fate of atrazine in the environment include hydrolysis, adsorption, microbial degradation, volatilization, and photodegradation.

Chemical hydrolysis of atrazine to hydroxyatrazine has been reported as an important pathway of atrazine degradation in soil (Armstrong et al., 1967). The rate of this first order reaction is mainly controlled by soil pH and organic matter content. An increased rate of atrazine hydrolysis was observed in acid soils. Half-lives of 95-165 d, 145-350 d, and 3-5 years were estimated for pHs of 4, 7, and 8, respectively. For soils of similar pH, atrazine degradation rates increased with greater atrazine adsorption. The rate of atrazine degradation by hydrolysis increased as a result of the catalyzing effect of soil adsorption (Burkhard and Guth, 1981). As adsorption increased, the half-life in soil decreased. The effect was attributed to a reversible adsorption process with an equilibrium maintained between solution phase and adsorbed atrazine and hydroxyatrazine. During the course of hydrolysis, hydroxyatrazine was less strongly adsorbed.

Clay, organic matter, temperature, and pH play important roles in the adsorption phenomenon. The K_d value (ratio of quantity adsorbed to quantity in equilibrium solution) for an s-triazine and exchanger was reported to remain relatively constant over a concentration range of 2 to 20 $mg \cdot L^{-1}$ (Talbert and Fletchall, 1965). In addition, the adsorption reaction equilibrated within 1 h. Atrazine adsorption was reversed by increasing temperatures or elution with water. Higher temperature and pH resulted in lower adsorption of atrazine. Increased adsorption occurred with increased concentrations of organic matter or clay, with the organic matter being much more adsorptive. Harris and Warren (1964) also reported organic matter adsorbed more atrazine residues than mineral materials. Desorption of atrazine was found to occur slowly and incompletely on organic soils.

Studies of chemical hydrolysis of atrazine in aqueous fulvic acid, believed to be the major soluble organic fraction in soil solutions, have indicated that half-lives were influenced by the concentrations of fulvic acid, pH, and incubation temperature. A half-life of 742 d was found for a system with low fulvic acid concentration (0.5 $mg \cdot mL^{-1}$) at neutral pH incubated at 25°C. In contrast, a half-life of 0.51 d was observed with 5.0 $mg \cdot mL^{-1}$ fulvic acid at pH 2.4 incubated at 60°C (Khan, 1978).

The significance of volatilization to atrazine dissipation is not fully understood. The available information indicated that volatilization can occur to some extent under conditions of high temperatures and prolonged light exposure (Ghassemi et al., 1981). For example, a 95% loss in 15 h at 60°C versus no loss in 25 h at 25°C from nickel-plated planchets was observed by Foy (1964). Kearney et al. (1964), however, found 80% loss at 25°C and 95% loss at 35°C in 24 h from nickel-plated planchets. Jordan et al. (1965) reported a 5% loss of atrazine in 48 h at 42°C using a similar system.

The volatility of atrazine from glass, plant, and soil surfaces has also been investigated. Temperature, air velocity, initial atrazine concentration, and atrazine purity were factors found to govern volatility. On glass, 70% of the atrazine volatilized after 48 h at an initial concentration of 1 μg compared to 10% at 1000 μg. Higher air velocity caused greater loss at 25°C than at 40°C, but the initial loss at 40°C was 25% greater than at 25°C. A 10% higher atrazine loss occurred with the formulated product compared with the pure technical material. Other data demonstrated that volatilization of atrazine is a major route of dissipation when applied to foliage, but not to soil (Jordan et al., 1970). On soil, volatility losses of atrazine ranged from 18%-32%

at 35°C to 27%-52% at 45°C in 48 h (Kearney et al., 1964). Another study showed only 10% loss in 48 h at 40°C in soil compared with 50% for a plant surface (Burt, 1974).

Levels in Water and Sediment

A large quantity of data has been generated concerning atrazine in surface and subsurface waters and drainage sediments. The existing data can generally be divided into two categories: (1) site-specific field studies in which known amounts of atrazine were applied and the runoff water was sampled over a period of time and (2) watershed monitoring studies consisting of water and sediment samples collected from natural streams and ground water from wells in agricultural areas. These studies are summarized in Appendix A using the review by Wauchope (1978) as a base of information.

The field runoff studies included a wide variety of situations. For example, studies have been conducted of atrazine in tailwater pits receiving runoff from irrigated sorghum and corn fields in Kansas (Kadoum and Mock, 1978) and tile drain water from intensive corn production in Quebec (Muir and Baker, 1976). The maximum water concentrations of atrazine in the tailwater pits were 128 and 250 $\mu g \cdot L^{-1}$ (sorghum and corn fields, respectively). Maximum concentrations of atrazine in the pit bottom soil (sediments) were 132.5 and 369 $\mu g \cdot kg^{-1}$ (sorghum and corn fields, respectively). Unfortunately, atrazine application rates were not stated and no indication was given regarding the length of time these concentrations remained at that level. Atrazine concentrations in the tile drain water sampled from June 1973 to December 1974 averaged 1.2 $\mu g \cdot L^{-1}$, with a maximum value of 10.8 $\mu g \cdot L^{-1}$ in May 1974. Atrazine (AAtrex 90W) applications were made in June of 1973 and 1974 at 2.8 $kg \cdot ha^{-1}$. Two atrazine degradation products (deethylated and deisopropylated atrazine) were also monitored in this study. Average values for deethylated and deisopropylated atrazine were 1.0 and 0.23 $\mu g \cdot L^{-1}$, respectively. Maximum values were 7.71 and 0.78 $\mu g \cdot L^{-1}$, deethylated and deisopropylated atrazine, respectively, and occurred at the same time as the maximum atrazine concentrations. There was no differentiation of dissolved and adsorbed atrazine in this study.

Other atrazine runoff studies have examined the management of atrazine applications (i.e., surface spray or subsoil incorporation), the use of strip cropping, and conventional versus no-tillage field preparation techniques to reduce atrazine loss in runoff water (Triplett et al., 1978a, 1978b; Hall et al., 1983). Methods or techniques that allow the penetration of atrazine into the soil or that restrict the flow of water from atrazine-treated fields were found to reduce atrazine concentrations in the runoff water. Liming of soil increased the loss of atrazine in runoff water, apparently by extending its persistence in soil (Gaynor and Volk, 1981).

Modelling of atrazine losses via surface runoff has been conducted and generally agreed with field collected data, but only within an order of magnitude basis (Haith, 1980). Increasingly complex models have explored the significance of such variables as weather, soil type, and application method and have succeeded in predicting atrazine losses more accurately (Haith, 1986).

Atrazine monitoring studies in the surface waters of Canada have been most intense in the southern Ontario region (Frank et al., 1982). This was due to the extremely large use of atrazine in this area. During the period of 1975-1977, 10 570 kg of atrazine were used in 11 agricultural watersheds in southern Ontario. This resulted in average unit area atrazine losses to natural streams draining these areas of 2250 $mg \cdot ha^{-1} \cdot a^{-1}$ (1975-1976) and 1890 $mg \cdot ha^{-1} \cdot a^{-1}$ (1976-1977). Atrazine was one of the most frequently detected pesticides in the surface waters of this area. The overall mean concentrations of atrazine in the area were 1.1 $\mu g \cdot L^{-1}$ and 1.6 $\mu g \cdot L^{-1}$ for 1975-1976 and 1976-1977, respectively. Highest recorded concentrations were 31.7 $\mu g \cdot L^{-1}$ (1975-1976) and 32.8 $\mu g \cdot L^{-1}$ (1976-1977) (Frank et al., 1982).

Of the 11 agricultural watersheds, approximately 18% were devoted to corn production, and 73% of this production was treated with atrazine at an average rate of 1.7 $kg \cdot ha^{-1}$. Monitoring of atrazine between May 1975 and April 1977 in 11 streams that were potentially impacted by atrazine applications produced mean concentrations of 1.4 $\mu g \cdot L^{-1}$ for atrazine plus deethylatrazine (Frank and Sirons, 1979).

One of the 11 agricultural watersheds, Hillman Creek, was monitored for atrazine and deethylatrazine between May 1973 and February 1975. Atrazine was detected in 89% of the 360 water samples collected from this drainage. The concentrations ranged from trace to 34.7 $\mu g \cdot L^{-1}$. The presence of deethylatrazine was monitored from May 1974 to February 1975 and appeared in 51% of the samples with a maximum concentration of 1.3 $\mu g \cdot L^{-1}$ (Roberts et al., 1979).

Two additional watersheds in southern Ontario, the Grand and Saugeen river basins, were also monitored for atrazine and metabolites. Although the mean concentrations of atrazine plus deethylatrazine at the mouths of the Grand and Saugeen rivers for the period May 1975 to April 1977 were only 0.4 and 0.15 $\mu g \cdot L^{-1}$, respectively, this represented mean annual loads of 903 and 286.5 kg atrazine$\cdot a^{-1}$, respectively (Frank, 1981).

A survey of 92 river mouths (including the Grand and Saugeen rivers) entering the Great Lakes from Ontario found atrazine in 77% of the water samples collected from these rivers from August 1974 to June 1976. The mean atrazine concentration was 1.6 $\mu g \cdot L^{-1}$. A maximum concentration of 26 $\mu g \cdot L^{-1}$ atrazine was accompanied by a maximum deethylatrazine concentration of 4.3 $\mu g.L^{-1}$ from Talbot Creek (Frank, Sirons, and Ripley, 1979; Frank, Sirons, et al., 1979). A detailed compilation of atrazine and other pesticides monitored in the streams and rivers of southern Ontario for the period 1974-1977 was presented by Frank et al. (1978).

The Yamaska River basin (Quebec) and its five subbasins also contained agricultural areas in which atrazine was used. Water samples collected from April to December in 1974 and 1975 in each of the five subbasins showed atrazine and deethylatrazine to range from 0.01 to 26.9 $\mu g \cdot L^{-1}$ and from <0.01 to 1.34 $\mu g \cdot L^{-1}$, respectively. The highest concentrations were found during June and July at all sampling sites (Muir et al., 1978).

Atrazine and atrazine metabolite concentrations in U.S. rivers and streams draining agricultural areas have been reported to be 12 $\mu g \cdot L^{-1}$ (Richard et al., 1975), 4.8 $\mu g \cdot L^{-1}$ (Wall et al., 1978), 23.93 $\mu g \cdot L^{-1}$ (Schepers et al., 1980), 10 $\mu g \cdot L^{-1}$ (Wu et al., 1983), and 23 $\mu g \cdot L^{-1}$ (Butler and Arruda, 1985). These studies are summarized in Appendix A.

Several ground-water studies have demonstrated the presence of atrazine in wells in agricultural areas of Canada, and the U.S.-Canadian investigations have demonstrated well-water contamination as the result of atrazine spills, spray drift, and surface runoff (Frank, Clegg, et al., 1987). A survey of 91 wells in southern Ontario during 1984 showed atrazine residues (range: 0.1-74 $\mu g \cdot L^{-1}$) in 11 wells (Frank, Ripley, et al., 1987). Agricultural areas in the U.S. also have ground-water problems related to atrazine contamination. For example, atrazine contamination was found in 41 monitoring wells (range: 0.01-8.29 $\mu g \cdot L^{-1}$) (Wehtje et al., 1983) and 13 of 268 household and livestock watering wells (range: 0.01-1.2 $\mu g \cdot L^{-1}$) in Nebraska (Exner and Spalding, 1985).

Persistence and Degradation

Degradation of atrazine in soil is the result of microbial action with dealkylation as the primary mechanism (Ghassemi et al., 1981). Biological dealkylation occurs simultaneously with chemical hydrolysis, which favours ring cleavage, and results in total microbial degradation (Goswami and Green, 1971). Chemical hydrolysis of atrazine to hydroxyatrazine (via adsorption to colloids or particulate material) has also received support from a number of studies as the first and most important reaction of atrazine degradation in soils (Skipper et al., 1967, 1978; Russell et al., 1968; Armstrong and Chesters, 1968; Obien and Green, 1969; Roeth et al., 1969).

Compared to soil studies, few field investigations exist of atrazine degradation over time after the application of a known amount of the herbicide to water. In many cases, especially those studies dealing with experimental microcosms, the responses of the various biological components (especially phytoplankton or periphyton) and microcosm functions (e.g., photosynthesis) were

followed over time after the introduction of atrazine. The return to normal or control levels by the particular biological component or function being monitored acted as an indirect, but less accurate, measure of atrazine persistence. In addition, some studies also measured atrazine concentrations in at least one of the microcosm components (usually water). These studies have produced half-life estimates of atrazine in aquatic environments ranging from 3.2 d (Kosinski, 1984) to 3-4 months (Kemp et al., 1985) to 7-8 months (Dewey, 1986).

The very same processes of chemical hydrolysis, microbial degradation, adsorption, volatilization, and photodegradation that act to reduce the persistence of atrazine in the terrestrial environment may also act to reduce the persistence of atrazine in the aquatic environment.

Due to atrazine's known affinity for particulate material, adsorption to suspended particulate material in the water column might be a major factor in its persistence. However, specific data were lacking in this regard. Klaassen and Kadoum (1979) found that atrazine was present in pond water at 2.6 $\mu g \cdot L^{-1}$, 120 d after an initial application of 300 $\mu g \cdot L^{-1}$. The atrazine was extracted from an unfiltered water sample, however, and the amount of atrazine adsorbed to suspended material in the sample was not given.

Colloidal organic matter from an estuarine environment was found to have a high adsorption capacity for atrazine, with a linear Freundlich adsorption constant of 1850. Comparative values for sediments from the estuary ranged from 78 to 213. Normalized for the organic carbon content, colloidal material was 10 to 35 times more adsorptive as a substrate for atrazine than sediment or soil organic matter. The presence of colloids in natural waters was postulated to be important in the transport and distribution of atrazine in aquatic systems (Means and Wijayaratne, 1982; Means et al., 1983).

Atrazine residues are expected to be more persistent in submerged sediments compared to terrestrial soils due to the lower rate of chemical hydrolysis and the slower microbial metabolism of atrazine under anaerobic conditions. The two primary pathways of atrazine degradation in sediments are chemical hydrolysis to hydroxyatrazine and biological dealkylation. Experiments conducted on submerged soils with ^{14}C-labelled atrazine or hydroxyatrazine generally produced either small or undetectable quantities of ^{14}C-labelled CO_2 (Hance and Chesters, 1969; Goswami and Green, 1971). Tests carried out with sediments from a Wisconsin lake, however, showed 4.2% to 6.3% CO_2 evolved from atrazine under anaerobic conditions. Thus under some circumstances, conditions do exist for the anaerobic degradation of atrazine (Hance and Chesters, 1969).

Laboratory experiments using estuarine water and sediment microcosms demonstrated the rapid degradation of atrazine. Initial concentrations of 0.1 $mg \cdot L^{-1}$ in these systems at ambient environmental temperatures (12°C-35°C) and natural sunlight for 80 d resulted in half-lives of 3-12 d (water) and 15-20 d (sediment). Hydroxyatrazine was the dominant short-term metabolite with low dissolved oxygen concentrations having little effect on degradation rate (Jones et al., 1982).

The chemical hydrolysis of atrazine via adsorption was heavily influenced by the adsorption-desorption kinetics of the compound in soil/sediment runoff slurries, which were a common mechanism of atrazine input to natural aquatic systems. Experiments exposing aqueous atrazine solutions to wet sediments and atrazine-contaminated sediments to atrazine-free water demonstrated rapid equilibrium development. In some cases, 75% equilibrium occurred in 3-6 min (Wauchope and Myers, 1985). Thus, when field runoff containing atrazine is released into a natural stream with lower suspended solids, a new equilibrium is rapidly established allowing more atrazine to be desorbed and increasing the amount of atrazine present in the dissolved fraction of the water.

Photodegradation of atrazine in surface waters was shown to be very slow and was not expected to be a significant factor in its removal from water (Ghassemi et al., 1981).

RATIONALE

Raw Water for Drinking Water Supply

Guideline

The interim maximum acceptable concentration (IMAC) for atrazine listed in the Guidelines for Canadian Drinking Water Quality 1987 is 60 $\mu g \cdot L^{-1}$ (Health and Welfare Canada, 1987). This value is based on a negligible daily intake (NDI) of 0.0066 $mg \cdot kg^{-1} \cdot d^{-1}$ established from a 2-year feeding study with dogs (Health and Welfare Canada, 1987). This IMAC is currently under review (G. Wood, 1988, Health and Welfare Canada, pers. com.).

Freshwater Aquatic Life

Accumulation and Elimination of Atrazine in Aquatic Organisms

The uptake of ^{14}C-atrazine by carp (Cyprinus carpio) from aqueous solutions of 1 $mg \cdot L^{-1}$ was found to occur at the rate of 0.16 mg atrazine$\cdot g^{-1}$ of tissue$\cdot h^{-1}$ over 72 h. Atrazine concentrations in the blood, gills, and muscle reflected the external concentration. Accumulation above external concentrations, however, was observed in the liver, kidney, and intestine. The liver tended to accumulate more atrazine than the other organs (four times the external media concentration) (Gluth et al., 1985).

Reported bioconcentration factors (BCFs) from field and laboratory investigations were generally low. Bioaccumulation was not reported for brook trout (Salvelinus fontinalis), fathead minnows (Pimephales promelas), or bluegill sunfish (Lepomis macrochirus) exposed to 0.74 $mg \cdot L^{-1}$, 0.21 $mg \cdot L^{-1}$, and 0.094 $mg \cdot L^{-1}$, respectively, for 43 to 44 weeks (Macek et al., 1976). A BCF of 11 was found for Gammarus affinus exposed to atrazine for 3 d (Metcalfe and Sanborn, 1975). They also reported BCFs of 7.5, 11.0, and 76.0 for snails, fish, and algae, respectively. BCFs of 4.4 and 2.2 were reported for daphnids in water containing 0.01 and 0.08 $mg \cdot L^{-1}$ atrazine, respectively (Ellgehausen et al., 1980). Unicellular algae (e.g., Chlorella) are much more efficient in atrazine uptake than either daphnids or fish (Erb et al., 1980).

Investigations of the mechanism of atrazine accumulation in a freshwater mollusc, Ancylus fluviatilis, and a fish, Coregonus fera, indicated that the majority of atrazine uptake was via the gills and that other body tissues were contaminated by the blood. Atrazine residues in the organs were proportional to their lipid content. BCFs of between 3 and 4 were found for the mollusc and a BCF of 2.8 was determined for the whole fish. Fish accumulated atrazine very rapidly and reached the concentration of atrazine in the water within 1 h (Gunkel and Streit, 1980; Gunkel, 1981). The time required to achieve steady-state conditions for atrazine between water and organism was a function of the atrazine concentration in the water. Lower aqueous atrazine concentrations required shorter time periods for equilibria than higher aqueous concentrations (Ellgehausen et al., 1980).

Depuration occurred mainly via the gills, and depuration half-lives increased with decreased atrazine concentrations in the organism. Depuration of atrazine followed second-order kinetics in the bullhead catfish (Ictalurus melas). A half-life of 26 h was found following exposure to 0.01 $mg \cdot L^{-1}$. Exposure to 0.8 $mg \cdot L^{-1}$ resulted in a half-life of 5 h (Ellgehausen et al., 1980). Metabolism of atrazine prior to elimination in aquatic animals appears to be accomplished mainly by glutathione conjugation and the subsequent production of nontoxic metabolites. Dechlorination of the atrazine molecule, however, was apparently not an important reaction in metabolic alteration (Pillai et al., 1979).

The fate and extent of atrazine bioconcentration/biomagnification in a lake column model ecosystem were investigated at concentrations of 6.8 to 235.7 $\mu g \cdot L^{-1}$. Atrazine was detected in most components of the mixed algae-Daphnia magna-Lebistes reticulata food chain. Reported concentrations in most samples were not much higher than those in water. A maximum bioaccumulation factor of 454 was found for Daphnia exposed to 20.5 $\mu g \cdot L^{-1}$. Residues were not detected, however, in Daphnia from the 12.1-$\mu g \cdot L^{-1}$ or the 125.0-$\mu g \cdot L^{-1}$ treatments. Bioaccumulation factors between 2 and 20 were observed in L. reticulata for the various exposure regimes (Millard et al., 1979).

Exposure to a mean atrazine concentration of 49.54 ± 39.76 $\mu g \cdot L^{-1}$ in a naturally derived model stream ecosystem resulted in BCFs ranging from 0.8 to 96.0 in the crayfish (Orconectes virilis), and from 5.2 to 480 in mayfly nymphs (Baetis sp.). Atrazine residues were not found in the same organisms during the depuration phase of the study (Lynch et al., 1982).

Toxicity to Aquatic Organisms

Extensive toxicity testing using a variety of aquatic organisms has been conducted with atrazine. A summary of the results of these tests is presented in Appendix B. The data base is divided into vertebrates (fish and amphibians), invertebrates, algae, and aquatic vascular plants.

Vertebrates

The response of aquatic vertebrates to acute atrazine exposure varied widely. The 96-h LC_{50} values for fish species ranged from 0.22 to 100 $mg \cdot L^{-1}$. Rainbow trout (Salmo gairdneri) and the guppy (Lebistes reticulata) seemed to be two of the more sensitive North American species, with 96-h LC_{50} values of 4.5 and 4.3 $mg \cdot L^{-1}$, respectively (Bathe et al., 1975, 1976). The tropical harlequin fish (Rasbora heteromorpha) was even more sensitive, with a 24-h LC_{50} of 0.55 $mg \cdot L^{-1}$ (Alabaster, 1969). The 96-h no-observed-effect concentration for the fathead minnow (Pimephales promelas) test species was 8.0 $mg \cdot L^{-1}$ (Macek et al., 1976). The maximum acceptable toxicant concentration derived for the estuarine sheepshead minnow (Cyprinodon variegatus) was >1.9 and <3.4 $mg \cdot L^{-1}$ (Ward and Ballantine, 1985).

The use of early life stages generally reduced the atrazine concentration, which produced significant mortality to <1 $mg \cdot L^{-1}$. For example, channel catfish (Ictalurus punctatus) exposed from the fertilized egg though 96-h post-hatch has an LC_{50} of 0.22 $mg \cdot L^{-1}$ (Birge et al., 1979, 1983). Brook trout (Salvelinus fontinalis) fry showed increased mortality at 0.24 $mg \cdot L^{-1}$, while adult mortality was unaffected by 0.72 $mg \cdot L^{-1}$ during 44 weeks of exposure (Macek et al., 1976). The longest known exposure period (18 months) demonstrated that bluegill sunfish (Lepomis macrochirus) were not affected in survival, growth, or hatching in 0.095 $mg \cdot L^{-1}$ (Macek et al., 1976).

Atrazine at a concentration of 100 $\mu g \cdot L^{-1}$ significantly increased serum glucose at 6-h and 24-h exposures and serium cortisol at 24-h and 72-h exposures in carp (Cyprinus carpio). Significant decreases were observed in serum protein, serum cholesterol, and liver glycogen at 72-h exposures. These reactions were considered toxic effects of the atrazine exposure (Gluth and Hanke, 1985).

Invertebrates

The toxicity of atrazine during acute exposures varied tremendously among invertebrate species with 48-h LC_{50}s ranging from <1 to >30 $mg \cdot L^{-1}$. The most sensitive invertebrate appeared to be the midge larvae (Chironomus tentans), with a 48-h LC_{50} of 0.72 $mg \cdot L^{-1}$ (Macek et al., 1976). Exposure of this species to 0.23 $mg \cdot L^{-1}$ for two generations caused reduced hatching success, increased larval mortality, retarded development, and reduced rates of pupation and emergence. The no-observed-effect level for the same exposure time was 0.11 $mg \cdot L^{-1}$ (Macek et al., 1976). A similar concentration (0.14 $mg \cdot L^{-1}$) produced reproductive effects and impaired offspring survival during 119-d exposures for the scud (Gammarus fasciatus) (Macek et al., 1976).

Algae

Concern over atrazine's mode of action in terrestrial plants (the inhibition of photosynthesis) has led to numerous studies on both macro- and microscopic algae. The rationale for these studies was that changes in the base of the food chain and the autotrophic component of aquatic ecosystems could have profound effects at much higher trophic levels (i.e., fish), which would not be as sensitive to the effects of the same atrazine exposure. Given atrazine's mode of action, it was not unexpected that very low concentrations were detrimental to the relatively simple, autotrophic plants making up phytoplankton and periphyton. Twenty-four-hour EC_{50}s (based on the inhibition of ^{14}C-labelled HCO_3^- uptake) ranged from 0.019 to 0.325 $mg \cdot L^{-1}$ (Larsen et al., 1986). Chlorophyll levels have often been used as biomass estimators

in algal atrazine toxicity tests. The use of this response variable is somewhat problematic since a consistent response pattern does not exist for aquatic plants and atrazine. Atrazine is known to both significantly reduce and stimulate photosynthetic pigment levels in aquatic plants exposed to sublethal concentrations.

A species of blue-green algae experienced more than a 90% inhibition of chlorophyll production during 7-d exposures of atrazine as low as 0.001 $mg \cdot L^{-1}$ (Torres and O'Flaherty, 1976). Conversely, chlorophyll accruals of 3X control levels were measured in algal microcosms exposed to 0.04 $mg \cdot L^{-1}$ (Larsen et al., 1986). Similar augmentations of up to 5X that of control levels were reported in aquatic macrophytes exposed to atrazine levels ranging from 0.13 to 1.2 $mg \cdot L^{-1}$ (Cunningham et al., 1984).

The toxicity of the hydrolytic and metabolic products of atrazine have been shown to be less toxic to algae than the parent compound, with decreasing toxicity demonstrated by deethylated atrazine, deisopropylated atrazine, diaminoatrazine, and hydroxyatrazine, in that order (Stratton, 1984).

Atrazine has been used experimentally as an aquatic herbicide in unused fish hatchery ponds in the southern U.S. to reduce filamentous algae development. Introduction of atrazine to a final concentration of 1 $mg \cdot L^{-1}$ provided control of filamentous algae, Pithophora, and an aquatic vascular plant, Najas guadalupensis. The blue-green planktonic alga Microcystis was replaced with a more desirable algal species (not given) within 1 week after 0.08-$mg \cdot L^{-1}$ atrazine treatment (Pierce et al., 1965).

Simple, algal growth inhibition tests (Burrell et al., 1985) conducted with unicellular chlorophytes reported the lowest EC_{50} for growth (based on 11-d standing crop estimates) as 25.0 $\mu g.L^{-1}$ for Chlorella vulgaris. Differential algal sensitivity to atrazine was apparent in experiments on primary productivity (Larsen et al., 1986). A complement of eight species of green and blue-green algae produced a range of EC_{50}s (^{14}C uptake following 24-h exposure) from 19 to 325 $\mu g \cdot L^{-1}$. The lowest mean value was an EC_{50} of 37.0 $\mu g \cdot L^{-1}$ for Chlamydomonas reinhardtii.

Aquatic Vascular Plants

As with algae, the concern over the effect of atrazine in surface runoff water on aquatic species extends to aquatic vascular plants. A summary of these investigations is given in Appendix B. Generally, these studies have focused on atrazine uptake by aquatic vascular plants using ^{14}C-labelled atrazine. Atrazine has been demonstrated to be taken up rapidly from water (equilibrium reached in 15 min) at atrazine concentrations ranging from 20 to 50 $\mu g \cdot L^{-1}$. Shoot tissue was more effective in atrazine uptake than rhizome tissue for submerged or floating leaved species (Jones et al., 1986). Atrazine adsorbed to soil particles and deposited on leaf surfaces was much less available to shoot and leaf tissue than dissolved atrazine (Jones and Estes, 1984). By contrast, other species (i.e., Spartina alterniflora, an emergent) exhibited rapid uptake of atrazine by the roots and translocation to the shoots. This species was much more resistant to the toxic effects of atrazine by virtue of its ability to rapidly metabolize the compound (Pillai et al., 1977).

Because the mode of action of atrazine is directed toward blocking an essential photosynthetic reaction, most of the studies have monitored photosynthetic related parameters (e.g., oxygen production, inorganic carbon uptake, chlorophyll content). Other measurements of toxic response have involved the adenosine triphosphate and total adenylate content of atrazine-exposed tissues (Delistraty and Hershner, 1984); microscopic observations of cellular activity (Beaumont et al., 1980; Dabydeen and Leavitt, 1981); whole plant mortality and morphological measurements of tissue growth (i.e., shoot length, number of leaves, etc.) (Forney and Davis, 1981); and changes in lipid metabolism (Grenier et al., 1979; Grenier and Beaumont, 1983). It is evident from the various studies with aquatic vascular plants that dissolved atrazine concentrations as low as 77 $\mu g \cdot L^{-1}$ caused significant photosynthetic inhibition in some plants. The inhibition increased with increasing atrazine concentrations and followed Michaelis-Menton kinetics. Nonlethal photosynthetic inhibition was apparently reversible once exposure ceased due to a combination of atrazine release from the plant and/or atrazine

metabolism by the plant. Atrazine metabolites apparently did not play a major role in photosynthetic inhibition (Jones and Winchell, 1984).

Aquatic Microcosm Studies of Atrazine Toxicity

In addition to the species-specific atrazine toxicity studies summarized in Appendix B, the published literature contained a number of reports on the effects of atrazine additions to laboratory and field microcosms. These various studies, summarized in Appendix C, exhibit considerable variation in the number of species and ecosystem components present as well as the types of aquatic ecosystems for which simulation was attempted.

It is clear from reviewing these studies that the introduction of atrazine had an immediate and significant effect on autotrophic organisms. In phytoplankton assemblages, these effects were manifested as reductions in oxygen production, inorganic carbon uptake, and changes in species composition. The magnitude of the effects was generally proportional to the quantity of atrazine added and the number of exposures. Concentrations in the range of 25 to 60 $\mu g \cdot L^{-1}$ generally produced an effect that, after a single dose, was followed by recovery (in 5-7 d) to pre-dose levels (de Noyelles et al., 1982). Higher single doses required longer periods for recovery (e.g., 500 $\mu g \cdot L^{-1}$ could require 24 d) (de Noyelles et al., 1982).

Aquatic vascular plants responded to atrazine additions by reactions related to the impairment of their photosynthetic apparatus. Because of their size, observation of mortality were easier to follow than in the microscopic phytoplankton. Significant mortalities (50%-100%) in aquatic vascular plant biomass have been reported after single exposures to atrazine concentrations in excess of 1000 $\mu g \cdot L^{-1}$ and as little as 12 $\mu g \cdot L^{-1}$ (Correll and Wu, 1982). Annual additions of atrazine, during a 3-year period, for a final concentration of 20 $\mu g \cdot L^{-1}$, reduced macrophyte coverage in experimental ponds by about 90% (Kettle et al., 1987).

Invertebrate populations in atrazine-dosed microcosms also exhibited changes, although the exact atrazine concentration promoting these changes appeared to vary widely. Whereas a single dose resulting in a concentration of 1000 $\mu g \cdot L^{-1}$ had no effect on Daphnia magna in a wetland/marsh microcosm (Johnson, 1986), the same species was eliminated from a lake water column simulation by three additions of atrazine (within 5 d), producing a final concentration of 221.4 $\mu g \cdot L^{-1}$ (Millard et al., 1979). Experimental pond zooplankton community structure was found to be altered as a result of atrazine-induced changes in the phytoplankton community (at 20 $\mu g \cdot L^{-1}$). Benthic insect community structure was also altered by 20 $\mu g \cdot L^{-1}$. These changes in invertebrate populations apparently reduced reproduction by bluegill sunfish (Lepomis macrochirus), in the same experimental ponds, which received a single dose of 20 $\mu g \cdot L^{-1}$ during one growing season (Kettle et al., 1987).

In reviewing the various microcosm studies, it was difficult to find atrazine concentrations that did not produce an effect. Atrazine concentrations of 10 and 100 $\mu g \cdot L^{-1}$ had varying effects on the individual components of prairie wetland microcosms during 30-d exposures (Johnson, 1986). There was no evidence that daphnid survival, growth, or reproduction was influenced by 10 or 100 $\mu g \cdot L^{-1}$ atrazine. These same concentrations also had no effect on submerged macrophyte or phytoplankton growth. However, aquatic community gross primary productivity was significantly reduced (23%) at a 10-$\mu g \cdot L^{-1}$ exposure. Recovery from the effects of a single 10-$\mu g \cdot L^{-1}$ dose of atrazine for this parameter was rapid (7 d).

Microcosms receiving a continuous input of atrazine to final concentrations of 0.5 and 5.0 $\mu g \cdot L^{-1}$ did not differ significantly from controls in oxygen production. As well, the communities making up the microcosms (filamentous algae, rotifers, and nematodes) all appeared healthy at 50 $\mu g \cdot L^{-1}$. Although oxygen production decreased as atrazine was slowly increased to a concentration of 50 $\mu g \cdot L^{-1}$, dilution of this concentration to below 10 $\mu g \cdot L^{-1}$ resulted in an immediate and total recovery of oxygen production (Brockway et al., 1984).

Estuarine microcosms using sediments and two species of aquatic vascular plants showed that 5 $\mu g \cdot L^{-1}$ atrazine produced significant depression

(22%) of dissolved oxygen in the water with Potamogeton perfoliatus after 2-3 weeks of exposure. Recovery to control levels occurred during week 4. The controls for the solvent carrier (methanol) also exhibited a significant decrease in dissolved oxygen during week 2. This fact makes the significance of the response to 5 $\mu g \cdot L^{-1}$ atrazine questionable. The same concentration caused significant enhancement (20%) of apparent photosynthesis in Myriophyllum spicatum (Kemp et al., 1985).

Acutely toxic values for aquatic plants were reported as low as 12.0 $\mu g \cdot L^{-1}$ (47-d LC_{50}) for the sensitive macrophyte Vallisneria americana (Correll and Wu, 1982). These tests were, however, conducted in estuarine microcosms where salinity levels differed from the source waters of the test plants and thereby may have provided an additional stress factor. In comparison, chronic, nonlethal levels of atrazine (EC_{50}, growth) for the same species under freshwater conditions ranged from 163 to 532 $\mu g \cdot L^{-1}$ (Forney and Davis, 1981).

In their efforts to provide a more environmentally relevant whole-system assessment of risk, model ecosystems studies have also contributed to the considerable variability in the data regarding the effects of atrazine on phytoplankton growth and community dynamics. A lower limit of 20 $\mu g \cdot L^{-1}$ was apparently sufficient to alter algal succession in artificially seeded ponds indirectly through differential growth and photosynthetic inhibition (deNoyelles et al., 1982). Other mesocosm studies indicated that levels of 20-25 $\mu g \cdot L^{-1}$ had no significant impact on algal assemblages in experimental ponds (Larsen et al., 1986) or on standing crop and gross primary productivity estimates in periphytic model stream communities (Lynch et al., 1982). In a recent model ecosystem investigation of atrazine toxicity, artificial floating substrates were used to measure structural (species numbers and biomass) and functional (colonization rates, O_2 production, protein and nutrient levels) responses of naturally derived microbial communities (Pratt et al., 1988). Oxygen production and the ability of communities to sequester magnesium and calcium were the most sensitive indicators of atrazine stress. Based on NOELs and LOELs derived from these endpoints, the lowest MATC was calculated to be 17.9 $\mu g \cdot L^{-1}$ atrazine.

Guideline

The fish toxicity data base for atrazine comprised 18 fish species, 35 acute toxicity tests (i.e., 96-h exposures or less), and 11 chronic studies. Of the 35 acute tests, 8 were conducted with North American freshwater salmonid species. The remainder used other North American freshwater species (18 tests), North American estuarine and marine species (3 tests), and freshwater European (5 tests) and tropical (1 test) species. Of the 11 chronic studies, 3 used North American freshwater salmonid species. The remainder of the chronic tests used other North American freshwater species. In addition to the fish toxicity data, chronic data were also available for several species of North American amphibians for the spawning to post-hatch portion of the life cycle.

A wide variety of invertebrate acute and chronic toxicity data was available in the scientific literature, although individual species designations and exposure times were not always given. Considering only those cases where both the species and exposure time were identified, 17 acute and 9 chronic toxicity tests were found that used either freshwater or estuarine invertebrates. Of the 17 acute toxicity tests, 5 used the freshwater zooplankter Daphnia, 2 tests used the midge larvae Chironomus, and 1 test used the amphipod Gammarus. These same species were also used in four chronic studies.

An extensive data base was available for various types of freshwater and estuarine algae for acute and chronic exposures to atrazine. A much smaller amount of data was available for aquatic vascular plants. Reports of the effects of atrazine on algae were found for 24 species, where both the species or genus and exposure times were given for a total of 56 tests. Thirty-three of these tests dealt with the effect of chronic (i.e., greater than 96 h) exposure to atrazine, while 23 tests reported the effects of acute exposure. Nine species of aquatic vascular plants were used for experiments dealing with the effects of atrazine exposure. Of the 14 tests reported, 6 used acute exposures and 8 used chronic exposures.

Along with the aforementioned single species toxicity testing data, the scientific literature also contained several microcosm studies of the

effects of atrazine on aquatic ecosystems. Thirty-two such studies were found in the literature review, with several publications devoted to various aspects of the same microcosm study.

The toxicity data reviewed were of sufficient quality and quantity to define a Canadian water quality guideline for the protection of aquatic life. Included in the toxicity information already discussed were nonlethal responses to chronic atrazine exposure for the bluegill (Lepomis macrochirus) and the brook trout (Salvelinus fontinalis) (Macek et al., 1976). The response of fish early life stage to chronic atrazine exposure was reported by Birge et al. (1979, 1983). The effects of chronic exposure to atrazine on the hatching success, larval mortality and development, rate of pupation, and emergence in two generations of the midge larvae (Chironomus tentans) were reported by Macek et al. (1976). Several maximum acceptable toxicant concentrations (MATCs) were developed from chronic studies using soft water. Estimates of MATCs ranged from 0.09 to 0.50 $mg \cdot L^{-1}$ for the bluegill (L. macrochirus), 0.21 to 0.52 $mg \cdot L^{-1}$ for the fathead minnow (Pimephales promelas), and 0.06 to 0.12 $mg \cdot L^{-1}$ for the brook trout (S. fontinalis). MATCs for invertebrates were estimated to be in the range of 0.11 to 0.23 $mg \cdot L^{-1}$ for the midge larvae (C. tentans), 0.14 to 0.25 $mg \cdot L^{-1}$ for Daphnia, and 0.06 to 0.14 $mg \cdot L^{-1}$ for the amphipod Gammarus fasciatus (Macek et al., 1976).

The quality of the experiments (i.e., controls, test tank measurements of atrazine, test organism loadings per test chamber, etc.) was sufficiently documented and conformed to accepted practice to support the validity of the resulting data.

The MATC boundary limit, 0.06 $mg \cdot L^{-1}$ or 60 $\mu g \cdot L^{-1}$ for the brook trout (S. fontinalis), wascausing detrimental effects to fish or aquatic invertebrates for acute and chronic exposures. Detrimental effects of algal growth were reported at this and lower concentrations, however, for freshwater and estuarine algal species (Torres and O'Flaherty, 1976; Véber et al., 1981; Correll and Wu, 1982; deNoyelles et al., 1982; Maule and Wright, 1984; Stratton, 1984; Burrell et al., 1985; Larsen et al., 1986; Mayasich et al., 1986; Turbak et al., 1986; Pratt et al., 1988). Significant mortality at 53 $\mu g \cdot L^{-1}$ and reduction in the number of leaves at 60 $\mu g \cdot L^{-1}$ were also reported for aquatic vascular plants (Forney and Davis, 1981; Hershner et al., 1983).

Most of the evidence showed that while 60 $\mu g \cdot L^{-1}$ would protect fish and aquatic invertebrates from the direct toxic effects, this concentration had the potential to cause detrimental effects to the algal and aquatic vascular plant components of the aquatic ecosystem. Such an impact could cause indirect effects to fish and aquatic invertebrates. This potential was supported by large-scale (pond) macrocosm experiments (deNoyelles et al., 1982; deNoyelles and Kettle, 1985; Dewey, 1986; Kettle et al., 1987) as well as smaller microcosm studies and single species tests (Correll and Wu, 1982; deNoyelles and Kettle, 1985; Stay et al., 1985; Larsen et al., 1986; Pratt et al., 1988). Similar reactions were reported for all systems when exposed to comparable concentrations of atrazine. The results of these experiments demonstrate that atrazine concentrations below 20 $\mu g \cdot L^{-1}$ are potentially detrimental to aquatic ecosystems. Other microcosm studies using low concentrations of atrazine have demonstrated (1) reduced gross primary productivity at 10 $\mu g \cdot L^{-1}$ (Johnson, 1986); (2) no decreased oxygen production at 5 $\mu g \cdot L^{-1}$ (Brockway et al., 1984); and (3) significant decreases in oxygen production by a species of macrophyte and significant enhancement by another species of macrophyte at 5 $\mu g \cdot L^{-1}$ (Kemp et al., 1985).

Thus, on the basis of toxicity studies with algae and aquatic vascular plants, 60 $\mu g \cdot L^{-1}$ could not be used for guideline development. In order to conform to the original intent of CCREM Canadian Water Quality Guidelines, the freshwater aquatic life guideline for atrazine must be designed to be protective of primary producers as well as consumers. In cases where several comparable MATCs are available on a pesticide, a safety factor of one order of magnitude is applied to the most sensitive maximum acceptable toxicant concentration (CCREM, 1987). Therefore, the MATC of 17.9 $\mu g \cdot L^{-1}$ (Pratt et al., 1988) was used to derive the guideline of 1.79 or 2.0 $\mu g \cdot L^{-1}$ for the protection of freshwater aquatic life.

Agricultural Uses

Livestock Watering

Toxicity, Uptake, Metabolism, and Depuration

A summary of avian toxicity data is presented in Appendix D, Table D-1. Generally, atrazine ingestion was not very toxic to birds and was reflected in LC_{50} values ranging from 700 to 19 650 $mg \cdot L^{-1}$ body weight for 5- to 7-d exposures. Although significant concentrations of atrazine remained in abdominal fat after cessation of exposure, chickens had the ability to metabolize atrazine by at least two separate pathways: N-dealkylation at the ethylamino group and hydrolysis of the ring-bound chlorine. These pathways produced deethylatrazine and hydroxyatrazine, respectively. Subsequent hydrolysis and N-dealkylation of these metabolites produced deethylhydroxyatrazine (Khan and Foster, 1976). Subsequent in vitro atrazine metabolism studies using chicken liver homogenates confirmed the presence of enzyme systems capable of dechlorinating the atrazine molecule to produce hydroxyatrazine (Foster et al., 1979).

Atrazine as an aqueous emulsion applied to fertile mallard (Anas platyrhynchos) eggs at 449 $g \cdot L^{-1}$ failed to produce sufficient toxicity for calculations of an LC_{50} and was one of the least toxic of 14 common agricultural herbicides tested by Hoffman and Albers (1984). As well, malformations at hatching or reduced growth were not observed among the treated embryos.

Mammalian toxicity data are summarized in Appendix D, Table D-2. While toxicity studies were conducted on domestic cattle and sheep, there is an absence of data for mammalian wildlife. The results of the available testing demonstrated low atrazine toxicity to mammals. Single acute oral dosages ranged from 1400 to 5100 $mg \cdot kg^{-1}$ body weight for rats and mice. Intraperitoneal injections produced much greater toxicity (i.e., LD_{50} = 125 $mg \cdot kg^{-1}$). The lethal dose for atrazine ingestion by cattle was reported to be two doses of 250 $mg \cdot kg^{-1}$ within 24 h (Palmer and Radeleff, 1964). Smaller doses produced reversible intoxication (Kobel et al., 1985).

Chronic oral intakes of 100 $mg \cdot kg^{-1}$ (for 21 d) and 760 $mg \cdot kg^{-1}$ (for 4 weeks) failed to induce significant adverse effects in cattle. Female sheep, however, were killed by daily dosages of 30 $mg \cdot kg^{-1}$ in 36 to 60 d (Binns and Johnson, 1970). Other routes of exposure (i.e., dermal and inhalation produced much less toxicity than oral intake (Geigy Agricultural Chemicals 1971a, 1971b).

Ingested atrazine was absorbed by the mammalian gastrointestinal tract, underwent limited metabolic alteration, and was excreted from the body mainly via the kidneys. In vivo metabolic studies of rats demonstrated that 85.8% of a single dose of atrazine was excreted from the body after 72 h. Of the atrazine remaining in the body after 72 h, liver, kidney, and lung tissue contained the highest concentrations of metabolites (Bakke, Larson et al., 1972). Various metabolic alterations of the parent atrazine molecule occurred in both in vivo and in vitro studies. Three points of attack for atrazine metabolism have been studied: (1) elimination of the isopropyl group at the 6 position of the carbon ring; (2) elimination of the ethyl group at the 4 position; and (3) elimination of the chlorine atom at the 2 position. Elimination of either the isopropyl or ethyl groups (N-dealkylation) appeared to be the first major metabolic alteration, with elimination of the isopropyl group favoured over the ethyl group (Dauterman and Muecke, 1974; Khan et al., 1979). The carbon-chlorine bond appeared to be stable in mammalian systems and did not undergo hydrolysis. Subsequent reactions of the parent compound or its dealkylated metabolite involved conjugation reactions with glutathione prior to elimination from the body or further metabolism (Dauterman and Muecke, 1974). Absorption of atrazine residues in plant material ingested by mammals was demonstrated to be very small (Bakke, Shimabukuro, et al., 1972). A detailed review of atrazine metabolism (and the metabolism of other triazine herbicides) was presented by Esser et al. (1975).

Mutagenicity, Teratogenicity, and Carcinogenicity

The mutagenicity of atrazine has been studied with a wide variety of different microbial, animal, and plant systems. Generally, these studies showed atrazine to be nonmutagenic both with and without

metabolic activation by animal systems (U.S. Department of Agriculture, 1984).

Salmonella typhimurium and Escherichia coli bacteriophage T_4 and T_4 mutant assays conducted by Andersen et al. (1972), Simmon et al. (1977), Loprieno and Adler (1980), and Seiler (1973) all produced negative results. A single report of atrazine mutagenicity in S. typhimurium (Njagi and Gopalan, 1980) was not sufficiently documented for an evaluation of the results.

Other microbial systems employed Saccharomyes cerevisiae, Aspergillus nidulans, E. coli, Schizosaccharomyces pombe, and Streptomyces coelicolor. While atrazine was nonmutagenic to S. cerevisiae, either as the parent compound or after mammalian metabolic activation (deBertoldi et al., (1978, 1980; Marquardt, 1980), mutagenic reactions were reported with atrazine-treated maize plant extracts (Plewa and Gentile, 1976).

The report of atrazine mutagenicity to E. coli (Solt and Neale, 1980) in a host-mediated system (i.e., mice orally dosed with atrazine and injected intravenously with E. coli) was not sufficiently documented for a critical evaluation of results. Another report on host-mediated mutagenicity (deBertoldi et al., 1978) concluded that atrazine was not mutagenic in host-mediated systems.

Atrazine was both mutagenic and nonmutagenic to A. nidulans depending on assay end point (i.e., antibiotic resistance, mitotic cross-over, mitotic gene conversion) and whether or not atrazine had been activated by plant enzyme systems (Carere and Morpugo, 1981). Positive mutagenic responses for atrazine have been reported for S. pombe and S. coelicolor in the presence of plant microsomes or atrazine-treated mouse liver microsomes (Loprieno and Adler, 1980).

Mutagenic responses in atrazine-exposed fruit flies (Drosophila melanogaster), as reported by Murnik and Nash (1977) and Loprieno and Adler (1980), are ambiguous, and definite conclusions using this organism cannot be reached.

Mammalian cell systems (i.e., Chinese hamster cells, mouse bone marrow cells, EUE human cells) also gave ambiguous results in atrazine-induced mutation assays reported by Loprieno and Adler(1980), Sobels et al. (1980), Ehling (1980), and Loprieno et al. (1979).

Much more uniform mutagenic responses were obtained with plants (i.e., barley and maize). Atrazine solutions of 10 and 20 $mg \cdot L^{-1}$ produced sister chromatid exchanges in maize seedling roots (Chou and Weber, 1981). This effect was apparently due to metabolic alteration of the atrazine by the plant. Other chromosomal aberrations were also reported by Wuu and Grant (1966a, 1966b; 1967) and Plewa and Gentile (1976). Although it was very probable that atrazine itself was not a bacterial mutagen, the possibility remained that plant and animal metabolites of atrazine were mutagenic in bacteria and other procaryotes (Grutman et al., 1984).

Teratogenic responses to atrazine were not observed in laboratory studies. Dietary concentrations up to 1000 $mg \cdot kg^{-1}$ had no effect on pregnant rats or their offspring. Subcutaneous injections of atrazine up to 200 $mg \cdot kg^{-1}$ in pregnant rats also had no effect on the number of pups per litter. Higher doses (i.e., 800 $mg \cdot kg^{-1}$) were embryotoxic, generally resulting in resorptions of the embryos (Peters and Cook, 1973). Teratogenic effects were also absent from pregnant mice orally dosed with 46.4 $mg \cdot kg^{-1}$ from day 6 through day 14 of gestation (Mrak, 1969). Pregnant ewes treated with 15 $mg \cdot kg.^{-1}$ atrazine through pregnancy and 30 d after birth, delivered and nursed apparently normal lambs (Binns and Johnson, 1970).

Long-term (18-month) carcinogenic bioassays using two hybrid strains of mice given the maximum tolerated oral atrazine dose (21.5 $mg \cdot kg^{-1}$) failed to develop a significant increase in tumors compared with controls (Innes et al., 1969). A report of induced cancer by subcutaneous injections of an atrazine-simazine mixture (Donna et al., 1981) was not of sufficient quality for conclusions to be drawn regarding atrazine carcinogenicity.

Guideline (Interim)

The existing toxicity data for birds and mammals (Appendices D and E, respectively) show that atrazine is not very toxic to livestock. It

is significant that all the studies summarized in Appendices D and E used atrazine-treated feed or oral doses (i.e., gavage) to expose the animals to atrazine via the gastrointestinal tract. None of the studies used atrazine-treated drinking water. The reason for this is not known, but could be related to the inability of lethal exposures to occur via normally available drinking water.

The sheep data of Binns and Johnson (1970) presented one of the lowest doses on a kilogram per day basis available in the published literature, but these data were not based on water consumption. Other studies (e.g., Peters and Cook, 1973; Suschetet et al., 1974) gave concentrations of atrazine in feed, but without sufficient information on daily intake for use in developing a guideline.

Derivation of a guideline for livestock watering requires valid, chronic toxicity and accumulation data for livestock consuming atrazine in their drinking water. This type of information was not available, however, so it was necessary to derive a guideline for livestock watering from the CCREM (1987) policy to use the guideline for pesticides in raw water for drinking water supply. This policy provides a margin of safety for livestock and prevents unacceptable residues in animal products (CCREM, 1987). As an interim guideline was available for atrazine in raw water for drinking water supply, 60 $\mu g \cdot L^{-1}$, this value is recommended as the interim guideline for livestock watering.

Irrigation

Atrazine residues in irrigation water have the potential to have an adverse impact on crops by way of transport through the soil (row irrigation) and subsequent root uptake or by transport through the air (sprinkler irrigation) with subsequent uptake by the foliage. The extreme sensitivity of the photosynthetic apparatus in plants to the action of atrazine has been previously discussed in the sections concerning algal and aquatic vascular plant toxicity as well as in the discussion of atrazine's effect on microcosms.

The specific mode of action of atrazine coupled with its occurrence in water prompted the U.S. EPA to suggest that atrazine and triazine herbicides in general should have stringent limitations on their presence in irrigation water (i.e., 10 $\mu g \cdot L^{-1}$) (U.S. EPA, 1977).

The presence of atrazine in irrigation water can occur as the result of irrigation return flows(i.e., drainage from atrazine-treated fields). The concentrations of atrazine recorded in runoff from treated fields were previously discussed (Levels in Water and Sediment). The use of atrazine in irrigation canals for weed suppression also poses a threat to irrigated crops.

A study conducted in Saskatchewan showed that atrazine applied in dry irrigation ditches for weed control at 22.4 $kg \cdot ha^{-1}$ in September resulted in atrazine residues in the irrigation water the following summer. Initial water ponding in the ditches in June resulted in mean atrazine concentrations of 240 ± 100 $\mu g \cdot L^{-1}$. Additional water samples taken during the first irrigation of the season resulted in mean atrazine concentrations of 45 ± 20 $\mu g \cdot L^{-1}$. Two years later, atrazine was still present in irrigation ditch water at 19 ± 2 $\mu g \cdot L^{-1}$. The authors of the study (Smith et al., 1975) concluded that irrigation water from the first two fillings of the ditches treated with atrazine should not be used for irrigation.

Guideline (Interim)

Given the extreme sensitivity of some crops (e.g., sugar beets) to the toxic effects of atrazine, the U.S. EPA concentration for atrazine in irrigation water of 10 $\mu g \cdot L^{-1}$ is recommended as a Canadian water quality interim guideline until further information becomes available.

Recreational Water Quality and Aesthetics

Guideline

There is no recommended guideline for atrazine in recreational waters.

Industrial Water Supplies

Guideline

There is no recommended guideline for atrazine in industrial water supplies.

SUMMARY

Following an evaluation of the published information on the pesticide atrazine, Canadian Water Quality Guidelines were derived (Table 3). The background information on atrazine in terms of uses and production, occurrence in the aquatic environment, persistence and degradation, and toxicity to nontarget organisms was reviewed. The rationale employed for the development of the recommended guidelines was summarized.

Table 3. Recommended Water Quality Guidelines for Atrazine

Uses	Guidelines
Raw water for drinking water supply	60 µg/L (IMAC)*
Freshwater aquatic life	2 µg/L
Agricultural uses	
Livestock watering	60 µg/L (interim)
Irrigation	10 µg/L (interim)
Recreational water quality and aesthetics	No recommended guideline
Industrial water supplies	No recommended guideline

* Existing drinking water guideline (Health and Welfare Canada, 1987).

ACKNOWLEDGMENTS

The authors appreciate the valuable assistance and helpful comments provided by the members of the Canadian Council of Resource and Environment Ministers (CCREM) Task Force on Water Quality Guidelines. This report benefited from the scientific reviewers' suggestions of M.C. Taylor, D. Valiela, and H. O'Neill of the Water Quality Branch; J. Maguire of the National Water Research Institute; K. Lloyd of the Canadian Wildlife Service; B. Ernst, M. Wan, and R. Sebastien of Environmental Protection; and V. Zitko of Fisheries and Oceans.

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Appendix A

Summary of Atrazine Residues found in Surface and Subsurface Waters

Table A-1. Summary of Atrazine Residues Found in Surface and Subsurface Waters

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
Canadian Studies				
Four corn fields in southern Quebec drained by tile drains; field area 1.75 ha; Atrex 90W applied at 2.8 kg/ha by spray on 6/6/73 and 12/6/74; sampling from 26/5/73 to 22/12/74.	Tile-drain water	23/23	Atrazine: 0.06-10.82 µg/L Dethylated atrazine: 0.36-7.71 µg/L Deisopropylatd atrazine 0.01-0.78 µg/L	Muir and Baker, 1976
Eleven agricultural watersheds in southern Ontario ranging in size from 162 to 6671 Km^2; sampling between April 1974 and May 1977; streambed sediments sampled May 1976-April 1977.	Surface water	1073/1338	Mean atrazine and/or dethylatrazine: 1.4 µg/L; Range: 0.04-32.8 µg/L	Frank et al., 1978; Frank and Sirons, 1979
	Stream sediments	4/22	7.6-15.8 ng/g atrazine (April 1977) 8.2 ng/g deethylatrazine (April 1977) 7.0-20.0 ng/g atrazine (October 1976)	
Five rivers draining agricultural areas in southern Quebec (Yamaska River basin); sampling at river mouths April to December 1974 and 1975.	Surface water	Not given/30	Range: 0.01-26.9 µg/L (atrazine) Range: <0.01-1.34 µg/L (deethylatrazine)	Muir et al., 1978
Hillman Creek drainage in southern Ontario (4500 ha); sampling between May 1973 and February 1975.	Surface water	320/360 (atrazine) 121/235 (deethylatrazine)	Monthly means: <0.02-5.0 µg/L Monthly means: <0.02-0.3 µg/L	Roberts et al. 1979

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
Twenty-two large and 28 small tributaries to the St. Lawrence River in Quebec and 24 locations in the St. Lawrence River itself.	Surface water	Not given	<u>Large tributaries</u> Atrazine average: 0.42 µg/L maximum: 11.1 µg/L 95% frequency of detection Deethylated atrazine average: 0.11 µg/L maximum: 2.00 µg/L 75% frequency of detection Deisopropylated atrazine average: 0.02 µg/L maximum: 0.52 µg/L 52% frequency of detection <u>Small tributaries</u> Atrazine average: 0.35 µg/L maximum: 13.33 µg/L 90% frequency of detection Deethylated atrazine average: 0.08 µg/L maximum: 4.48 µg/L 76% frequency of detection Deisopropylated atrazine average: below detection maximum: 1.63 µg/L 48% frequency of detection	Environment Canada, 1986

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
			St. Lawrence River Atrazine average: 0.04 µg/L maximum: 0.32 µg/L 91% frequency of detection Deethylated atrazine average: 0.02 µg/L maximum: 0.13 µg/L 64% frequency of detection Deisopropylated atrazine average: below detection maximum: 0.08 µg/L 8% frequency of detection	
Ninety-two streams draining into Great Lakes from Ontario; samples collected at stream mouths during July 1977.	Surface water	71/92 (atrazine) 48/92 (deethylatrazine)	Mean atrazine: 1.6 µg/L Mean deethylatrazine: 0.3 µg/L	Frank, Sirons, et al., 1979
	Suspended solids	0/45 (atrazine & deethylatrazine)	Detection Limit: 0.05 µg/L	
Grand and Saugeen river basins, southern Ontario, sampling conducted May 1975-April 1977.	Surface water	15/24 (Grand) 15/24 (Saugeen)	Atrazine and deethylatrazine Range: <0.1-2.0 µg/L for Grand River Range: <0.1-1.5 µg/L for Saugeen	Frank, 1981
	Suspended solids	0/22	Not detected at 0.05 µg/g	
	Riverbed sediments	0/8	Not detected as 0.05 µg/g	

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
Eleven agricultural watersheds in southern Ontario ranging in size from 162 to 6671 km^2; sampling between May 1975 and April 1977.	Surface water	Not given/949; atrazine in 80.4% of samples in 1975-76; present in 80.0% of samples in 1976-77.	1975-76: overall mean = 1.1 µg/L maximum value = 31.7 µg/L 1976-77: overall mean = 1.6 µg/L maximum value = 32.8 µg/L	Frank et al., 1982
Well waters in southern Ontario sampled from 1969 to 1978.	Ground water	50/393	Range: 0.1->10 000 ug/L	Frank, Sirons, and Ripley, 1979
Well waters in southern Ontario sampled in 1985.	Ground water	87/1843	7 wells had atrazine above 46 µg/L (the interim guideline for maximum, acceptable concentrations)	Ripley et al., 1986
Waterworks in southern Ontario at which raw and treated drinking water sampled for atrazine in 1985. Nine locations for raw water, 8 locations for treated water. In addition, 351 private wells were sampled.	Raw drinking water	47/120	Maximum concentrations 6.4 µg/L (as atrazine & deethylatrazine)	Ontario Ministry of the Environment, 1987a
	Treated drinking water	26/111	Maximum concentration 4.3 µg/L (as atrazine & deethylatrazine)	
	Ground water	169/1881	6 wells with >46 µg/L; 146 wells with <9.2 µg/L; 17 wells with >9.2, <46 µg/L	
Forty-two domestic and municipal wells sampled for atrazine in 1986; 25 water-works supplied by surface water sampled for atrazine in raw and treated drinking water.	Ground water	31/42	Atrazine range: 0.14-4.2 µg/L Deethylatrazine range: 0.11-7.6 ug/L	Ontario Ministry of the Environment, 1987b
	Raw drinking water	263/422	Atrazine range: 0.05-29.4 µg/L	

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
	Treated drinking water	114/150	Atrazine range: 0.05-37 μg/L	
Ninety-one wells from farms on mineral soil across southern Ontario, samples collected in 1984.	Ground water	11/91	Range 0.1-74 μg/L	Frank, Clegg, et al., 1987
U.S. Studies				
Small agricultural watersheds in western Iowa ranging from 0.53 to 1.5 ha; atrazine applied as wettable powder by spraying at 2.24 kg/ha in 1967 and 1968. In 1969 and 1970 atrazine applied at 3.36 kg/ha. A comparison of runoff from surface-contoured and ridged watersheds; 10-15% slope.	Surface water runoff from treated fields	Not given	4.91-1.1 mg/L in water 7.35-1.77 $mg \cdot kg^{-1}$ in sediment	Ritter et al., 1974
20-m^2 plots in Georgia, plowed and harrowed one week before atrazine application as 80% wettable powder at 3.36 kg/ha. Overhead nozzles simulated rainfall intensity of 6.4 cm/h for 1 h.	Surface water runoff from treated plots	Not given	For atrazine applied 1 h before rain: 7.94 mg/L for 1.3 cm rainfall 2.54 mg/L for 3.2 cm rainfall 1.39 mg/L for 6.4 cm rainfall For atrazine applied 96 h before rain: 3.66 mg/L for 1.3 cm rainfall 1.13 mg/L for 3.2 cm rainfall 0.62 mg/L for 6.4 cm rainfall	White et al., 1967
Fourteen 40-m^2 plots in Pennsylvania with 14% slope planted to corn. Atrazine applied as 80% wettable powder at 7 rates (9, 0.6, 1.1, 2.2, 4.5, 6.7, and 9.0 kg-ai/ha.	Surface water and suspended solids runoff from treated	Not given	First run samples collected 23 d after application ranged from 0.3 mg/L (0.6 kg/ha) to 4.68 mg/L (9.0 kg/ha) in water. Atrazine in suspended solids	Hall et al., 1972

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
Applications on one date only. Runoff collected from May-November 1967 and May-October 1968.	plots		from same samples ranged from 0.33 to 6.23 mg/kg (0.6-9.0 kg/ha) Average concentrations in water and suspended solids in 1968 from: 0.6 kg/ha = 0 mg/L & <0.01 mg/kg 1.1 kg/ha = <0.01 mg/L & 0.10 mg/kg 2.2 kg/ha = 0.01 mg/L & 0.12 mg/kg 4.5 kg/ha = 0.01 mg/L & 0.15 mg/kg 6.7 kg/ha = 0.02 mg/L & 0.37 mg/kg 9.0 kg/ha = 0.02 mg/L & 0.41 mg/kg	
Tailwater pits in Kansas each receiving irrigation runoff water from one or more fields of corn. Sampling in 1973 before first runoff of growing season, immediately after first runoff, at midseason, in late summer, and in autumn. In 1974, each pit was sampled in May, June, July, August, and November without regard to runoff. Application rates not given.	Pit water	98/109 (1973)	Mean = 13.9 µg/L Maximum = 250 µg/L	Kadoum and Mock, 1978
	Pit bottom soil	81/96 (1973)	Mean = 42.9 µg/kg Maximum = 369 µg/kg	
	Pit water	14/129 (1974)	Mean = 56.2 µg/L Maximum = 1074.1 µg/L	
	Pit bottom soil	109/129 (1974)	Mean = 90.8 µg/kg Maximum = 1068.3 µg/kg	
Tailwater pits in Kansas receiving irrigation runoff water from grain sorghum fields in 1973. Sampling in 1973 as above.	Pit water	22/46	Mean = 20.4 µg/L Maximum = 128 µg/L	Kadoum and Mock, 1978

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
	Pit bottom soil	13/40	Mean = 47.1 µg/kg Maximum = 132.5 µg/kg	
0.4-3.5 ha experimental watersheds in eastern Ohio. Atrazine broadcast at rates from 1.12 to 3.92 kg/ha. First runoff events sampled. No attempt made to determine atrazine in runoff suspended solids. Study to compare atrazine in runoff from conventional (C) and no-tillage (NT) corn fields. Limit of atrazine detection was 10 µg/L.	Runoff water	Not given	(NT)3.36 kg/ha, 51 d post-application, produced no detectable atrazine; (C)2.24 kg/ha, 2 d post-application, produced 0.10 mg/L; (NT)1.68 kg/ha, 4 d post-application, produced 0.34 mg/L; (NT)1.12 kg/ha, 10 d post-application, produced 0.2 mg/L; (C)3.92 kg/ha, 1 d post-application, produced 0.48 mg/L; (NT)1.68 kg/ha, 87 d post-application, produced no detectable atrazine; (C)1.12 kg/ha, 20 d post-application, produced 0.13 mg/L; (NT)1.12 kg/ha, 37 d post-application, produced no detectable atrazine; (NT)2.24 kg/ha, 37 d post-application, produced 0.11 mg/L;	Triplett et al., 1978a, 1978b

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
			(NT)1.79 kg/ha, 31 d post-application, produced 0.14 mg/L.	
2025-ha watershed in Nebraska. Atrazine applied to corn and sorghum fields in May and early June. Atrazine in water resulted from previous applications, no carry-over from year to year. Study carried out under drought conditions. Application rates not given.	Water from natural drainages through out the watershed	Not given	June 18, 1975: 16.43 µg/L average of 4 samples; May 25, 1976: 14.00 µg/L average of 6 samples; June 1, 1977: 23.93 µg/L average of 10 samples.	Schepers et al., 1980
Four 27-m^2 plots with 3% slope in Oregon; rototilled to a depth of 15 cm. Lime at 11.2 t/ha rototilled into 2 plots. Atrazine applied 2 weeks later at at 3.6 ka-ai/ha[1] as 80% wettable powder. Water applied to plots 12 h and 8 d at rate of 3.1 cm/h (total 7 cm) post-atrazine treatment.	Surface water runoff from plots	Not given	Unlimed, 12 h, range: 0.3-0.9 mg/L Unlimed, 8 d, range: 0.2-0.5 mg/L Limed, 8 d, range: 0.0.3 mg/L (no runoff from limed, 12 h plots)	Gaynor and Volk, 1981
	Surface runoff solids from plots		Unlimed, 12 h, range: 0. mg/kg Unlimed, 8 d, range: 6.2-35.7 mg/kg Limed, 12 h, range: 0 mg/kg Limed, 8 d, range: 0-2.8 mg/kg	
Nine 40-m^2 plots in Pennsylvania with 14% slope, rototilled at 12 cm. Corn planted with and without oats as a strip crop at the slope base. Atrazine applied preemergence at 2.2 and 4.5 kg/ha and preplant incorporated at 2.2 and 4.5 kg/ha. Atrazine concentrations presented in graphic format of such small size that individual concentrations could not be identified.	Plot runoff water	Not given	Preemergence application: 2.2 kg/ha produced 3.53% loss from non-stripped plots and 0.33% loss from stripped plots. 4.5 kg/ha produced 1.13% loss from non-stripped plots and 0.39% loss from stripped plots. Pre-plant incorporation: 2.2 kg/ha produced 0.94% loss from non-stripped plots and 0.33% loss	Hall et al., 1983

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
			from stripped plots. 4.5 kg/ha produced 0.85% loss from non-stripped plots and 0.15% loss from stripped plots.	
16.4-ha watershed in Maryland coastal plain used as cornfield. Atrazine applications were May 7, 1976 (1.7 kg/ha), May 14, 1977 (1.0 kg/ha), and May 25, 1978 (1.0 kg/ha).	Surface drainage in natural channels	Not given	1976 range: 0.04-13 µg/L 1977 range: 0.1-4.0 µg/L 1978 range: <01-4.0 µg/L	Wu et al., 1983
Two separate cornfield watersheds in Maryland, one planted using conventional tillage (CT) procedures (contour ploughed, disc-harrowed and cultipacked) and the other using no-till procedures (NT). CT watershed was 0.37 ha, 6% slope; NT watershed was 0.27 ha, 7% slope. Atrazine applied pre-emergence at 2.2 kg-ai/ha to both watersheds immediately after planting in 1979, 1980, 1981, and 1982.	Surface runoff from fields Note: no surface runoff from NT watershed 3, 13, 21, 26 August.	Not given	For atrazine applied 4 June 1979: 18 June - 1332 µg/L(CT), 975 µg/L(NT) 16 July - 426 µg/L(CT), 226 µg/L(NT) 3 Aug. - 83 µg/L(CT) 13 Aug. - 23 µg/L(CT) 21 Aug. - 10 µg/L(CT) 26 Aug. - 7 µg/L(CT) 28 Aug. - 5 µg/L(CT), 3 µg/L(NT) 6 Sept. - 9 µg/L(CT), 14 µg/L(NT) 24 Sept. - 9 µg/L(CT), 6 µg/L(NT) 1 Oct. - 6 µg/L(CT), 4 µg/L(NT) 3 Oct. - 16 µg/L(CT), 4 µg/L(NT) 9 Oct. - 5 µg/L(CT), 0.7 µg/L(NT)	Glenn and Angle, 1987
	Note: no surface runoff from NT watershed in June or July		For atrazine applied 11 May 1981: 8 June - 47 µg/L(CT) 22 June - 28 µg/L(CT) 2 July - 14 µg/L(CT)	

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
	Note: no surface runoff from NT watershed in May or June		For atrazine applied 14 May 1982: 20 May - 60.2 µg/L(CT) 24 May - 22.0 µg/L(CT) 13 June - 5.0 µg/L(CT) 17 June - 2.6 µg/L(CT)	
Ten plots in Ohio (average surface area 0.02 ha/plot) each equipped with earthen borders, surface interceptor gutters, flume and tanks for measuring and sampling surface runoff. Atrazine applications of 4.48 kg/ha to 4 plots (2x treatment) and 2.24 kg/ha to 5 plots (1x treatment); applications in 1974 and 1975.	Surface runoff	Not given	1974: atrazine below 10 µg/L for both treatments after 7 d and zero after 23 d. 1975: atrazine maximum of 290 µg/L from 2x treatment and 99 µg/L from 1x treatment 10 d after application. 26 d after application atrazine concentrations of 35 µg/L (2x) and 14 µg/L (1x); concentrations decreased to zero after 68 d.	Rohde et al., 1981
Fourteen locations throughout midwestern U.S. for atrazine residues in Mississippi River and major tributary streams.	River water	Not given	Atrazine residues peaked in June and July in range 2-17 µg/L and continued to be detectable in most streams in remainder of year at generally below 1 µg/L. No nitrosoatrazine residues could be detected (detection limit = 0.1 µg/L).	Newby and Tweedy, 1976
Maumee River basin, Ohio. Filtered stream water sampled and bottom sediments.	Filtered river water	Not given	Blanchard River: 1.8 mg/L Auglaize River: 0.3 mg/L Maumee River: 4.8 mg/L	Wall et al., 1978

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
	Bottom sediment	?/21	Blanchard River: <0.01-0.03 µg/g Auglaize River: <0.01 µg/g Maumee River: <0.01-0.02 µg/g	
Fifty-eight lake monitoring sites, 19 raw drinking water supply lake sites in Kansas.	Surface water	43/?	Large lakes (440-6400 surface ha) Mean: 4.8 µg/L Range: 1.4-23.0 µg/L	Butler and Arruda, 1985
	Surface water	5/?	Small lakes (10-300 surface ha) Mean: 2.0 µg/L Range: 1.2-2.8 µg/L	
	Surface water	4/?	Water supply lakes (1983 survey) Range: 1.4-4.0 µg/L	
	Treated water	10/?	Range: 1.2-4.8 µg/L	
	Surface water	Not given	Water supply lakes (1984 survey) Range: 2.1-16.0 µg/L	
	Treated water	Not given	Range: 3.1-9.5 µg/L	
Small agricultural drainage in northeastern Indiana (Black Creek watershed).	Surface water	0/7	Limit of detection: 100 µg/L Limit of detection: 100 µg/kg	Dudley and Karr, 1980
	Sediment	0/14	Lower limit of detection: 100 µg/kg	
	Fish	0/18		
Surface, subsurface, and finished waters in Iowa, 1974	Surface water (South Sunk River)	16/18	Range: 0.16-12.0 µg/L	Richard et al., 1975

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
	(Indian Creek)	15/15	Range: 0.163-42.0 µg/L	
	(drainage ditch)	15/15	Range: 0.132-9.0 µg/L	
	(Des Moines River)	Not given	Mean: 0.211 µg/L Range: 0.050-0.800 µg/L	
	(Raccoon River)	Not given	Mean: 0.814 µg/L Range: 0.120-3.3 µg/L	
	(Red Rock Reservoir)	Not given	Mean: 0.813 µg/L Range: 0.060-2.5 µg/L	
	(Red Rock Reservoir)	Not given	Mean: 0.921 µg/L Range: 0.100-1.90 µg/L	
	(Rathbun Reservoir)	Not given	Mean: 4.094 µg/L Range: 0.207-9.40 µg/L	
	(Rathbun Reservoir)	Not given	Mean: 1.285 µg/L Range: 0.165-3.750 µg/L	
	(Cedar River)	1/1	6.35 µg/L	
	(Iowa River)	1/1	3.00 µg/L	
	(Skunk River)	1/1	0.05 µg/L	
	(Mississippi River)	2/2	0.1 and 0.331 µg/L	

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
	(Gremore Lake)	1/1	0.190 µg/L	
	(Missouri River)	1/1	0.08 µg/L	
	(Farm pond)	1/1	0.90 µg/L	
	Finished water from subsurface raw water for the cities			
	(Cedar Rapids)	Not given	0.483 µg/L	
	(Marshalltown)	Not given	0. 06 µg/L	
	(Oskaloosa)	Not given	0.014 µg/L	
	(Waterloo)	Not given	0.004 µg/L	
	(Iowa Falls)	Not given	<0.001 µg/L	
	(Sioux City)	Not given	<0.001 µg/L	
	Finished water from surface raw water for the cities			
	(Davenport)	Not given	0.405 µg/L	

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
	(Iowa City)	Not given	0.200 µg/L	
	(Des Moines)	Not given	0.029 µg/L	
7.4 km^2 Mahantango Creek watershed in central Pennsylvania. Land use about 57% cropland, 35% forest, and 8% pasture. 20 wells sampled 10-20 Dec. 1985 and 18-28 Aug. 1986. Spring sampled 13 Feb. and 21 Aug. 1986.	Ground water	28/38	22 samples ranged from 0.013 to 1.110 µg/L 6 samples ranged from 0.003 to 0.009 µg/L 10 samples below detection limits of 0.003 µg/L	Pionke et al., 1988
Field (size not given) in the central Platte River valley of Nebraska. Atrazine applied at 4.4 kg/ha at beginning of 1979 growing season. Application reduced to 2.2 kg/ha during 1980. Field received 44.2 cm of water (irrigation and precipitation) during 1979 and 1980. Samples taken from observation wells down gradient from field.	Ground water	Not given	Range: 0.2-0.8 µg/L	Wehtje et al., 1981
Thirty monitoring wells, central Platte River valley of Nebraska, 16 on terrace, 14 in bottomland. Samples from all wells collected 4 times: April 8-10, June 11-19, October 13-15, 1980;, and April 27-28, 1981.	Ground water	116/116	Terrace wells: April range: 0.01-8.29 µg/L June range: 0.03-1.56 µg/L Oct. range: 0.01-1.51 µg/L April range: 0.01-1.05 µg/L	

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
			Bottomland wells: April range: 0.02-2.76 µg/L June range: 0.01-0.86 µg/L Oct. range: 0.02-1.98 µg/L April range: 0.01-0.28 µg/L	
Thirty-five monitoring wells, central Platte Rivervalley of Nebraska, 6 wells on terrace in principal aquifer; 4 terrace and bottomland wells in secondary aquifers; 10 bottomland wells in principal aquifer and down gradient from irrigated cropland; 15 bottomland wells in principal aquifer where influenced by Platte River and near pristine conditions exist.	Ground water	64/?	6 terrace wells: June range: <0.01-0.38 µg/L Sept. range: 0.05-2.66 µg/L 4 terrace and bottomland wells: June range: <0.01-0.02 µg/L Sept. range: <0.01-0.02 µg/L 10 bottomland wells down gradient from cropland: June range: <0.01-1.09 µg/L Sept. range: <0.01-88.36 µg/L 15 bottomland wells - near pristine conditions: Sept range: 0.01-0.27 µg/L	Junk et al., 1980
2848 km^2 agricultural land in southeastern Nebraska; household and livestock watering wells.	Ground water	13/47	Range: 0.01-1.2 µg/L Average: <0.08 µg/L	Exner and Spalding, 1985
Tiffin, Ohio; West Lafayette, Indiana; Parsons, West Virginia; Potsdam, New York.	Rainwater (Indiana)	8/14	0.1->1.0 µg/L	Richards et al., 1987

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
	(Ohio)	14/24	<0.1->1.0 μg/L	
	(West Virginia)	11/20	<0.1-0.5 μg/L	
	(New York)	10/21	<0.1->1.0 μg/L	
Estuarine water samples from Rhode River (Chesapeake Bay), Maryland. Rainwater and dry precipitation collected on top of tall building (Edgewater, Maryland). Collections made in 1977 and 1978.	Surface water (surface layer and subsurface)	Not given	60% of samples at 0.01-0.10 μg/L; atrazine in surface layer 0.01-1.0 μg/L, with 50% samples >0.1 μg/L; range: 0.003-2.19 μg/L.	Wu, 1981
	Bulk precipitation	?/68	January to April 1977 samples ranged from 0.003 to 0.97 μg/L. Maximum atrazine concentration occurred in May (2.19 μg/L).	
Twenty sampling sites in Quebec, 1977 to 1981; locations unknown.	Surface water	66/75	Maximum: 4.5 μg/L Mean: 0.126 μg/L Detection limit: 0.02 μg/L	M. Wong, 1987, Water Quality Branch, Environment Canada, pers. com.
Nineteen sampling sites in Quebec, 1977 to 1981; locations unknown.	Surface water	5/63	Maximum: 0.30 μg/L Mean: 0.26 μg/L Detection limit: 0.02 μg/L	
Twenty sampling sites in Quebec, 1977 to 1981; locations unknown.	Surface water	38/75	Maximum: 1.50 μg/L Mean: 0.55 μg/L Detection limit: 0.02 μg/L	

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
Thirteen sampling sites in the prairie provinces, 1985 to 1986.	Surface water	5/72	Maximum: 0.40 µg/L Mean: 0.107 µg/L Detection limit: 0.10 µg/L	
Twenty-four rivers or lakes that empty into the St. Lawrence River, Quebec, July 1977 to June 1978. Maximum concentration at Port du Quebec.	Surface water	Not reported (91% frequency of detection)	Maximum: 0.32 µg/L Mean: 0.04 µg/L Detection limit: 0.02 µg/L	Environment Canada, n.d.
The mouths of 20 large tributaries of the St. Lawrence River, May to Sept. 1976. Maximum concentration at Riviere Rigaud.	Surface water	Not reported (95% frequency of detection)	Maximum: 11.0 µg/L Mean: 0.42 µg/L Detection limit: 0.02 µg/L	
The mouths of 29 small tributaries of the St. Lawrence River, July to August 1976. Maximum concentration at Riviere Marguerite.	Surface water	Not reported (90% frequency detection)	Maximum: 13.33 µg/L Mean: 0.35 µg/L Detection limit: 0.02 µg/L	
Fourteen sampling sites in the St. Lawrence River and Lac Saint-Pierre. Maximum concentration at Riviere Yamaska.	Surface water	31/31	Maximum: 5.10 µg/L Detection limit: 0.02 µg/L	
Mitchells Bay water treatment plant.	Raw surface water	0/1	Detection limit: 0.05 µg/L	
	Treated water	0/1	Detection limit: 0.05 µg/L	
Stony Point water treatment plant (July 2 to Nov. 4, 1985).	Raw surface water	0/2	Detection limit: 0.05 µg/L	I. Cornish, 1987, Agriculture Canada, pers. com.
	Treated water	0/1	Detection limit: 0.05 µg/L	

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
Wallaceburg water treatment plant (July 3 and Oct. 7, 1985).	Raw surface water	0/2	Detection limit: 0.05 µg/L	
	Treated water	0/2	Detection limit: 0.05 µg/L	
Walpole Island water treatment plant (Nov. 6, 1985).	Raw surface water	0/1	Detection limit: 0.05 µg/L	
	Treated water	0/1	Detection limit: 0.05 µg/L	
Windsor water treatment plant (Oct. 21, 1985).	Raw surface water	0/1	Detection limit: 0.05 µg/L	
	Treated water	0/1	Detection limit: 0.05 µg/L	
Municipal sources in Ontario (80) and Alberta (15); fall of 1986.	Unknown	3/95	Maximum: 1.8 µg/L Detection limit: 1 µg/L	K.J. Kjartanson, 1987, Environmental Control Services, Manitoba Environment and Workplace Safety and Health, pers. com.
Quebec, Oct. 1984 and July 1985.	Ground water	10/24	-	J. Vachon, 1985, Ministry of the Environment, Government of Quebec, pers com.
Rural private wells in Ontario, 1979 to 1984.	Ground water	57/160	Detection limit: 0.1 µg/L	Frank, Clegg, et al., 1987

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
Harrow, Ontario.	Raw water	0/1	Detection limit: 0.05 µg/L	D. Maroontate, 1985, Ontario Ministry of the Environment, pers. com.
	Treated water	0/1	Detection limit: 0.05 µg/L	
288 private wells in Ontario, 1985.	Ground water	180/491	Maximum: 1200 µg/L Detection limit: µg/L	Regional Director, Ontario Ministry of the Environment 1986, pers. com.
Amherstburg water treatment plant, Oct. 28, 1985.	Raw water Treated water	0/1	Detection limit: 0.05 µg/L Detection limit: 0.05 µg/L	Ontario Ministry of the Environment, 1986
Eleven canning facilities in Nova Scotia, June 1986.	Unknown	3/11	Maximum: 0.8 µg/L Detection limit: 0.04 µg/L	M. Shreve, 1986, Soils and Crop Branch, Nova Scotia Department of Agriculture and Marketing, pers. com.
Farm well, Prince Edward Island.	Ground water	1/1	Maximum: 70.0 µg/L	P.E.I. Department of Community and Cultural Affairs, 1985
Nine water treatment plants on St. Lawrence River, June to July 1977.	Raw and treated water	Not reported (83% frequency of detection)	Maximum: 0.10 µg/L Mean: 0.03 µg/L Detection limit: 0.02 µg/L	Environment Canada, n.d.

Table A-1. Continued

Location and conditions	Matrix	Samples with atrazine/ samples collected	Concentration	Reference
Quebec municipalities, Feb. 1986.	Raw water	12/17	Maximum: 0.137 µg/L Detection limit: 0.025 µg/L	Government of Quebec, 1987
	Treated water	11/16	Maximum: 0.129 µg/L Detection limit: 0.025 µg/L	
Quebec municipalities, July 1986.	Raw water	15/18	Maximum: 1.202 µg/L Detection limit: 0.025 µg/L	
	Treated water	13/18	Maximum: 0.783 µg/L Detection limit: 0.025 µg/L	

Appendix B
Summary of Atrazine Toxicity Data for Aquatic Organisms

Table B-1. Summary of Atrazine Toxicity Data for Aquatic Organisms

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
VERTEBRATES					
Rainbow trout (Salmo gairdneri)	Atrazine (Technical)	96 h	LC_{50} = 4.5 mg/L (3.5 to 5.7 mg/L)	Static test. 14 ± 2°C. NR. Avg. pH = 7.2	Bathe et al., 1976
Bluegill (Lepomis macrochirus)	Atrazine	96 h	LC_{50} >8.0 mg/L	Flow-through test. 19 ± 1°C. M. Fish darkened and stressed at 1.4 mg/L	Macek et al., 1976

[1] 95% confidence limits in parentheses.

[2] From U.S. Department of Agriculture (1984) with additional data from:
Ashton et al., 1966
Boger and Schlue, 1976
Burrell et al., 1985
Gramlich and Frans, 1964
Hartman and Martin, 1985
Hollister and Walsh, 1973
Johnson, 1986
Kratky and Warren, 1971
Larsen et al., 1986
Mayasich et al., 1986, 1987
Millie and Hersh, 1987
Stratton, 1984
Thomas et al., 1973
Torres and O'Flaherty, 1976
Turbak et al., 1986
Véber et al., 1981
Ward and Ballantine, 1985

Note:

NOEL = no-observed-effect level.
M = Concentrations of atrazine measured in test tanks
NR = Presence or absence of test tank measurements not reported, assumed to be unmeasured.

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Brook trout (Salvelinus fontinalis)	Atrazine	96 h	LC_{50} = 6.3 mg/L (4.1 to 9.7 mg/L)	Flow-through test. 13 ± 1°C. M. Fish darkened and stressed at 1.4 mg/L	Macek et al., 1976
Fathead minnow (Pimephales promelas)	Atrazine	96 h	LC_{50} = 15 mg/L (11 to 20 mg/L) NOEL = 8.0 mg/L	Flow-through test. 19 ± 1°C. M. Fish darkened and stressed at 1.4 mg/L	Macek et al., 1976
Bluegill (Lepomis macrochirus)	Atrazine	28 h	Fish exposed to 0.5 mg/L became lethargic, fed poorly, partially lost equilibrium.	Flow-through test. Toxic effects dose-related. M.	Macek et al., 1976
Fathead minnow (Pimephales promelas) (fry)	Atrazine	96 h	3- to 5-d-old fry exposed to 0.52 mg/L had 25% mortality.	Static test. Mortality dose-related. M.	Macek et al., 1976
Brook trout (Salvelinus fontinalis)	Atrazine	44 wk	Fish exposed to 0.72 mg/L not affected in parental survival, egg production, and hatchability. Growth and survival of fry were reduced with 90-d exposure to 0.72, 0.45 and 0.24 mg/L.	M.	Macek et al., 1976

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Rainbow trout (Salmo gaidneri)	Gesaprim (80% wettable powder)	48 h 96 h	LC_{50} = 30 mg/L LC_{50} = 17 mg/L	Static test. 14 ± 2°C.	Litchfield and Wilcoxon, 1949
Crucian carp (Carassius carassius)	Gesaprim (80% wettable powder)	48 h 96 h	LC_{50} = 100 mg/L LC_{50} = 100 mg/L	Static test. 14 ± 2°C. M.	Bathe et al., 1975
Catfish (Ictalurus melas)	Gesaprim (80% wettable powder)	48 h 96 h	LC_{50} = 37 mg/L LC_{50} = 35 mg/L	Static test. 20 ± 2°C. M.	Bathe et al., 1975
Perch (Perca sp.)	Gesaprim (80% wettable powder)	48 h 96 h	LC_{50} = 80 mg/L LC_{50} = 50 mg/L	Static test. 20 ± 2°C. M.	Bathe et al., 1975
Bluegill (Lepomis macrochirus)	Atrazine (wettable powder)	96 h	LC_{50} approx. 6 mg/L		Walker, 1964, cited in Lorz et al., 1979
Coho salmon (Oncorhynchus kisutch)	AAtrex^{R}	144 h	Concentration dependent mortality in fresh water with 0% mortality at 5 mg/L, 5% mortality at 8 mg/L, and 25% mortality at 15 mg/L.	When survivors transferred to seawater for 244 h, those previously exposed to 5 mg/L had 6% mortality; those exposed to 15 mg/L had 25% mortality.	Lorz et al., 1979

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Bluegill (Lepomis macrochirus)	Atrazine	18 mo	Fish exposed to 0.095 mg/L not affected in survival, growth, or hatching.	M.	Macek et al., 1976
Fathead minnow (Pimephaleas promelas)	Atrazine	43 wk	Fish exposed to 0.213 mg/L not affected in survival, growth, and spawning.	M.	Macek et al., 1976
Rainbow trout (Salmo gairdneri)	Atrazine	48 h	LC_{50} = 12.6 mg/L		U.S. Department of the Interior, 1968, cited in Pimentel, 1971
Harlequin fish (Rasbora heteromorpha)	Atrazine	24 h	LC_{50} = 0.55 mg/L		Alabaster, 1969, cited in Pimentel, 1971
Spot (Leiostomus xanthurus)	Atrazine	48 h	No effect at 1.0 mg/L	NR.	Butler, 1965
Bluegill (Lepomis macrochirus)	Atrazine	96 h	LC_{50} = 15 mg/L	Static test.	Klaassen and Kadoum, 1979, cited in Spehar et al., 1981
Bluegill (Lepomis macrochirus)	Atrazine	12 d	No mortality at 10 mg/L	NR.	Hiltibran, 1967
Bluegill (Lepomis macrochirus)	Atrazine (wettable powder)	12 d	No mortality at 5 mg/L	NR.	Hiltibran, 1967

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Bluegill (Lepomis macrochirus) (fry)	Atrazine (granular)	8 d	No mortality at 10 mg/L	NR.	Hiltibran, 1967
Green sunfish (Lepomis cyanellus) (fry)	Atrazine (granular)	8 d	No mortality at 11 mg/L	NR.	Hiltibran, 1967
Lake chubsucker (Erimyzon sucetta) (fry)	Atrazine (wettable powder)	8 d	No mortality at 10 mg/L	NR.	Hiltibran, 1967
Smallmouth bass (Micropterus dolomieui) (fry)	Atrazine (wettable powder)	72 h	Fish died within 3 d when exposed to 10 mg/L.	NR.	Hiltibran, 1967
Rainbow trout (Salmo gairdneri)	Atrazine	48 h 96 h	LC_{50} = 10 mg/L LC_{50} = 8.8 mg/L	14 ± 2°C	Litchfield and Wilcoxon, 1949, cited in Bathe et al., 1975
Crucian carp (Carassius carassius)	Atrazine	48 h 96 h	LC_{50} = 100 mg/L LC_{50} = 76 mg/L	14 ± 2°C	Litchfield and Wilcoxon, 1949, cited in Bathe et al., 1975
Catfish (Ictalurus melas)	Atrazine	48 h 96 h	LC_{50} = 8 mg/L LC_{50} = 7.6 mg/L	20 ± 2°C	Litchfield and Wilcoxon, 1949, cited in Bathe et al., 1975
Perch (Perca sp.)	Atrazine	48 h 96 h	LC_{50} =>21 mg/L LC_{50} = 16 mg/L	14 ± 2°C	Litchfield and Wilcoxon, 1949, cited in Bathe et al., 1975
Guppy (Lebistes reticulata)	Atrazine	48 h 96 h	LC_{50} = 10 mg/L LC_{50} = 4.3 mg/L	20 ± 2°C	Litchfield and Wilcoxon, 1949, cited in Bathe et al., 1975

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Orfe (Leuciscus sp.)	Atrazine	48 H	LC_{50} = 70 mg/L	14 ± 2°C	Litchfield and Wilcoxon, 1949, cited in Bathe et al., 1975
Channel catfish (Ictalurus punctatus)	Atrazine	Spawning through 96-h post-hatch	LC_{50} = 0.22 mg/L (0.15 to 0.32 mg/L)	Exposure to 0.06 0.43, 4.83, and 46.7 mg/L caused 4%, 13%, 69%, and 100%, respectively, of hatched fish to display teratogenic effects. Flow-through test. M.	Birge et al., 1979, 1983
Rainbow trout (Salmo gairdneri)	Atrazine	Spawning through 96-h post-hatch	LC_{50} = 0.87 mg/L (0.63 to 1.15 mg/L)	Exposures to 0.05, 0.54, and 5.02 mg/L caused 3%, 6%, and 62%, respectively, of hatched fish to display teratogenic effects. No fish hatched from eggs exposed to 50.9 mg/L. Flow-through test. M.	Birge et al., 1979, 1983

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Rainbow trout (Salmo gairdneri)	AAtrex	96 h	LC_{50} = 4.5 mg/L		Ciba-Geigy Chemical Corporation data cited in Weed Science Society of America, 1983
Bluegill (Lepomis macrochirus)		96 h	LC_{50} = >24 mg/L		Ciba-Geigy Chemical Corporation data cited in Weed Science Society of America, 1983
Goldfish (Carassius auratus)	Atrazine	96 h	LC_{50} = 60 mg/L		Geigy Agricultural Chemical Company product literature cited in U.S. Department of Agriculture, 1978
Spot (Leiostomus xanthurus)	Atrazine	96 h	LC_{50} = 8.5 mg/L (6.0 to 12 mg/L)	Static test. M. Salinity = 13 g/L	Ward and Ballantine, 1985
Sheepshed minnow (Cyprinodon variegatus)	Atrazine	96 h	LC_{50} = >16 mg/L MATC = >1.9, <3.4 mg/L	Flow-through test. M. Salinity = 13 g/L	Ward and Ballantine, 1985
Bullfrog (Rana catesbeiana)	Atrazine	Spawning through post-hatch	LC_{50} = 0.41 mg/L (0.27 to 0.59 mg/L)	Exposures to 0.4, 6.33, 14.8, 26.4, and 45.8 mg/L caused 3%, 7%, 22%, 47% and 100%, respectively, of hatched toads to	Birge et al., 1980. 1983

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
				display teratogenic effects. Flow-through test. M.	
American toad (Bufo americanus)	Atrazine	Spawning through 96-h post-hatch	LC_{50} = >48 mg/L	Flow-through test. M. Exposures to 10.8, 24.8, and 48.2 mg/L caused 3%, 6%, and 17%, respectively, of hatched toads to display teratogenic effects.	Birge et al., 1980, 1983
Bullfrog (Rana catesbeaina)	Atrazine	Spawning to hatching	LC_{50} = 11.55 mg/L (9.8 to 13.26 mg/L)	Flow-through test. M.	Birge et al., 1980
Leopard frog (Rana pipiens)	Atrazine	Spawning to hatching. Spawning through 96-h post-hatch.	LC_{50} = 22.89 mg/L (17.18 to 30.01 mg/L) LC_{50} = 7.68 mg/L (4.84 to 11.90 mg/L)	Flow-through test. M.	Birge et al., 1980
Pickerel frog (Rana palustris)	Atrazine	Spawning to hatching. Spawning through 96-h post-hatch.	LC_{50} = 20.20 mg/L (17.77 to 22.96 mg/L) LC_{50} = 17.97 mg/L (15.86 to 20.11 mg/L)	Flow-through test. M.	Birge et al., 1980

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Leopard frog (Rana pipiens)	Atrazine	96 h	Lethal threshold = 8.5 mg/L	Static test.	Hovey, 1975, cited in Hine et al., 1981
Leopard frog (Rana pipiens) (tadpoles)	Atrazine	54 d	Tadpoles exposed to 0.31 to 12 mg/L without significant mortality for first 27 d; afterward a significant increase in mortality. Concentrations of 0.31 mg/L significantly retard growth.		Hine et al., 1981.
INVERTEBRATES					
Midge larvae (Chironomus tentans)	Atrazine	48 h	LC_{50} = 0.72 mg/L (0.36 to 1.44 mg/L).	20 ± 1°C Static test. M.	Macek et al., 1976
Midge larvae (Chironomus tentans)	Atrazine	2 generations	Exposure to measured concentrations of 0.23 mg/L or more through 2 generations caused reduced hatching success, increased larval mortality, retarded development, and reduced rate of pupation and emergence. NOEL = 0.11 mg/L	Static test. M.	Macek et al., 1976

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Mosquito larvae (Culex restuans)	Atrazine	18 h	LC_{50} = 200 mg/L for animals stressed with 0.4% methanol in 25-mL test system.	Static test. NR.	Bowman et al., 1981
Cladoceran (Daphnia pulex)	Atrazine	18 h	LC_{50} = 0.6 mg/L (0.22 to 14.44 mg/L); animals stressed with 0.4% methanol in 25-mL test system.	Static test. NR.	Bowman et al., 1981
Cladoceran (Daphnia pulex)	Atrazine 4L[R] (40.8% atrazine)	48 h	LC_{50} = 36.5 mg/L (28.8 to 46.3 mg/L) (without susp. sed.) LC_{50} = 46.5 mg/L (39.6 to 54.6 mg/L) (with susp. sed.)	NR.	Hartman and Martin, 1985
Cladoceran (Daphnia pulex)	Atrazine (Atrazin 99.2%)	28 d and entire lifespan	Longevity not affected up to 10 mg/L, but reduced in animals exposed to 20 mg/L. Reproduction was reduced at 1 mg/L.	Ethanol (0.5%) solvent significantly reduced longevity and reproduction. Synergistic effect between atrazine and ethanol. NR.	Schober and Lampert, 1976, 1977
Cladoceran (Daphnia magna)	Atrazine	48 h	LC_{50} = 6.9 mg/L (5.2 to 8.1 mg/L), mortality observed at 3.0 mg/L.	Static test. M. 20 ± 1°C	Macek et al., 1976

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Amphipod (Gammarus fasciatus)		48 h	LC_{50} = 5.7 mg/L (3.6 to 8.0 mg/L), mortality observed at 2.4 mg/L.	Static test. M. 20 ± 1°C	Macek et al., 1976
Cladoceran (Daphnia magna)	Atrazine	21 d	Exposure to 1.15 mg/L did not adversely affect survival through 3 generations. Mean number of young per female during first generation exposure significantly reduced.	Data indicated D. magna reproduction more sensitive to atrazine than survival. Static test. M.	Macek et al., 1976
Amphipod (Gammarus fasciatus)	Atrazine	30 d to 17 wk	Survival of individuals exposed for 30 d to 0.94 mg/L was reduced. No reduction in survival of individuals exposed to 0.49 mg/L for 119 d. Reproductive effects impaired survival of offspring at 0.14 mg/L.	Static test. M.	Macek et al., 1976
Scud (Hyalella azteca)	Atrazine	18 h	LC_{50} = 8.8 mg/L (7.2 to 18.64 mg/L) for animals stressed with 0.5% methanol in 25-mL test systems.	Static test. NR.	Bowman et al., 1981

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Fiddler crab (Uca pugnax)	AAtrex^{R} (80% wettable powder)	10 wk	Treatment at 10 000 mg/L resulted in decreased survival.	Tests conducted in field enclosures and greenhouses. Salinity = 20 g/L	Plumley et al., 1980
Fiddler crab (Uca pugnax)	AAtrex^{R} (80% wettable powder)	8 wk	1000 mg/L either killed crabs or eliminated escape response. Adverse effects noted at 100 mg/L with severity a function of crab size and sex.	Static tests conducted in laboratory. Test confirmed response varied with season. Salinity = 20 g/L	Plumley et al., 1980
Cladoceran (Daphnia magna)	Atrazine	48 h	LC_{50} = 3.6 mg/L		U.S. Department of the Interior, 1968, cited in Pimentel, 1971
Brown shrimp (Penaeus aztecus)	Atrazine	48 h	30% mortality or paralysis at 1 mg/L	Salinity unknown. NR.	Butler, 1965
Shore crab (Carcinus maenus)	Atrazine	Unknown	LC_{50} = >100 mg/L	Salinity unknown. NR.	Portmann and Wilson, 1971
Clam (Pelecypoda)	Atrazine	Unknown	Clams reduced to 1/8 of original number after dosages of 0.5 to 2.0 mg/L.	Tests in pond enclosures. Salinity unknown.	Walker, 1962, cited in Pimentel, 1971

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Snails (Gastropoda)	Atrazine	Unknown	Snail population increased nearly 4 times at 0.5 to 2.0 mg/L.	Tests in pond enclosures. Salinity unknown.	Walker, 1962, cited in Pimentel, 1971
Eastern oyster (Crassostrea virginica)	Atrazine	96 h + unknown period of growth	No noticeable effect on shell growth in oysters at 1 mg/L.	Salinity unknown. NR.	Butler, 1965
Cockle (Cardium edule)	Atrazine	Unknown	LC_{50} = >100 mg/L	Salinity unknown. NR.	Portmann and Wilson, 1971
Cladoceran (Daphnia magna)	Atrazine	48 h	EC_{50} = 3.6 mg/L	Immobilization. NR.	Johnson, 1986
Midge larvae (Chironomus riparius)	Atrazine	48 h	EC_{50} = 1.0 mg/L	Immobilization. NR.	Johnson, 1986
Freshwater benthic organisms (primarily insects and insect larvae)	Atrazine	Unknown	Most species reduced at least 50% after application of 0.5 to 2.0 mg/L.		Walker, 1962, cited in Pimentel, 1971
Eastern oyster (Crassostrea virginica) (embryo)	Atrazine	48 h	EC_{50} = >30 mg/L	Static test. M. Salinity = 16 g/L	Ward and Ballantine, 1985
Calanoid copepod (Acartia tonsa)	Atrazine	96 h	LC_{50} = 0.094 mg/L (0.052 to 0.167 mg/L)	Static test. M. Salinity = 20 g/L	Ward and Ballantine, 1985

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Mysid shrimp (*Mysidopsis bahia*)	Atrazine	96 h	LC_{50} = 1.0 mg/L (0.65 to 3.1 mg/L)	Flow-through test. M. Salinity = 13 g/L	Ward and Ballantine, 1985
Grass shrimp (*Palaemonetes pugio*)	Atrazine	96 h	LC_{50} = 9.0 mg/L (5.3 to 16 mg/L)	Static test. M. Salinity = 26 g/L	Ward and Ballantine, 1985
Pink shrimp (*Panaeus duorarum*)	Atrazine	96 h	LC_{50} = 6.9 mg/L (4.1 to 12 mg/L)	Static test. M. Salinity = 26 g/L	Ward and Ballantine, 1985
Fiddler crab (*Uca pugilator*)	Atrazine	96 h	LC_{50} = >29 mg/L	Static test. M. Salinity = 26 g/L	Ward and Ballantine, 1985
Leech (*Glossiphonia complanata*)	Atrazine (99.2%)	28 d	LC_{50} = 6.3 mg/L (2.2 to 15.9 mg/L)	Static test. M.	Streit and Peter, 1978
Leech (*Helobdella stagnalis*)	Atrazine (99.2%)	27 d	LC_{50} = 9.9 mg/L (5.2 to 14.3 mg/L)	Static test. M.	Streit and Peter, 1978
ALGAE					
Green algae (*Chamydomonas reinhardi*)	Atrazine	2 wk	Autotrophic growth completely inhibited at 0.5 mg/L, but heterotrophic growth not affected.		Loeppky and Tweedy, 1969
(*Chlamydomonas eugametos*)	Atrazine	2 wk	Autotrophic growth only slightly affected at 5.0 mg/L.		Loeppky and Tweedy, 1969

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
(Chlorella vulgaria)	Atrazine	2 wk	Slight toxic effect at 5.0 mg/L.		Loeppky and Tweedy, 1969
(Chlorella pyrenoidosa)	Atrazine	2 wk	Marked toxic effect.		Loeppky and Tweedy, 1969
Green alga (Nannochloris occulata)	Atrazine	Not specified. Kept until a constant growth rate and then observed for 72 h.	At 0.1 mg/L atrazine, percent inhibition in culture growth ranged from 46.2% at 15°C to 54% at 25°C.		Karlander et al., 1983
Blue-green algae (Cyanobacteria)	Atrazine	Unknown	EC_{50} = 40 to 520 µg/L for exponential growth rate inhibition.		Hutber et al., 1979
Plantonic algae (12 isolates)	Atrazine (99%)	2 wk	Algae isolates not capable of growth at 1 mg/L.		Butler et al., 1975b
Natural phytoplankton assemblage	Atrazine 41% ai	136 d	6.3% decrease in primary productivity as measured by ^{14}C-uptake at atrazine concentration of 5 µg/L.	24-h ^{14}C-uptake tests	deNoyelles et al., 1982

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Green alga (Chlorella pyrenoidosa)	Atrazine	8-9 d	76% growth inhibition by 2.16 mg/L.		Gramlich and Frans, 1964
Marine unicellular algae (Chlorophyceae)	Atrazine	60 min	EC_{50} = 0.104 mg/L	Avg. of 6 species	Hollister and Walsh, 1973
(Bacillariophyta)		60 min	EC_{50} = 0.265 mg/L	Avg. of 8 species	Hollister and Walsh, 1973
(Chrysophyceas)		60 min	EC_{50} = 0.092 mg/L	Avg. of 3 species	Hollister and Walsh, 1973
(Rhodophyceae)		60 min	EC_{50} = 0.079 mg/L	1 species EC_{50} = 50% decrease in O_2 evolution	Hollister and Walsh, 1973
Green alga (Chlorella pyrenoidosa)	Atrazine	18-36 h	1 mg/L caused 50% or greater inhibition.	Chlorophyll analysis used to measure response.	Kratky and Warren, 1971
Estuarine phytoplankton (Nannochloris oculata)	Atrazine	7 d	Inhibitory effect on growth significantly increased by high temperature and light intensity.	Study assessed interaction of light, temperature, and atrazine (0.05 and 0.1 mg/L) on cell growth.	Mayasich et al., 1986
(Phaeodactylum tricornutum)	Atrazine	7 d	Inhibitory effect on growth significantly decreased by low light intensity.		Mayasich et al., 1987

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
(Bialgal assemblage of N. oculata and P. tricornutum)	Atrazine	7 d	Inhibitory response more severe for P. tricornutum in bialgal assemblage than in unialgal culture. Enhanced sensitivity of N. oculata to atrazine in bialgal assemblage produced P. tricornutum dominance.	Study assessed interaction of light, temperature, and atrazine (0.015, 0.030, 0.05 mg/L) on cell growth in unialgal culture and bialgal assemblage.	Mayasich et al., 1987
Unicellular diatom (Cyclotella meneghiniana)	Atrazine	7 min	EC_{50} = 0.099 mg/L (Arizona) EC_{50} = 0.105 mg/L (Iowa) EC_{50} = 0.243 mg/L (Minnesota)	Atrazine concentrations ranged from 0.001 to 0.338 mg/L. Study assessed effects of atrazine on geographical races of diatom. EC_{50} = 50% reduction in oxygen production.	Millie and Hersh, 1987
Green alga (Chlorella pyrenoidosa)	Atrazine	Not stated	Paper disc agar diffusion not satisfactory for tests with atrazine (conc. not given).	Failure of atrazine to inhibit C. pyrenoidosa growth due to glucose in medium.	Thomas et al., 1973

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Green algae *Chlorella vulgaris*	Atrazine	7 d	Dose-related inhibition of chlorophyll production from 0.001 to 1 mg/L. Complete inhibition at 10 mg/L. 50% inhibition at 0.001 mg/L.		Torres and O'Flaherty, 1976
(*Stigeoclonium tenue*)	Atrazine	7 d	67% chlorophyll inhibition at 0.001 mg/L; 90% inhibition at 10 mg/L.		Torres and O'Flaherty, 1976
Yellow-green algae (*Tribonema sp.*)	Atrazine	7 d	42% chlorophyll inhibition at 0.001 mg/L; 75% inhibition at 1.0 mg/L; 100% inhibition at 10 mg/L.		Torres and O'Flaherty, 1976
(*Vaucheria geminata*)	Atrazine	7 d	41% chlorophyll inhibition at 0.001 mg/L; 100% inhibition at 2.0 mg/L.		Torres and O'Flaherty, 1976
Blue-green alga (*Oscillatoria lutea*)	Atrazine	7 d	93% chlorophyll inhibition at 0.001 mg/L; 100% inhibition at 1.0 mg/L.		Torres and O'Flaherty, 1976
Green alga (*Chlorella pyrenoidosa*)	Atrazine (98.2%)	96 h	EC_{50} (growth) = 60 µg/L		Maule and Wright, 1984

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Blue-green alga (Gloeocapsa alpicola)	Atrazine (98.2%)	96 h	EC_{50} = 5360 µg/L	EC_{50} = conc. causing 50% decrease in growth.	Maule and Wright, 1984
Green alga (Chlorella vulgaris)	Atrazine	0-72 h	70 mg/L atrazine stopped growth; effect counteracted by 2% glucose. Little effect on structure of chloroplast.		Ashton et al., 1966
Green alga (Chlorella vulgaris)	Zeasin 50% (W/W)	<1 h to 96 h	No growth at 5 mg/L atrazine; marked growth-inhibitory effect at 0.25 mg/L.	After short-term exposure, algal cells resuspended in atrazine-free media. Longer exposures apparently used for atrazine removal but paper unclear regarding effects on growth.	Véber et al., 1981
Yellow-green alga (Bumilleriopsis filiformis)	Atrazine	6-7 d	0.2 mg/L caused 50% reduction in O_2 production. Normal growth resumed in atrazine-free media.	Effects on photosynthetic membrane system investigated. In tact cell and cell-free system inhibited in same conc. range.	Boger and Schule, 1976

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Green algae (Chlorella pyrenoidosa)	Atrazine (A)	12-14 d	EC_{50} = 0.5 mg/L	EC_{50} = conc. causing 50% decrease in photosynthesis.	Stratton, 1984
	Deethylated A		EC_{50} = 1.8 mg/L		
	Deisopropylated A		EC_{50} = 3.6 mg/L		
	Diamino - A		EC_{50} = >100 mg/L		
	Hydroxy - A		EC_{50} = >100 mg/L		
(Scenedesmus quadricauda)	Atrazine (A)	12-14 d	EC_{50} = 0.3 mg/L	EC_{50} = conc. causing 50% decrease in photosynthesis.	Stratton, 1984
	Deethylated A		EC_{50} = 1.8 mg/L		
	Deisopropylated A		EC_{50} = 4.0 mg/L		
	Diamino - A		EC_{50} = >100 mg/L		
	Hydroxy - A		EC_{50} = >100 mg/L		
(C. pyrenoidosa)	Atrazine (A)	12-14 d	EC_{50} = 0.3 mg/L	EC_{50} = conc. causing 50% decrease in growth yield as measured by absorbance.	Stratton, 1984
	Deethylated A		EC_{50} = 3.2 mg/L		
	Deisopropylated A		EC_{50} = >10 mg/L		
	Diamino - A		EC_{50} = >10 mg/L		
	Hydroxy - A		EC_{50} = >10 mg/L		
(S. quadricauda)	Atrazine (A)	12-14 d	EC_{50} = 0.1 mg/L	EC_{50} = conc. causing 50% decrease in growth yield as measured by absorbance.	Stratton, 1984
	Deethylated A		EC_{50} = 1.2 mg/L		
	Deisopropylated A		EC_{50} = 6.9 mg/L		
	Diamino - A		EC_{50} = 4.6 mg/L		
	Hydroxy - A		EC_{50} = >10 mg/L		
(C. pyrenoidosa)	Atrazine (A)	12-14 d	EC_{50} = 1.0 mg/L	EC_{50} = conc. causing 50% decrease in growth rate; method not given.	Stratton, 1984
	Deethylated A		EC_{50} = 7.2 mg/L		
	Deisopropylated A		EC_{50} = >10 mg/L		
	Diamino - A		EC_{50} = >10 mg/L		
	Hydroxy - A		EC_{50} = >10 mg/L		

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
(S. quadricauda)	Atrazine (A) Deethylated A Deisopropylated A Diamino - A Hydroxy - A	12-14 d	EC_{50} = 0.2 mg/L EC_{50} = 2.0 mg/L EC_{50} = 6.5 mg/L EC_{50} = 10.0 mg/L EC_{50} = >10 mg/L	EC_{50} = conc. causing 50% decrease in growth rate; method not given.	Stratton, 1984
Blue-green algae (Anabaena inequalis)	Atrazine (A) Deethylated A Deisopropylated A Diamino - A Hydroxy - A	12-14 d	EC_{50} = 0.3 mg/L EC_{50} = 2.5 mg/L EC_{50} = 9.0 mg/L EC_{50} = >100 mg/L EC_{50} = >100 mg/L	EC_{50} = conc. causing 50% decrease in photo-synthesis.	Stratton, 1984
(A. cylindrica)	Atrazine (A) Deethylated A Deisopropylated A Diamino - A Hydroxy - A	12-14 d	EC_{50} = 0.5 mg/L EC_{50} = 4.8 mg/L EC_{50} = 9.3 mg/L EC_{50} = >100 mg/L EC_{50} = >100 mg/L	EC_{50} = conc. causing 50% decrease in photo-synthesis.	Stratton, 1984
(A. variabilis)	Atrazine (A) Deethylated A Deisopropylated A Diamino - A Hydroxy - A	12-14 d	EC_{50} = 0.1 mg/L EC_{50} = 0.7 mg/L EC_{50} = 4.7 mg/L EC_{50} = 100 mg/L EC_{50} = >100 mg/L	EC_{50} = conc. causing 50% decrease in photo-synthesis.	Stratton, 1984
(A. inequalis)	Atrazine (A) Deethylated A Deisopropylated A Diamino - A Hydroxy - A	12-14 d	EC_{50} = 0.03 mg/L EC_{50} = 1.0 mg/L EC_{50} = 2.5 mg/L EC_{50} = 7.0 mg/L EC_{50} = >10 mg/L	EC_{50} = conc. causing 50% decrease in growth yield as measured by absorbance.	Stratton, 1984

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
(A. cylindrica)	Atrazine (A) Deethylated A Deisopropylated A Diamino - A Hydroxy - A	12-14 d	EC_{50} = 1.2 mg/L EC_{50} = 8.5 mg/L EC_{50} = >10 mg/L EC_{50} = >10 mg/L EC_{50} = >10 mg/L	EC_{50} = conc. causing 50% decrease in growth yield as measured by absorbance.	Stratton, 1984
(A. variabilis)	Atrazine (A) Deethylated A Deisopropylated A Diamino - A Hydroxy - A	12-14 d	EC_{50} = 4.0 mg/L EC_{50} = 3.5 mg/L EC_{50} = 5.5 mg/L EC_{50} = >10 mg/L EC_{50} = >10 mg/L	EC_{50} = conc. causing 50% decrease in growth yield as measured by absorbance.	Stratton, 1984
(A. inequalis)	Atrazine (A) Deethylated A Deisopropylated A Diamino - A Hydroxy - A	12-14 d	EC_{50} = 0.1 mg/L EC_{50} = 4.0 mg/L EC_{50} = 7.0 mg/L EC_{50} = >10 mg/L EC_{50} = >10 mg/L	EC_{50} = conc. causing 50% decrease in growth rate; method not given.	Stratton, 1984
(A. cylindrica)	Atrazine (A) Deethylated A Deisopropylated A Diamino -A Hydroxy - A	12-14 d	EC_{50} = 3.6 mg/L EC_{50} = 5.5 mg/L EC_{50} = >10 mg/L EC_{50} = >10 mg/L EC_{50} = >10 mg/L	EC_{50} = conc. causing 50% decrease in growth rate; method not given.	Stratton, 1984
(A. variabilis)	Atrazine (A) Deethylated A Deisopropylated A Diamino - A Hydroxy - A	12-14 d	EC_{50} = 5.0 mg/L EC_{50} = 7.5 mg/L EC_{50} = 9.2 mg/L EC_{50} = >10 mg/L EC_{50} = >10 mg/L	EC_{50} = conc. causing 50% decrease in growth rate; method not given.	Stratton, 1984

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Green algae (Selenastrum capricornutum)	Atrazine	24 h	EC_{50} = 0.053 mg/L (0.043 to 0.064 mg/L) EC_{50} = 0.034 mg/L (0.029 to 0.040 mg/L) EC_{50} = 0.042 mg/L (0.037 to 0.045 mg/L)	EC_{50} based on 50% decrease of ^{14}C-uptake as HCO_3^-.	Larsen et al., 1986
(Ankistrodesmus sp.)	Atrazine	24 h	EC_{50} = 0.072 mg/L (0.062 to 0.082 mg/L) EC_{50} = 0.061 mg/L (0.054 to 0.068 mg/L)	EC_{50} based on 50% decrease of ^{14}C-uptake as HCO_3^-.	Larsen et al., 1986
(Chlamydomonas reinhardi)	Atrazine	24 h	EC_{50} = 0.037 mg/L (0.019 to 0.048 mg/L)	EC_{50} based on 50% decrease of ^{14}C-uptake as HCO_3^-.	Larsen et al., 1986
(Scenedesmus obliquus)	Atrazine	24 h	EC_{50} = 0.038 mg/L (0.027 TO 0.050 mg/L) EC_{50} = 0.057 mg/L (0.051 to 0.064 mg/L) EC_{50} = 0.049 mg/L (0.044 to 0.055 mg/L)	EC_{50} based on 50% decrease of ^{14}C-uptake as HCO_3^-.	Larsen et al., 1986
(Chlorella vulgaris)	Atrazine	24 h	EC_{50} = 0.325 mg/L (0.298 to 0.357 mg/L) EC_{50} = 0.305 mg/L (0.277 to 0.334 mg/L) EC_{50} = 0.293 mg/L (0.273 to 0.314 mg/L)	EC_{50} based on 50% decrease of ^{14}C-uptake as HCO_3^-.	Larsen et al., 1986

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
(Stigeoclonium tenue)	Atrazine	24 h	EC_{50} = 0.127 mg/L (0.108 to 0.151 mg/L) EC_{50} = 0.224 mg/L (0.195 to 0.265 mg/L)	EC_{50} based on 50% decrease of ^{14}C-uptake as HCO_3^-.	Larsen et al., 1986
(Ulothrix subconstricta)	Atrazine	24 h	EC_{50} = 0.088 mg/L (0.060 to 0.132 mg/L)	EC_{50} based on 50% decrease of ^{14}C-uptake as HCO_3^-.	Larsen et al., 1986
Blue-green alga (Anabaena cylindrica)	Atrazine	24 h	EC_{50} = 0.253 mg/L (0.173 to 0.483 mg/L) EC_{50} = 0.178 mg/L (0.130 to 0.026 mg/L) EC_{50} = 0.182 mg/L (0.140 to 0.268 mg/L)	EC_{50} based on 50% decrease of ^{14}C-uptake as HCO_3^-.	Larsen et al., 1986
Green alga (Chlorella pyrenoidosa	Atrazine 80W	14 h	0.1 mg/L slightly inhibitory; concen-centrations above 1 mg/L were completely inhibitory.		Wells and Chappell, 1965
Green algae (Chlorococcum sp.)	Atrazine (Tech. acid)	90 min	EC_{50} (O_2 production) = 0.10 mg/L EC_{50} (growth) = 0.10 mg/L		Walsh, 1972
	Atrazine (80% W.P.)	90 min	EC_{50} (O_2 production) = 0.40 mg/L EC_{50} (growth) = 0.10 mg/L		

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
(Dunaliella tertiolecta)	Atrazine (Tech. acid)	90 min	EC_{50} (O_2 production) = 0.30 mg/L EC_{50} (growth) = 0.30 mg/L		Walsh, 1972
	Atrazine (80% W.P.)	90 min	EC_{50} (O_2 production) = 0.60 mg/L EC_{50} (growth) = 0.40 mg/L		
Green algae (Ankistrodesmus braunii)	Atrazine (99.9%)	11 d	EC_{50} (growth) = 0.06 mg/L		Burrell et al., 1985
(Chorella vulgaris)	Atrazine (99.9%)	11 d	EC_{50} (growth) = 0.025 mg/L		
Green algae (Selenastrum capricornutum)	AAtrex 80W	24 h	EC_{50} (O_2 production) = 0.070 mg/L (0.065 to 0.094 mg/L)	Using synthetic algal media.	Turbak et al., 1986
		24 h	EC_{50} (O_2 production) = 0.85 mg/L (0.79 to 0.93 mg/L)	Using natural water.	
		2-3 wk	EC_{50} (growth) = 0.059 mg/L (0.048 to 0.071 mg/L)	Using synthetic algal media.	
		2-3 wk	EC_{50} (growth) = 0.41 mg/L (0.59 to infinity)	Using natural water.	

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
AQUATIC VASCULAR PLANTS					
Pondweed (Potamogeton perfoliatus)	Atrazine	4 h	I_{50} = 0.080 mg/L 87% photosynthetic reduction by 0.650 mg/L	I_{50} = 50% photosynthetic inhibition	Jones et al., 1986
Pondweed (Potamogeton perfoliatus)	Atrazine	2 h	I_{50} = 0.077 mg/L I_1 = 0.020 mg/L	I_{50} = 50% photosynthetic inhibition I_1 = 1% photosynthetic inhibition	Jones and Winchell, 1984
Water milfoil (Myriophyllum spicatum)	Atrazine	2 h	I_{50} = 1.104 mg/L I_1 = 0.020 mg/L	I_{50} = 50% photosynthetic inhibition I_1 = 1% photosynthetic inhibition	Jones and Winchell, 1984
Horned pondweed (Zannichellia palustris)	Atrazine	2 h	I_{50} = 0.091 mg/L I_1 = 0.017 mg/L	I_{50} = 50% photosynthetic inhibition I_1 = 1% photosynthetic inhibition	Jones and Winchell, 1984
Wigeon grass (Ruppia maritima)	Atrazine	2 h	I_{50} = 0.102 mg/L I_1 = 0.020 mg/L	I_{50} = 50% photosynthetic inhibition I_1 = 1% photosynthetic inhibition	Jones and Winchell, 1984

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Pondweed (Potamogeton perfoliatus)	Atrazine	4 wk	I_{50} = 0.130 mg/L	I_{50} = 50% photosynthetic inhibition	Kemp et al., 1985
Eel grass (Zostera marina)	Atrazine	21 d	50% mortality at approx. 0.1 mg/L.	Salinity = 19-22 g/L	Delistraty and Hershner, 1984
Waterweed (Elodea canadensis)	Atrazine	3-6 wk	50% growth inhibition at 0.080 and 0.109 mg/L; 1% inhibition at 0.003 and 0.012 mg/L.		Forney and Davis, 1981
Eel grass (Vallisneria) americana)	Atrazine	3-6 wk	50% growth inhibition at 0.532, 0.414, and 0.163 mg/L; 1% inhibition at 0.005, 0.014, 0.008, and 0.004 mg/L.		Forney and Davis, 1981
Pondweed (Potamogeton perfoliatus)	Atrazine	3-6 wk	50% mortality at 0.053 mg/L; 50% decrease in dry wt. at 0.907 mg/L; 50% decrease in length at 0.474 mg/L.	1% mortality at 0.011 mg/L; 1% decrease in dry wt. at 0.004 mg/L; 1% decrease in length at 0.006 mg/L.	Forney and Davis, 1981
Watermilfoil (Myriophyllum spicatum	Atrazine	3-6 wk	50% growth inhibition at 1.104 mg/L; 1% growth inhibition at 0.044 mg/L.		Forney and Davis, 1981

Table B-1. Continued

Organisms	Chemical or formulation	Exposure time	Effects[1]	Comments	Reference[2]
Common seagrass (Thalassis testudinum	Atrazine (Tech. grade)	40 h	50% inhibition of O_2 evolution at 0.32 mg/L; 15.8% at 0.1 mg/L; 77.2% at 0.5 mg/L.	Salinity = 30 g/L	Walsh et al., 1982
Sago pondweed (Potamogeton pectinatus	Atrazine 4L^R (40.8% atrazine)	48 h	Significantly inhibited growth at 0.10 mg/L.		Hartman and Martin, 1985
Eel grass (Zostera marina)	Atrazine	21 d	50% growth inhibition for shoot length at 0.410 mg/L; 50% inhibition of leaf number at 0.060 mg/L.	Salinity unknown.	Hershner et al., 1983

Appendix C

Summary of Microcosm Studies Dealing with Atrazine Exposure

Table C-1. Summary of Microcosm Studies Dealing with Atrazine Exposure

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
Forty-two, 50-L glass aquaria; 32x26x48 cm. Potamogeton perfoliatus or Myriophyllum spicatum (both plants not in same aquarium) Filtered (5 μm) Chesapeake Bay water, sediments, 8 cm deep.	Salinity: 8-12 g/L Temp: 21.5 ± 1.5°C Light: 150-200 $\mu E/m^2/s$ Photoperiod: 14L:10D D.O.: 3.4 mg/L Dev. period: 7 wk Test period: 4 wk	Technical grade; diss. in 100 mL methanol for final microcosm conc. of 5, 50, 100, 500, and 1000 μg/L. One exposure.	P. perfoliatus: ≥50 μg/L caused sign. O_2 production depression in week 1-2 posttreat; 5 μg/L caused sign. depression in wk 2-3. ≥100 μg/L caused sign. loss of biomass in wk 4 posttreat; ≥500 μg/L caused sign. loss of biomass in wk 1. M. spicatum: ≥50 μg/L caused sign. O_2 production depression in wk 1-2 post-treat; 5 μg/L caused sign. enhancement of O_2 production; ≥500 μg/L caused sign. loss of biomass in week 1-4; no effects on biomass at conc. ≤100 μg/L.	Kemp et al., 1985

min = minutes(s)
h = hour(s)
d = day(s)
wk = week(s)
mo = month(s)
yr = year(s)

conc. = concentrations
dev. period = development period
dia. = diameter
diss. = dissolved
D.O. = dissolved oxygen
exp. = experiment

sev. = several
sign. = significant(ly)
std. = standard
temp. = temperature
wt. = weight

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
Sixteen 4-L glass jars; 3.8 L of water (mix of std. reconstituted water and natural wetland water, 8:1, v/v) and hydrosoil of a ratio of 9:1 (v/v). Lemna sp., Ceratophyllum sp., Elodea sp. Natural communities of invertebrate and algae (developed within each microcosms and cross-seeded). Daphnia magna (25 adults) introduced into each microcosm unit 48 h pretreatment; continuous additions of 25 adults if population declined to fewer than 5 adults.	Light: 1400 lux Photoperiod: 16L:8D Dev. period: sev. wk Temp.: 20 ± 1°C Test period: 30 d	Technical grade; 85.5% active, wettable powder; final microcosm conc. of 10, 100, and 1000 µg/L of active ingredient. Introduced into microcosm as soil slurry. One exposure.	Viability of D. magna not sign. different from control at any conc.; 7-d chronic toxicity tests using D. magna from test microcosms show 1000 µg/L dose did not affect life cycle after 30 d in microcosm; 100- and 1000-µg/L treatments reduced algal growth by 40% as determined by std. algal bioassay at end of 30 d. Immediate gross primary production reduction at 10 and 1000 µg/L upon atrazine introduction. Recovery of D.O. in 10 µg/L after 7 d. Macrophyte biomass reduced by 50% in 1000-µg/L treatment after 30 d. 1000-µg/L treatment increased microcosm conductivity and alkalinity and decreased pH.	Johnson, 1986
Seamless glass aquaria (20x30x18); 0.5-cm layer of pond sediment; 7 L pond water; inoculum of net plankton plus aufwuchs from natural pond. Microcosms mixed continuously by chain-riven, 50-rpm stirrers. Each microcosm with separate	Temp.: 19-24.5°C Light: 6500 lux Photoperiod: 12L: 12D Test period: Exp. 1: 12 d Exp. 2: 7 d Dev. period: 39 wk Note: description of experimental	Exp 1: 50, 500, and 5000 µg/L atrazine. Exp. 2: 0.5, 5, and 100 µg/L. In addition, conc. "spikes" of atrazine introduced at various	Sign. decrease in oxygen production at 50 µg/L and above. No differences observed in community structure in Exp. 2 at 0.5 and 5 µg/L.	Brockway et al., 1984

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
nutrient feed system added at 0.6 mL/min, 8.1 d retention time.	design extremely convoluted and confusing.	times to bring total atrazine conc. up to 100 µg/L in Exp. 2 at 0.5 µg/L.		
Six 700-L glass aquaria; 1.8x0.6x0.8 m; filtered (5 µm) estuarine water; estuarine sediments 12 cm deep; Potamogeton perfoliatus (75 plants per microcosm).	Temp.: 22-26°C Salinity: 9.5-10.5 g/L Photoperiod: 14L:10D Dev. period: 3 wk Test period: 30 d	2 treatments: 86 and 860 mg atrazine; each dissolved in 100 mL acetone; 100 kg dry sediment added with acetone removed prior to addition of sediment to microcosms; 130-140 µg/L exposure; 860 mg produced 1100-1310 µg/L exposure.	130-140 µg/L sign. reduced photosynthesis in wk 1 with sign. recovery by wk 4; 1100-1310 µg/L sign. reduced photosynthesis over entire posttreatment period (4 wk). Sign. decline in density of stems with leaves of conc. 1100-1310 µg/L between wk 5 and 7; final shoot density about 20% of control. Sign. declines in total plant biomass in both treatments at wk 2.	Cunningham et al., 1984

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
Glass aquaria; 50x25x30 cm; 6 kg (dry) sediments; 25 L well water plus Instant Ocean Salt mix; Zannichellia palustris, Potamageton pectinatus, Zostera marina, and Vallisneria americana.	Light: 100 $\mu E/m^2/s$ pH: 8 Temp: varied with different tests Test period: "sev. wk" (exact time not given)	Exp. 1: 75 and 650 $\mu g/L$ Exp. 2: 1.3, 12, 120, and 1060 $\mu g/L$	Exp. 1: Z. palustris: O_2 production sign. inhibited at both conc. V. americana: sign. inhibited at high conc. P. pectinatus and Z. marina: sign. inhibited at upper concentrations but sign. stimulated at lower conc. Exp. 2: V. americana: rapid and complete mortality at 1060 $\mu g/L$; slower mortality rate but complete in 30 d at 120 $\mu g/L$; 50% mortality in 47 d at 12 μ/L.	Correll and Wu, 1982
Glass, water-jacketed 40-L aquaria; uncontaminated soil (6-7 cm depth), Zanichellia palustris (200 per microcosm), well water plus Instant Ocean Salt mix.	Temp: 23°C Photoperiod: 16L:8D Salinity: 5 g/L pH: 8 Dev. period: 0 Test period: 4 wk	Atrazine added as conc. solution in methanol and mixed in soil.	Net oxygen production and gross photosynthesis sign. inhibited by bottom sediments (0.5-2 mg/kg) and water column (0.1-1.4 mg/kg) atrazine. Plants exposed to 2 mg/L or more in sediments died after 14 d.	Correll et al., 1978
Pyrex glass jars (0.56 to 1.0 L), polyethylene tops; 5 g (dry wt.) benthic sediment, 10 mL reconstituted water, 10 1st instar Daphnia magna, 10 1st instar Chironomus riparius, also indigenous population of other cladocerans, ostracods, tubificid worms, filementous algae, duckweed, and other macrophytes.	Temp: 18-23°C Photoperiod: 16L:8D Light: 0.75-0.87 $\mu E/m^2/s$ Dev. period: 2 wk Test period: 6 wk	Atrazine added as suspended sediment/water mixture (95.1% to total atrazine in water). Atrazine was mixture of nonlabelled and ^{14}C-atrazine for total input of aprox. 40 $\mu g/L$ (including direct input of 4 μg atrazine dissolved in acetone).	Disappearance of atrazine in water approximated biphasic sediment sorption kinetics and also involved volatilization and degradation. At end of 6 wk, 50% of total microcosm atrazine was in water, 40% in sediments; plants and invertebrates each contained less than 1%. Highest atrazine conc. in microcosm components occurred in algae and macrophytes, 2nd highest in midge larvae, 3rd in sediment. Water had lowest conc.	Huckins et al., 1986

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
Sixteen 11-L glass aquaria with continuous flow of dechlorinated tap water; periphyton assemblage obtained from local rivers and incubated in laboratory for sev. wk.	24-h retention time at 7.5-L storage volume. Photoperiod: 12L: 12D Temp: 25°C Dev. period: 6 wk Test period: 4 wk and 3 wk recovery period	50, 100, and 150 µg/L added once daily for 4 wk. Atrazine dissolved in methanol.	All conc. caused sign. reductions in D.O. conc. but returned to within 90% of pretreated D.O. conc. 48 h after atrazine input stopped. All atrazine conc. caused sign. nitrate reductions during exposed periods. After atrazine input stopped, nitrate levels increased to within 90% of pretreatment levels.	Rocchio and Malanchuk, 1986
35-cm dia. plastic tubs with 10-cm layer of soil; 7.6 L of water. Tidal action simulated; edaphic algae; fiddler crabs (Uca pugnax)(lab study).	Salinity: 20 g/L Microcosm was flooded with atrazine-containing water twice daily for 5 d. Water in reservoirs supplying "tidal water" changed after after 5 d to atrazine-free water.	Atrazine introduced into "tidal water" at 2.16 mg/L. One application.	Reduction in primary productivity and chlorophyll content of 0-5 mm layer in Feb. 1977. Cell numbers and chlorophyll content of surface algae not affected. In April, content of surface algae reduced but not in soil. Little effect on community structure.	Plumley and Davis, 1980
36-cm dia., 29-cm deep plastic tubs filled to a depth of 15 cm with surface soil creek bank. Tubs partially buried so soil levels inside and outside matched. 3-cm dia. hole allowed tidal water movement in and out of tubs (field study).	Dev. period: 7 d For atrazine applications, tub removed to high ground and flooded twice daily for 5 d with 2.16-mg/L atrazine solution.	As above.	Carbon fixation of edaphic algae sign. decreased at 7 and 18 d after treatment. The presence of the plastic tub had a sign. effect on community structure in field study.	Plumley and Davis, 1980

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
Twelve aluminum cylinders, 1.8 m dia., 90 cm high, pressed 15 cm into soil surface (75 cm above ground). Single 5-cm hole (with screen) allowed tidal inflow/outflow with crabs (Uca pugnax) retained in system (estuarine field study).	Not stated.	Atrazine applied as in 500 mL of water at 100, 1000, and 10 000 mg/L (0.05, 0.5, and 5.0 g/m^2). One application.	Carbon fixation by edaphic algae sign. reduced for 0.05 and 0.5 g/m^2 rates 16 d after treatment. 5.0 g/m^2 inhibited carbon fixation through 42 d.	Plumley and Davis, 1980
12-cm dia. Büchner funnel containing salt marsh soil and connected by tubing to 1-L bottle with 750 mL of seawater. Bottle raised and lowered to flood and drain soil surfaces (twice daily for 20 d). Spartina alterniflora leaves from plants previously grown in ^{14}C-labelled atrazine solution for 2 d, then in atrazine-free nutrient solution for 3 d. Dried leaves placed on top of soil in funnel.	Prior to atrazine exposure, S. alterniflora plants cultured in growth chamber. Photoperiod: 14L:10D Temp. 28°C (light) 24°C (dark) Light: 35 lux Test period: 20 d	S. alterniflora plants grown in 0.26 mg/L ^{14}C-atrazine solution.	During the 20-d test period a decrease in the amount of chloroform-soluble material corresponded to an increase in water-soluble atrazine metabolites. About 67% of initial total radio activity in S. alterniflora leaves recovered in seawater used to inundate microcosm leaves and soil. About 11% of total radioactivity recovered from soil.	McEnerney and Davis, 1979

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
49x49x30-cm plexiglass tanks divided into 2 areas (water reservoir and individual sediment chambers). Sediment chambers filled with atrazine-free estuarine sediments in 3 compartments (2 subsurface and 1 surface) Fourth compartment [surface and upslope (40%) of untreated sediment] contained ^{14}C-atrazine. 25-g quantities of treated sediment also placed in beakers for continuous submersion. 17 L of 9.5 ppt salinity estuarine water per microcosm. No macroorganisms present.	Two tidal flooding events per day. Other conditions not stated. Reference to Caplan et al., 1984, for more details. Organic content of sediment 11.2%. 35-d experiment.	Fourth treated sediment compartment contained 25 g of sediment at 4 mg/kg atrazine. Beakers contained same conc.	About 17% of total ^{14}C moved vertically from treated to untreated sediment after 3 d. Little additional movement afterward. One of 3% of ^{14}C moved downslope to untreated sediment. Decreased extraction efficiency over time corresponded to increased ^{14}C recovered by oxidation. Extracts of tidal sediment and continuously flooded sediment were 89% atrazine at day 1 and 18% at day 35. 54% of total radioactivity was metabolites at day 35. Only 1.3% and 2.7% of extractable radioactivity was atrazine in tidal and flooded sediments, respectively, at day 35.	Isensee, 1987
Six 125-m^3 limnocorrals, 5x5x5 m, including sediment; in 10.3-ha mesotrophic lake; periphyton added from lake on PVC strips.	Natural conditions. Exp. 1: Aug. to Dec. 1982 Exp. 2: Aug. 83 to June 1984 Periphyton dev. period: Exp. 1: 53 d Exp. 2: 39 d	Exp. 1: 2 corrals at 1.56 mg/L; 2 corrals at 0.14 mg/L, both as single doses. Exp 2: 3 corrals at 0.08 mg/L, two doses, 35 d apart.	All doses produced decline in net productivity, cell numbers, number of taxa, chlorophyll a, and ^{14}C-uptake. Periphyton exhibited "quick" recovery (21 d) for productivity at all doses. Different periphyton community components recovered at different rates (e.g., chlorophyta recovered	Hamilton et al., 1987

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
	Test period: Exp. 1: 56 d Exp. 2: 223 d		from 0.08 mg/L at end of Exp. 2 (223 d).	
Lake column simulators; stainless steel columns, 4.5 m high, 1 m dia.; containing 3336 L of water (at 4.25 m height). Phytoplankton from dense, mixed species batch culture; zooplankton (Daphnia magna); fish (Lebistes reticulata).	Photoperiod: 15L:9D Light: 175-225 $\mu E/m^2/s$ Temp: Exp. 1: 20-22°C Exp. 2: 25-26°C Test period: 40 d	Exp. 1: 7 doses applied on alternate days, 4 wk after algae added. Low dose = 3.49 mg/dose; high dose = 24.9 mg/dose. Exp. 2: 3 doses within 5 d. Low dose = 9.9 mg/dose, high dose = 99.0 mg/dose. Note: Doses in Exp. 1 and 2 were AAtrex^R (90% atrazine).	Exp. 1: Chlorophyll a conc. declined following both doses to day 15 with subsequent increase. Particulate organic carbon had similar response. Exp. 2: Decrease of chlorophyll a and particulate organic carbon in control columns. Exp. 1 and Exp. 2: Atrazine conc. in unfiltered water was 10X greater in top 2.0 m than in bottom 2.0 m of column. Exp. 2: 85% of total atrazine in water was "soluble" (i.e., passed through glass fiber filters). Exp. 1: Atrazine residues not detected in D. magna (high dose); 0.2 mg/kg in fish (high dose); highest residues in sedimented particulate matter (21.3 mg/kg) in high dose. Conc. in water (unfiltered) were 12.1 and 0.6 $\mu g/L$ (upper and lower levels, respectively) for low dose; 125 and 14.1 $\mu g/L$ (upper and lower levels, respectively) for high dose. Bioconcentration factors were 20X for suspended particulates, 170X for sedimented particulates, and 2X for fish. Exp. 2: Atazine in D. magna at 9.3 mg/kg	Millard et al., 1979

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
			(bioconcentration factor 454X) for low dose. No zooplankton in high dose. Atrazine in fish at 0.4 and 2.1 mg/kg (low and high doses, respectively) for bioconcentration factors of 20X and 9X (low and high doses, respectively). Conc. in water was 20.5 and 1.9 µg/L (upper and lower levels, respectively) for low dose; 221.4 and 7.6 µg/L (upper and lower levels, respectively) for high dose.	
Unialgal cultures of diatom (Nitzschia actinastroides) grown in presence of atrazine. Diatoms fed to limpets (Ancylus fluviatilis), which were in turn fed to leeches (Glossiphonia complanata). Study conducted in glass vessels of unspecified type.	For algal growth: Temp.: 20°C Light: 8000 lux Photoperiod: continuous light Nutrient solution: Chu No. 12	50 µg/L in diatom culture as ^{14}C-atrazine.	Conc. factions for atrazine in diatoms depended on culture age, but were generally just below 295X (on a dry wt. basis). Limpets that fed on atrazine-contaminated algae had only slightly higher concentration factors (for atrazine) than non-fed limpets exposed to atrazine in the surrounding water. Food chain magnification of atrazine and bioconcentration of atrazine by limpets feeding on atrazine-contaminated algae were not observed.	Streit, 1979
Taub microcosms: 10 algal species, 2 protozoan species, 1 amphipod species, 1 ostracod species, 1 daphnid species, and an assortment of bacteria and fungi; 3 L of	Dev. period: 7 d Test period: 2 mo Temp: 20 ± 1°C Light: 900 ft-cdl Photoperiod: 12L:12D	60, 100, 200, 500, 1000, and 5000 mg/L (one exposure per conc.).	^{14}C-HCO_3^- uptake decreased immediately with atrazine treatments; recovery began after 10 d in 60- and 100-µg/L treatments; slight recovery in 200-µg/L treatment; others remained depressed. Apparent stimulation of chlorophyll a	Larsen et al., 1986

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
synthetic media; 200 g of silica sand enriched with 0.5 g ground chitin and 0.5 g ground cellulose; 3.7 L wide-mouth pickle jars.			production in 60- to 200-μg/L treatments; sign. chlorophyll a reduction at 1000- and 5000-μg/L treatments. Conc. of 200 μg/L or more inhibited D.O. increase in light and decreased in dark; at 60 and 100 μg/L inhibition was less apparent and intermittent.	
As described above (Larsen et al., 1986)	As described above (Larsen et al., 1986).	As described above (Larsen et al., 1986)	Two general types of community level responses; one associated with high conc. (500 to 5000 μg/L) and one associated with low conc. (60, 100, and 200 μg/L). High conc. caused immediate decline and suppression through experiment. Low conc. caused apparent effects (depression), but were not consistent throughout the 60-d experiment. Some recovery of the microcosms at low conc. was noted at the end of 53 d (posttreatment).	Stay et al., 1985
Experimental ponds, 0.045-ha surface area, 2-m depth, 470-m^3 volume. Water and plankton from an adjacent 0.33-ha reservoir maintained by well water. Additions of bluegill (Lepomis macrochirus), channel catfish (Ictalurus punctatus), gizzard shad (Dorosoma cepedianum), and grass carp (Ctyenopharyngodon idella)	Not given.	Exp. 1: 20- and 500- μg/L exposures over single growing season (1979).	Exp. 1: 500 μg/L caused immediate depression of phytoplankton ^{14}C-HCO_3^- uptake activity followed by recovery and then depression. Exp. 1 not long enough to determine if ^{14}C-HCO_3^- uptake activity returned to control levels. No clear effects on photosynthesis at 20 μg/L.	
		Exp. 2: 3-year study with exposures of 20, 100,	Exp. 2: 100 and 200 μg/L caused immediate and sign. lowering of ^{14}C-HCO_3^- uptake for 2 wk, followed by	

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
(added in Exp. 2, 1981 study). Assorted aquatic macrophytes invaded ponds.		200, and 500 µg/L as annual doses (1981-1984).	a return to control levels for 2 wk, followed by a depression in ^{14}C uptake for 4 mo. After 4 mo posttreatment, ^{14}C was not different from controls. Chlorophyll a did not show clear treatment effects (as with ^{14}C-HCO_3^-) at 100 µg/L and greater treatments, but long-term inhibition did occur. No effects at 20 µg/L.	
As described above (Larsen et al., 1986).	Test period: 136 d	20- and 500-µg/L exposures over single growing season (1979). Same as Exp. 1 above (Larsen et al., 1986).	Only pH and D.O. affected by atrazine; sign. not given. At 20 µg/L, ^{14}C-HCO_3^- uptake and algal biomass declined sign. by day 2, but returned to control level by day 7 and remained there through day 63. At 500 µg/L, ^{14}C-HCO_3^- and algal biomass averaged less than in control ponds for entire study (136 d). Succession of phytoplankton species was altered at both concentrations. Zooplankton community structure altered at both concentrations apparently in response to change in phytoplankton community. Growth of aquatic vascular plants also reduced at both levels.	deNoyelles et al., 1982; deNoyelles and Kettle, 1985

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
As described above (Larsen et al., 1986)	Test period: 3 yr	20, 100, 200, and 500 µg/L with annual doses over a 3-yr study.	Mean turbidity increased sign. with increased conc. Aquatic macrophyte production decreased with increasing conc. Abundance of emerging chironomids was sign. reduced at 20 µg/L. Benthic insect species richness, equitability, and total emergence all declined sign. with atrazine treatments. Nonpredatory insects were more reduced relative to predatory insects. The emergence periods of several herbivorous insects were also altered by atrazine.	Dewey, 1986
As described above (Larsen et al., 1986)	Test period: 136 d	20- and 500-µg/L exposures over single growing season (1979). Same as Exp.1 above (Larsen et al., 1986).	Of the 3 fish species introduced, only bluegill reproduced during the study. Number of young from treated ponds sign. less than controls. Mortality not sign. different among ponds. Stomach contents differed sign. between treatments and control in terms of food diversity and quantity. Macrophyte coverage declined about 90% in 20-µg/L treatment and over 95% in 500-µg/L treatment.	Kettle et al., 1987
Nine opaque PVC tubes, 50 cm dia. containing approx. 180 L of water placed into 7-yr-old pond (approx. 4x2.5 m and	Dev. period: 3 wk Test period: 19 wk	1.08 mg giving water conc. of 200 µg/L.	Sharp decline in D.O. conc. to detection limit (not given) in 5 d posttreatment. At 40 d posttreatment, D.O. in treatments same as control. Treat-	Lay et al., 1984; Peichl et al., 1984

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
0.8 m deep) and pressed 0.3 m into sediment. Phytoplankton from existing pond.			ment pH values sign. lower immediately after treatment and for the following 29 d after which pH values were not different from control. Conductivity increased above control 5 to 125 d post-treatment. Phytoplankton taxa decreased shortly after treatment. 32 phytoplankton species (7 phyla) existed in pretreatment microcosms. After treatment only two phyla survived (surviving species not given). Sign. increase in rotifer Keratella sp. 3 d posttreatment, then decreasing below controls at 7 to 30 d posttreatment.	
PVC tubes, 1.25 m dia. containing approx. 980 L in pond (approx. 15x15 m and 0.8 m deep) and pressed 0.3 m into sediment.	Test period: 50 d	10 µg/L	Confirmation of previous reports (Peichl et al., 1984) that changes in rotifer populations were due to changes in phytoplankton populations.	Peichl et al., 1985
Limnocorrals (5x5x5 m) in mesotrophic lake in Lake Ontario sediment part of microcosm. Weekly nutrient supplements given.	Dev. period: 3 wk Test period: 329 d	Atrazine applications on 1 June 1983 and 6 July 1983 to give 100 µg/L at each application. Conc. ranged from 80 to 400 µg/L after June	No sign. chemical or physical effects after June treatment. July treatment caused sign. reductions in D.O. and sign. increases in transparency, dissolved inorganic carbon, and NO_2-NO_3 nitrogen. All parameters except nitrogen recovered to control levels by end of experiment. Treatments sign.	Herman et al., 1986

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
		treatment. Conc. increased 20%-30% after July treatment.	reduced periphyton biomass, but effect was not consistent over time. No sign. effects on chlorophyll until after July treatment. Afterwards treatments were lower than controls, but not always sign. Species composition altered. June treatment eliminated blue-green algae; July treatment generally reduced greens and diatoms. No recovery of biomass. ^{14}C uptake reduced only after July treatment.	
Farm ponds I (0.49 ha), III (0.63 ha), and IV (0.56 ha). Bluegill (Lepomis macrochirus), phyto-and zooplankton, crayfish (species unknown), and tadpoles (species unknown).	Test period: 2 yr	AAtrex 4L^{R}, 43% atrazine added in July 1973 to ponds I and III at 0.30 mg/L and again in May 1974.	Atrazine residues (165-353 µg/L) in all components except tadpoles immediately after treatment. Residues decreased slightly during growing season, but were still present at end of growing season. Prior to treatment in 1974, low residue levels (e.g., 21 µg/L or less) were found in water and mud, but not in biological components. The same pattern of decay followed the 1974 treatment. Biological magnification was not observed.	Klaassen and Kadoum, 1979
U.S. EPA's Aquatic Ecosystem Simulator (AEcoS). A controlled environmental chamber containing 4 channels (artificial streams). Periphyton	Dev. period: 43 d Flow: 250 L/d Temp: 15°C Photoperiod: 12L:12D	100 µg/L maintained for 14 d.	Net productivity decreased rapidly within hours of atrazine addition to 23% of control values on daily basis. Slight effect on community respiration producing small increases in nighttime	Hamala and Kollig, 1985

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
Six artificial streams constructed from existing concrete troughs in an abandoned fish hatchery. Water diverted from small woodland stream. Benthic organisms and periphyton colonization from diverted water and introduced natural substrates.	Temp: 15.5°C (May) to 0.5°C (Dec.) Dev. period: 2 yr Test period: 30-d period during each season.	Technical grade atrazine at 25 µg/L.	Increase in invertebrate drift (compared to solvent control) only during summer atrazine additions. No sign. effects on periphyton standing crop (as dry wt.). No treatment effects found for primary productivity or community respiration or on community macroinvertebrate structure.	Lynch et al., 1985
As described above (Lynch et al., 1985). Biological colonization resulted from organisms incidentally introduced with substrated and diverted water. Fish (Cottus bairdi), clams (Strophitis rugosus), and crayfish (Orconectes sp.) added from other streams.	Dev. period: 1 yr Temp: 15.5°C (May) to 0.5°C (Dec.) Test period: 30-d period during each season.	Technical grade and radiolabelled atrazine; total mean conc.: 49.54 ± 39.76 µg/L.	Atrazine conc. in substrates were usually less than 1.0 µg/L where they were detected. Patterns of accumulation or clearance could not be discerned. Atrazine remained in substrate after 54 d of clearance during winter and spring experiments. Atrazine conc. (when detected) were generally less than 3.0 µg/g in biota during atrazine additions. Atrazine residues in biota were not found during depuration phases. When calculated for individual samples of organisms, bioconcentration factors ranged from 0.8 to 480, but were generally less than 50.	Lynch et al., 1982
Thirty-two recirculating artificial streams. Periphyton communities derived from natural spring and agriculturally impacted river.	Streams placed on roof of building with translucent fiberglass covers. During colonization	AAtrex^{R} 80 WP; 0.1, 1.0, and 10 mg/kg atrazine applied after 3-4 wks colonization.	Sign. acute effects of atrazine resulted in progressive decrease in biovolume over the 0-10 mg/kg treatment sequence. A 27-fold decline in total biovolume occurred in the 10-mg/kg	Kosinski, 1984; Kosinski and Merkle, 1984

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
established from pond plankton and littoral sediments.	Light: 8608 lux Test period: 37 d (21 d recovery).		respiration. Several changes in community structure, including decreased algal density and diversity, altered species composition, and reduced rates of biomass accumulation. Rapid recovery of net productivity in recovery period (posttreatment) suggests atrazine's effect is algistatic. Only little to partial recovery within recovery period.	
As described above (Hamala and Kollig, 1985).	As described above (Hamala and Kollig, 1985).	As described above (Hamala and Kollig, 1985).	Normal diurnal pH fluctuation of 1.9 (i.e., 7.3-9.2) reduced to 0.5 immediately after treatment. Recovery started immediately after input of atrazine stopped and was about 90% of control in 10 d. D.O. had similar pattern to pH, i.e., 7-13.5 mg/L before treatment, 3.5-6.5 mg/L midway through treatment, and recovery to a 6.4-12 mg/L fluctuation at end of experiment. NO_3 conc. decreased sign. upon treatment, increased above control levels after treatment (approx. 7 d), then returned to control level. No sign. difference between orthophosphate levels in treatments and control until after atrazine input stopped. Afterward, treatment microcosms were sign. lower than controls.	Malanchuk and Kollig, 1985

Table C-1. Continued

Microcosm type and components	Environmental conditions	Atrazine concentrations	Results	Reference
	period (3-4 wk) 0.01 mg/kg atrazine maintained in half of streams used. Test period: 2 yr		treatment in one year. No evidence of induced resistence by exposure to low conc. Different algal species varied in their response to atrazine. Photosynthesis was significantly depressed by 1 and 10 mg/kg atrazine. Indications of 1 slight inhibition of photosynthesis by 0.1 mg/kg.	
As described above (Kosinski, 1984).	As described above, except: Dev. period: 5 wk	AAtrex^{R} 80 WP; 0.1, 1.0, and 10 mg/kg atrazine applied after dev. period.	Sign. decrease of net community productivity (NCP) at all conc. Sign. decline of NCP with time in control streams made data interpretation difficult. No sign. differences in respiration rates in streams receiving atrazine. No major shifts in numerical importance of dominant algal groups.	Moorhead and Kosinski, 1986

Appendix D
Atrazine Toxicity Data

Table D-1. Atrazine Toxicity Data For Birds[1]

Formulation	Organism	Nature of exposure	Exposure Time	Effects	Comments	References
Atrazine (99% ai)	Bobwhite	Ingestion	5 d (+3 d observation)	LC_{50} >5000 mg/kg in feed.	No mortality to 5000 mg/L. 9-d-old birds.	Hill et al., 1975
Atrazine (99% ai)	Japanese quail	Ingestion	5 d (+3 d observation)	LC_{50} >5000 mg/kg in feed.	No mortality to 2500 mg/L, 7% mortality at 5000 mg/L. 7-d-old birds.	Hill et al., 1975
Atrazine (99% ai)	Ring-necked pheasant	Ingestion	5 d (+3 d observation)	LC_{50} >5000 mg/kg in feed.	No mortality to 5000 mg/L. 10-d-old birds.	Hill et al., 1975
Atrazine (99% ai)	Mallard	Ingestion	5 d (+3 d observation)	LC_{50} >5000 mg/kg in feed.	No mortality to 2500 mg/L, 30% mortality at 5000 mg/L. 10-d-old birds.	Hill et al., 1975
Atrazine (80% wettable powder)	Chicken	Ingestion by capsule	10 daily doses	Chickens treated with 0, 25, 50, 100, and 250 mg/kg had weight changes of +45%, +61%, +24%, +20%, and -2%, respectively.	-	Palmer and Radeleff, 1969
AAtrex^{R}, 80W	Chicken	Ingestion	7 d (+7 d observation)	100 mg/kg in diet. No toxic symptoms, visible adverse physiological effects, or changes in egg production or egg weight.	-	Foster and Khan, 1976

[1] From U.S. Department of Agriculture, 1984.
d = day(s)
wk = week(s)

Table D-1. Continued

Formulation	Organism	Nature of exposure	Exposure Time	Effects	Comments	References
AAtrex[R], 80W	Bobwhite mallard	Ingestion Ingestion	8 d 8 d	LC_{50} = 5760 mg/kg in feed. LC_{50} = 19 650 mg/kg in feed.	-	Ciba-Geigy Chemical Corporation data in Weed Science Society of America, 1983
AAtrex[R], 80W (80% ai)	Pheasant (female)	Ingestion by capsule	15 doses (one per wk)	Weekly oral doses of 100, 200, and 400 mg atrazine did not affect weight gain, number of eggs laid, eggshell thickness, visual cliff performance of offspring, and survival and weight gain of offspring.	-	Melius, 1975
Atrazine	Bobwhite	Ingestion	5 d (+3 d observation)	LC_{50} = 700 to 800 mg/kg	-	Heath et al., 1972, from U.S. Environmental Protection Agency registration data reported by Ghassemi et al., 1981

Table D-2. Atrazine Toxicity Data for Mammals[1]

Formulation	Organism	Nature of exposure	Effects	References
Atrazine	Rat	Single dose	LD_{50} = 3000 mg/kg	Bashmurin, 1974, cited in Hayes, 1982
	Rat	Single dose	LD_{50} = 1400 mg/kg	Gzhegotskiy et al., 1977, cited in Hayes, 1982
Atrazine, Technical (AAtrex^{R})	Rat	Single dose	LD_{50} = 3080 mg/kg	Geigy Agricultural Chemicals, 1971a
Atrazine, 80W	Rat	Single dose	LD_{50} = 5100 ± 400 mg/kg	Geigy Agricultural Chemicals, 1971b
Atrazine	Mouse	Single dose	LD_{50} = 1750 mg/kg	Bashmurin, 1974, cited in Hayes, 1982
Atrazine, Technical (AAtrex^{R})	Mouse	Single dose	LD_{50} = 1750 mg/kg	Geigy Agricultural Chemicals, 1971a
Atrazine	Cattle	2 doses/24 h (250 mg/kg per dose)	Lethal	Palmer and Radeleff, 1964
Atrazine	Sheep	1 dose/24 h (250 mg/kg per dose)	Lethal	Palmer and Radeleff, 1964

[1]Adapted from U.S. Department of Agriculture (1984) with additional data from Palmer and Radeleff (1964), Jowett et al. (1986), and Kobel et al. (1985).

h = hour(s) wk = week(s) d = day(s) yr = year(s) mo = month(s)

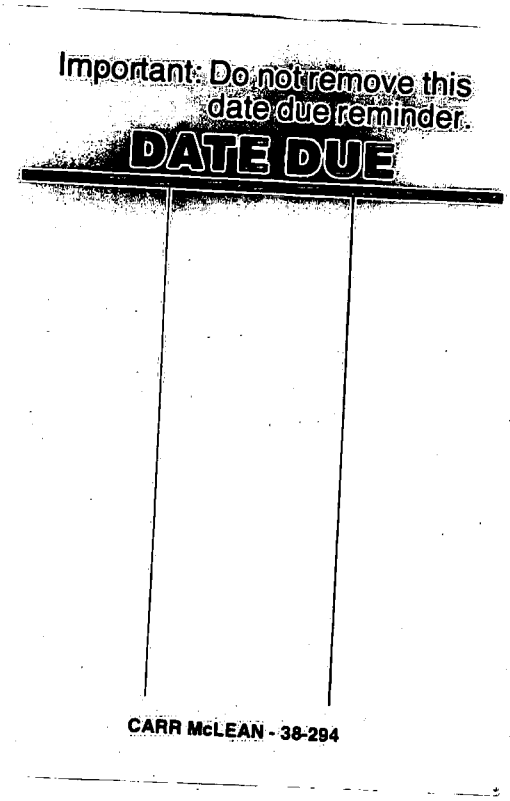
Table D-2. Continued

Formulation	Organism	Nature of exposure	Effects	References
Atrazine	Sheep	16 doses/24 h (100 mg/kg per dose)	Lethal	Palmer and Radeleff, 1964
Atrazine	Sheep	199 doses/24 h (50 mg/kg per dose)	Lethal	Palmer and Radeleff, 1964
AAtrex, 80W	Cattle	Ingestion (12 300 mg/kg in rumen contents)	Lethal in 6-8 h	Jowett et al., 1986
Atrazine	Rat	I.P. injection	LD_{50}= 125 mg/kg	Gzhegotskiy et al., 1977, cited in Hayes, 1982
AAtrex	Cattle	400 mg/kg by gavage	Lethal in 48-72 h	Kobel et al., 1985
Atrazine, 80W	Cattle	Cows fed 100 mg/kg, i.e., for 21 d or 30 mg/kg for 28 d	No observable effects.	Geigy Agricultural Chemicals, 1971a
Atrazine	Rats	Dietary levels of 100 and 500 mg/kg for 6 mo	Growth retardation.	Suschetet et al., 1974

Table D-2. Continued

Formulation	Organism	Nature of exposure	Effects	Reference
Atrazine	Sheep	Fed hay with an avg. of approx. 500 and 760 mg/kg for 4 wk for total intake of approx. 865 and 1200 mg/kg body weight.	No significant adverse effects.	Johnson et al., 1972
Atrazine	Calf	Fed hay containing approx. 500 and 760 mg/kg for 4 wk.	No significant adverse effects.	Suschetet et al., 1974
Atrazine	Cattle, dog, horse, rat	Animals fed 25 mg/kg over "extended periods."	No observable effects.	Geigy Agricultural Chemicals, 1971a
Atrazine	Rat	100 mg/kg in diet for 2 yr.	No gross or microscopic effects observed.	National Research Council, 1971, cited in U.S. Department of Agriculture, 1978
Atrazine	Rat	Rats fed dietary levels of 50, 100, 200, 300, 400, 500, and 1000 mg/kg from day 1 throughout gestation.	No effects on number of pups per litter or their weights at weaning.	Peters and Cook, 1973

Table D-2. Continued

Formulation	Organism	Nature of exposure	Effects	Reference
Atrazine	Rat	Rats injected subcutaneously at 50, 100, 200, 800, 1000, and 2000 mg/kg body weight on days 3, 6, and 9 of gestation.	No effects on number of pups per litter observed at levels up to 200 mg/kg. Levels of 800 mg/kg or higher were embryotoxic. Resorptions occurred in most of the litters. Critical day of treatment was day 6.	Peters and Cook, 1973
Atrazine	Mouse	Females dosed with 46.4 mg/kg from days 6 through 14 of gestation.	No significant increase in fetal anomalies in three strains of mice tested.	Mrak, 1969, cited in Hayes, 1982
Atrazine	Sheep	Ewes treated with 15 mg/kg/d throughout pregnancy.	No adverse effects. A dosage of 30 mg/kg/d killed pregnant and nonpregnant ewes in 36 to 60 d.	Binns and Johnson, 1970, cited in Hayes, 1982

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