Groundwater Residues of Atrazine and Alachlor Under Water-table Management Practices

P. K. Kalita, R. S. Kanwar, J. L. Baker, S. W. Melvin

Abstract. *This study was conducted to investigate the effects of various water-table management (WTM) practices on the concentrations of two surface-applied herbicides, atrazine and alachlor, in a shallow groundwater system. Groundwater samples were collected by installing piezometers and suction tubes at Iowa State University's research centers near Ames and Ankeny during three corn-growing seasons, 1989-1991. At the Ames site, experiments were conducted by maintaining constant water-table depths (WTD) of 0.3, 0.6, and 0.9 m in nine field-type lysimeters, and groundwater samples were collected from various depths during the corn-growing seasons. At the Ankeny site, a dual-pipe subirrigation system was installed on a 0.85 ha field, and variable water-table depths were maintained. Analysis of water samples collected in 1989, 1990, and 1991 clearly indicates that atrazine and alachlor concentrations in groundwater could be substantially reduced by maintaining shallow WTD during the growing season. It was also observed that atrazine concentrations were higher than those of alachlor. Alachlor was not detected in many samples; however, atrazine was detected in all samples, with high concentrations at the Ames site at the 0.9 m WTD, and at the Ankeny site at deeper WTD. Pesticide concentrations in groundwater decreased with soil depth and time. Results of this study suggest a positive influence of WTM practices in reducing pesticide concentrations in groundwater.*
Keywords. *Groundwater quality, Water table management, Atrazine, Alachlor.*

Groundwater is used for drinking by about half of the people in the U.S., and by over 75% in the rural areas (Hallberg, 1986). Detection of organic chemicals, such as pesticides, in groundwater has led to a serious concern about the potential water-quality problems associated with the increasing use of agricultural chemicals. Widely used herbicides, such as alachlor, atrazine, metolachlor, and cyanazine, have been detected in the groundwater systems of several states (Holden, 1986; Ritter, 1986). The U.S. Environmental Protection Agency (1987) estimated that at least 19 pesticides have been detected in groundwater in 24 states as a result of agricultural practices. Groundwater contamination is explainable at sites where highly soluble pesticides are applied to very permeable soils. A major concern, however, is that low concentrations of less soluble but widely used pesticides are being detected in shallow aquifers under a wide range of agricultural and climatic conditions, and three corn-production herbicides, alachlor [2-chloro-2′, 6′-diethyl-N-(methoxymethyl) acetanilide], atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-S-triazine], and cyanazine [2-chloro-4-(cyano-1-methylamino)-6-ethylamino-S-triazine] fall into this category (Isensee et al., 1988). Direct, downward leaching is found to be largely responsible for atrazine residues at low levels detected in groundwater in many irrigated corn-production areas.

Alachlor has been reported in groundwater samples in Maryland, Iowa, Nebraska, and Pennsylvania at residue levels of 0.1 to 10 µg L^{-1} (Cohen et al., 1986). Alachlor concentrations in groundwater were found to be as high as 16 µg L^{-1} in Iowa (Kelley et al., 1986). Libra et al. (1986) and Kelley et al. (1986) reported that atrazine concentrations of 10 µg L^{-1} were detected in a karst aquifer in Iowa. These concentrations were higher than the health advisory limits for atrazine (3.0 µg L^{-1}) and alachlor (0.4 µg L^{-1}). Although alachlor was found to be less persistent in soil than atrazine, Isensee et al. (1988) reported that alachlor and atrazine have similar mobilities, and that alachlor would leach as deeply as atrazine if differences in persistence were not a factor. Smith et al. (1990) found atrazine concentration of 350 µg L^{-1} in the soil water at a shallow depth 19 days after application, and this concentration was as high as 90 µg L^{-1} in the shallow groundwater even 16 months after application. But alachlor was not detected below a depth of 0.45 m, and most of the alachlor had apparently degraded during their experimental period. Experiments on pesticide and nutrient movement into subsurface tile drainage were also conducted by Kladivko et al. (1991) in which they found less than 1% of the atrazine, alachlor, and cyanazine applied were lost. They found that the total mass of pesticides, nutrients, sediments, and water removed on a per-area basis was greatest for the 5 m drain spacing and least for the 20 m drain spacing. Baker et al. (1985) observed pesticides at concentrations less than 1 µg L^{-1} in subsurface drainage water entering agricultural drainage wells, but higher levels of up to 80 µg L^{-1} were detected when surface runoff water

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The authors are **Prasanta K. Kalita**, ***ASAE Member Engineer,*** Assistant Professor, Biological and Agricultural Engineering Department, Kansas State University, Manhattan, Kans.; and **Rameshwar S. Kanwar,** ***ASAE Member Engineer,*** **James L. Baker**, ***ASAE Member Engineer,*** and **Stewart W. Melvin**, ***ASAE Member Engineer,*** Professors, Agricultural and Biosystems Engineering Department, Iowa State University, Ames, Iowa. **Corresponding author:** Prasanta K. Kalita, Biol. and Agric. Engineering Dept., Kansas State University, Manhattan, KS 66506-2906; tel.: (913) 532-5580; fax: (913) 532-5825; e-mail: <lkclass@falcon.age.ksu.edu>.

was also entering the wells. Baker (1980) and Baker and Johnson (1976) found that the concentrations of most insecticides and herbicides were higher in surface runoff than in subsurface drainage, but non-adsorbed chemicals, such as anionic herbicides, usually had higher concentrations in subsurface drainage. In two different recent studies by Kanwar et al. (1993) and Kanwar and Baker (1993), atrazine and alachlor were found more often in shallow groundwater than at deeper depths.

Jury (1986) described the factors that influence the transport of chemicals in porous media: (a) the physical and chemical properties that affect the fate of pesticides are solubility, vapor pressure, toxicity, adsorption rate, and soil reactivity; (b) the environmental conditions such as rainfall, soil properties, temperature, and erosion rate; and (c) the management factors, including the rate of pesticide application, method of application, cropping method, irrigation and/or drainage practices, and chemical used and its formulation. Some of the soil properties influencing pesticide transport are water content, bulk density, permeability, clay content, organic matter content, and water retention (Smith et al., 1990). Helling and Gish (1986) presented results of a simple modeling exercise to demonstrate the effects of several soil-properties on pesticide transport. Donigian and Rao (1986) explained that the uptake, translocation, accumulation, and transformation by plants affect pesticide availability for transport processes, and the plant processes can serve as both a sink and a source of pesticide residues available for transport. Birk and Roadhouse (1964) found atrazine to be more persistent in soil planted to corn than in fallow soil; this was attributed to the maintenance of relatively dry soil through crop transpiration and reducing the microbiological degradation of the herbicide. In contrast, Sikka and Davis (1966) reported that uptake and metabolism by the crop reduced atrazine persistence in soil planted to corn; atrazine concentration was found to be less in the 0 to 0.15 m soil depth of cropped plots than in fallow plots at all sampling dates up to 6 months after planting. Hiltbold (1974) reports that soil flooding and temporary anaerobiosis may permit reductive degradation of certain pesticides and markedly alter their persistence. Results of laboratory experiments by Castro and Yoshida (1971), and field experiments by Guenzi et al. (1971) show the influence of flooding on biodegradation rather than chemical degradation of pesticides.

Management practices have received much attention recently as potential measures to reduce groundwater contamination from agricultural chemicals. Water-table management (WTM) practices that include drainage, controlled drainage, and subirrigation reduce chemical concentrations in shallow groundwater and improve crop yield (Evans et al., 1989; Skaggs et al., 1991; Kalita and Kanwar, 1992a, 1993). Kalita and Kanwar (1990, 1992a, 1993) reported, from WTM studies in Iowa, that NO_3-N and atrazine concentrations in groundwater can be reduced by maintaining shallow water-table depth; also, corn yield increased with an increase in water-table depth up to 0.7-0.9 m and then decreased with any further increase in the water-table depth. Bengtson et al. (1989) reported a reduction in atrazine loss by 55% and metolachlor loss by 51% by subsurface drainage, and concluded that subsurface drainage substantially reduced atrazine losses; over 2/3 of the losses occurred within 30 days after herbicide application. Fausey et al. (1990) also reported that metolachlor concentrations in groundwater were influenced by water-table elevations. Results of these studies have accelerated research interests on the use of WTM practices to protect groundwater quality from contamination by agricultural chemicals.

The overall objective of this study was to investigate the effect of WTM practices on groundwater quality and crop yields at two different field locations in Iowa. The effects of WTM practices on photosynthesis and other corn-growth parameters, corn yield, and NO_3-N concentrations in shallow groundwater have been reported earlier (Kalita and Kanwar, 1992a, 1992b, 1993). The specific objective of this report was to discuss the effect of WTM practices on groundwater residues of two surface-applied herbicides, atrazine and alachlor, during three corn-growing seasons (1989-1991) in Iowa.

Methods and Materials

Site Description

Experiments were conducted during 1989-1991 at Iowa State University's research centers in Ames and Ankeny, Iowa. The soils are predominantly Nicollet loam at the Ames site, and Nicollet silt-loam at the Ankeny site. Some of the physical properties of the soils at these two sites are presented by Kalita and Kanwar (1993).

At the Ames site, nine field-lysimeters of 3 m × 6 m were installed in 1986. Lysimeters were enclosed using a 0.25 mm thick plastic barrier to a depth of 1.2 m to prevent lateral subsurface water movement between plots. A perforated plastic tube (100 mm diameter) was installed around each lysimeter at 1.2 m depth and a corrugated plastic pipe (0.46 m diameter × 1.35 m deep) was installed as a sump at the corner of each lysimeter without disturbing the lysimeter soil. In 1989, all lysimeters were enclosed with a 0.25 mm thick PVC flexible liner to a depth of 1.7 m. Each liner encased a square area (9 m × 9 m) with the 3 m × 6 m field lysimeter located in the center. A float mechanism was installed in each sump to maintain the desired water level in the lysimeter. Each lysimeter was connected to a water-supply tank using a 75 mm diameter PVC irrigation pipe. At the Ankeny site, a dual-pipe subirrigation system was installed in 1988 on a 0.85 ha area with natural surface slope of 2.5%. Shallow irrigation pipes were installed at a depth of 0.5 to 0.6 m, parallel to and midway between drainage pipes, which were installed at a depth of 1.2 m. The natural slope along the length of the field allowed water tables to be maintained at various depths by controlling the subsurface drainage outflows and by supplying irrigation water through the subirrigation pipes. Detailed descriptions of the lysimeter construction and the subirrigation system are given by Kalita and Kanwar (1993).

Water-table Treatments

At the Ames site, water-table depths (WTD) were maintained at 0.3, 0.6, and 0.9 m during the period from 53, 52, and 50 days after planting (DAP) to harvesting in 1989, 1990, and 1991, respectively. It took almost three days to raise the water tables to the treatment depths. Water-table treatments were replicated three times by using nine field-lysimeters every year. The elapsed time from planting to water-table treatment allowed corn roots to develop within the 0.3 to 0.9 m soil profile. Water-table elevations were maintained at treatment depths until harvest time. Observation wells (25 mm diameter and 1.5 m long PVC pipes) were installed in each lysimeter to monitor water levels.

At the Ankeny site, water-table depths ranged from 0.03 to 1.25 m during the growing season. The average water-table depths at five different locations where monitoring devices were installed in the subirrigation field were maintained at 0.2, 0.3, 0.6, 0.9, and 1.1 m, respectively. A maximum water-table depth of 1.25 m was observed at the highest elevation (north boundary) of the field in the beginning of the season, and a minimum water-table depth of 0.03 m was observed at the lowest elevation site of the field once during the growing season due to heavy rainfall in 1990. Water-table depths, however, were maintained through subirrigation from 53 to 96 DAP in 1989 and 1990 and from 45 to 97 DAP in 1991.

GROUNDWATER SAMPLING

For collecting shallow groundwater samples from both sites, solute suction tubes (suction lysimeters) were made by coupling a 200 kPa porous ceramic cup to the end of 38 mm diameter PVC pipes. The suction tubes of different lengths were sealed at the top of the pipes with rubber stoppers. At the Ames site, suction tubes were installed at the center of all nine lysimeters (for three replications) to collect water samples from depths of 0.15, 0.3, 0.6, 0.9, 1.2, 1.5, and 2.1 m. Piezometers made of 25 mm diameter PVC pipes were installed in each lysimeter at 1.2, 1.8, and 2.4 m depths to collect water samples and to monitor piezometric heads.

At the Ankeny site, solute suction tubes were installed at 0.9, 1.2, 1.5, and 2.1 m depths at three locations with three replications at each location. Piezometers were also installed at 1.2, 1.8, and 2.4 m depths at three locations with three replications at each location. Water samples were collected from piezometers and solute suction tubes, biweekly in 1989 and monthly in 1990 and 1991, from both sites for pesticide analysis. The sample collection schedule was independent of rainfall events, however, daily rainfall data during all the growing seasons are provided in figure 1. A vacuum pump was used to create a vacuum in the solute suction tubes one day before sample collection. Piezometers were also pumped out one day before sampling, and water samples were collected on the following day and preserved in the cold chamber at 4°C for analysis. Soil moisture contents by depths were monitored weekly by using a neutron probe in the lysimeter plots as reported by Kalita and Kanwar (1992b).

CROP AND CHEMICAL APPLICATION

Corn (Pioneer 3379) was planted on 23 May in 1989 and 8 May in 1990 at both Ames and Ankeny sites. Harvesting dates were 31 October in 1989 and 16 October in 1990 at both sites. In 1991, corn was planted on 24 May at the Ames site and 27 May at the Ankeny site; it was harvested on 10 October at both sites. Planting and harvesting in the lysimeters were done manually every year. The plant population was 66,600 ha^{-1} with a row width of 0.75 m and plants spaced every 0.2 m at each site.

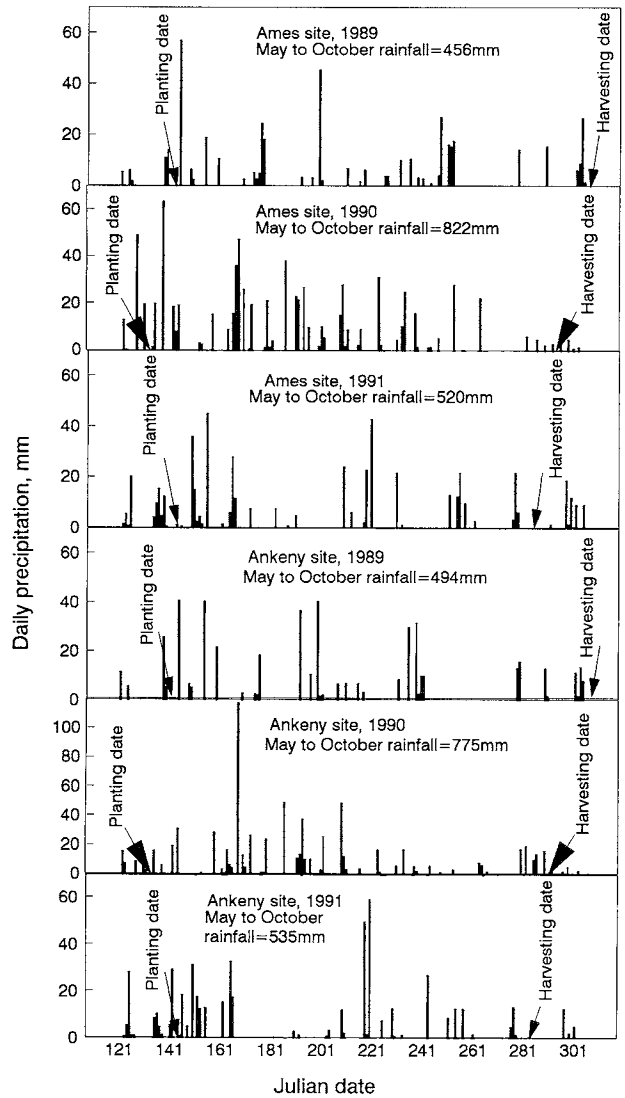

Figure 1–Growing season rainfall at the Ames and Ankeny sites in 1989-1991.

Urea nitrogen fertilizer was applied at planting time at both sites every year at the rate of 200 kg-N ha^{-1}. The herbicides atrazine and alachlor were applied at the rate of 2.2 kg ha^{-1} for each herbicide every year at the Ames site, but only in 1989 and 1991 at the Ankeny site.

ANALYTICAL PROCEDURES

Herbicides were extracted from water samples by using liquid-liquid extraction with dichloromethane. Dichloromethane was evaporated, and the herbicide residue redissolved in toluene. A very small portion of the toluene extract was injected into a Tracor 560 GC with a N-P thermionic detector. Operating conditions were: column oven at 160°C, inlet at 245°C, detector at 245°C, helium carrier gas at the rate of 18 cm^3 min^{-1}, hydrogen reaction gas at the rate of 3.5 cm^3 min^{-1}, and air reaction gas at the rate of 100 cm^3 min^{-1}. Herbicides were separated by using a 3% OV-1 column. In 1991, herbicide analysis of some samples were done at the Iowa Hygienic Laboratory in Iowa City, Iowa.

Results and Discussion

Rainfall during the growing seasons substantially affected the pesticide concentrations in groundwater at both Ames and Ankeny sites. Daily precipitation patterns during the growing season (May to October) of 1989-91 at both sites are shown in figure 1. The 1989 season was relatively dry, with May to October rainfall totals of 456 and 494 mm at the Ames and Ankeny sites, respectively. The 1990 season was extremely wet, with rainfall totals of 822 and 775 mm at Ames and Ankeny sites, respectively. Seasonal rainfall (May to October) totals in 1991 were 520 and 535 mm at the Ames and Ankeny sites, respectively.

Groundwater Atrazine Data at the Ankeny Site

Piezometer Water Samples. Groundwater atrazine concentrations in piezometer water samples at the Ankeny site are shown in figures 2 and 3 and table 1. Figure 2 shows atrazine concentrations in groundwater at the Ankeny site in 1989. Water-table depths at piezometer locations fluctuated from 1.6 to 1.0, 1.1 to 0.35, and 0.8 to 0.12 m during the growing season of 1989 and are referred to as deep, medium, and shallow water-table depths. Atrazine concentration in groundwater for these water-table depths varied from 0 to 67 µg L^{-1}. The highest concentration of atrazine was observed at 1.2 m depth, 34 DAP and herbicide application (subirrigation practice started 53 DAP), but with subirrigation, atrazine concentrations in groundwater substantially decreased at the Ankeny site. For most of the groundwater samples taken in 1989, atrazine concentrations decreased with shallow water-table conditions with few exceptions. The fluctuations in water table did cause some irregularities in this trend. Atrazine concentrations in groundwater also decreased with increases in soil depth and time after the planting date. Groundwater samples collected at the end of the growing season showed that under shallow water-table condition, atrazine concentration at 1.2 m soil depth was only 0.34 µg L^{-1}, and no atrazine was detected at 1.8 and 2.4 m soil depths.

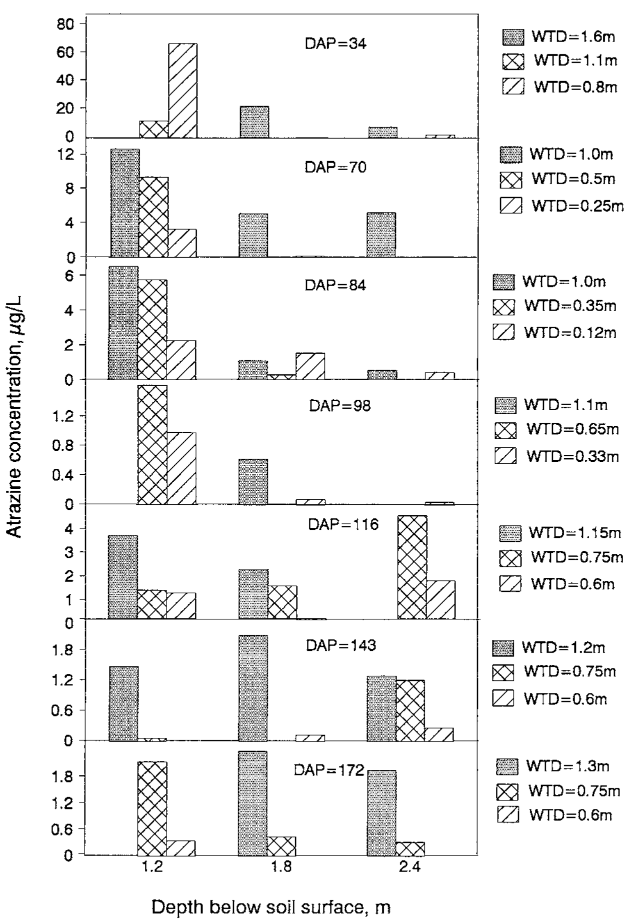

Figure 2–Atrazine concentrations in piezometer water samples at the Ankeny site in 1989.

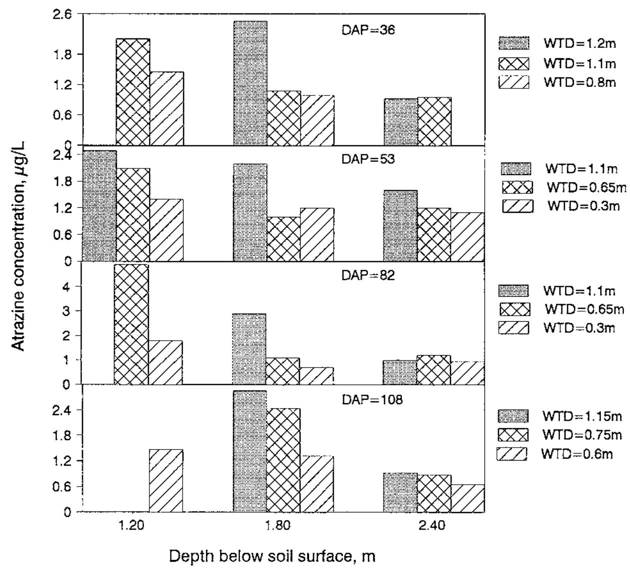

Figure 3–Atrazine concentrations in piezometer water samples at the Ankeny site in 1991.

Table 1. Herbicide concentrations in groundwater at the Ankeny site

Year	DAP	WTD (m)	Piezometer Depth 1.2 m	1.8 m	2.4 m	DAP	WTD (m)	Suction Tube Depth 0.9 m	1.2 m	1.5 m	2.1 m
Atrazine (µg/L)											
1990	37	1.20	1.1	0.9	0.8	37	1.20	0.4	-	1.0	0.3
		0.90	2.2	0.5	-		0.90	1.2	1.3	0.7	0.7
		0.60	0.5	0.4	0.2		0.75	1.6	0.4	0.5	0.8
	153	1.30	-	0.7	0.5	92	0.90	-	0.6	0.7	0.8
		1.00	0.6	0.2	0.2		0.60	1.2	1.6	0.3	0 3
		0.75	0.4	0.2	0.1		0.30	1.6	0.2	0.1	0.4
						153	1.20	-	-	0.4	0.3
							1.00	-	0.8	0.1	0.1
							0.90	1.1	0.1	0.3	0.4
Alachlor (µg/L)											
1989	34	1.60	-	0.0	0.0	34	1.45	27.5	-	8.7	1.0
		1.10	0.0	0.0	0.0		1.10	-	1.3	0.0	0.0
		0.80	0.0	0.0	0.0		1.00	2.4	0.0	0.0	0.0
	84	1.00	0.7	0.1	0.3	70	0.90	0.0	-	-	-
		0.35	0.3	0.6	0.0		0.50	-	-	0.0	-
		0.12	0.4	0.3	0.3		0.35	6.2	0.0	0.0	-
1991	36	1.20	-	0.7	0.2	36	1.20	-	-	0.0	0.0
		1.10	0.0	0.0	0.0		1.10	-	-	0.0	0.0
		0.80	0.0	0.4	-		0.90	0.0	-	0.0	0.0
	53	1.10	0.3	2.1	2.4	53	0.90	-	-	1.0	0.2
		0.65	0.3	0.3	0.2		0.65	0.2	-	0.0	0.0
		0.30	0.2	0.7	0.2		0.45	0.0	-	0.0	0.0
	82	1.10	-	1.1	5.3	82	0.90	0.1	-	0.7	0.0
		0.65	0.4	0.5	0.4		0.65	0.4	-	0.0	0.0
		0.30	0.7	0.2	0.1		0.45	0.0	-	0.0	0.0
	108	1.15	-	0.0	4.1	108	1.00	-	-	0.0	0.0
		0.75	-	0.0	0.4		0.75	-	-	0.0	0.0
		0.60	0.0	0.0	0.3		0.65	-	-	0.1	0.0

DAP — days after planting; WTD — water table depth.

The 1990 was a very wet year. Although no herbicide was applied in 1990 at the Ankeny site, groundwater samples collected at the beginning and end of the growing season showed low atrazine concentrations. These data are presented at the top of table 1. The highest atrazine concentration in a piezometer water sample in 1990 was 2.2 µg L^{-1} on 37 DAP, and the lowest concentration of 0.1 µg L^{-1} was observed on 153 DAP at 2.4 m depth under a water table depth of 0.75 m. These concentrations probably occurred from the residual pesticides left in the soil profile from the previous year (1989) and after the heavy rain events during the early part of the 1990 growing season. Crop growth was very poor at this site in 1990 because of weed competition. The effect of water-table depths on the residual atrazine concentrations in this high rainfall year (the entire soil profile was nearly saturated throughout the season) was not very clear.

Atrazine concentrations in piezometer water samples in 1991 are shown in figure 3. In 1991, the deep, medium, and shallow water table depths varied from 1.2 to 1.1 m, 1.1 to 0.65 m, and 0.8 to 0.3 m, respectively. The highest atrazine concentration was nearly 5 µg L^{-1} in a groundwater sample collected on 82 DAP immediately after a continuous three-day, 112 mm rainfall. However, 1991 piezometer samples showed a definite influence of WTM practices on atrazine concentrations in groundwater. Atrazine concentrations were, in most cases, lower in shallow water-table conditions compared with deep water-table conditions, and these concentrations decreased with increased soil depth. In 1991, shallow, medium, and deep water-table depths were constantly maintained at 0.3, 0.65, and 1.1 m depths, respectively, during most of the subirrigation period. This might be the reason for a relatively more distinct trend of atrazine concentration with WTD in 1991 than in 1989.

Suction-tube Water Samples. Atrazine concentrations in groundwater samples collected from the suction tubes at the Ankeny sites in 1989 are shown in figure 4. In 1989, the highest atrazine concentration (23 µg L^{-1}) was observed at 2.1 m depth before subirrigation was started, but atrazine concentrations in groundwater at all depths decreased after subirrigation had started. At shallow WTD, atrazine concentrations at 0.9, 1.2, 1.5, and 2.1 m soil depths substantially decreased. The fluctuation of the water-table during the growing season at each location caused some irregularities. At the end of the growing season in 1989, atrazine concentrations in groundwater reduced to 2.1, 0.9, 0.4 and 1.3 µg L^{-1} at 0.9, 1.2, 1.5, and 2.1 m soil depths, respectively, where the water table was maintained at a shallow depth. Although in most cases atrazine concentrations in groundwater decreased with increase in depths, these concentrations at 2.1 m depth were always higher than those at 1.5 m depth in deep water-table conditions, and these differences increased towards the end of the growing season after subirrigation was cut off. One explanation could be the leakage of atrazine from the soil surface with rain water to the suction-tube depth through unseen cracks developed near the suction tube at that location.

Residual atrazine concentrations in groundwater collected from the suction tubes in 1990 are shown at the top of table 1. These data are similar to those of piezometer samples of 1990, and no distinct trend between atrazine

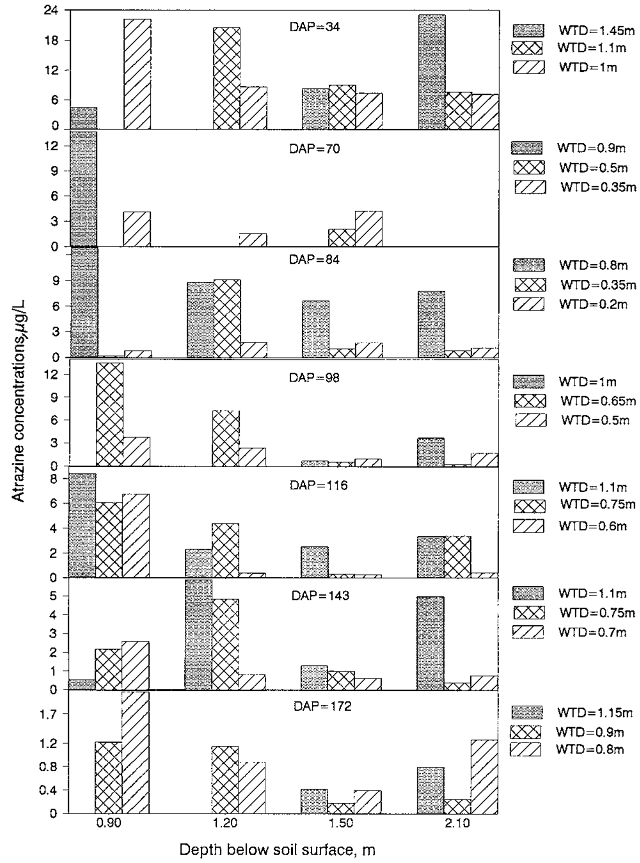

Figure 4–Atrazine concentrations in suction-tube water samples at the Ankeny site in 1989.

concentrations and water-table depth was observed. Atrazine concentrations in groundwater collected on 37, 92, and 153 DAP were also very low.

In 1991, water samples were collected from 0.9, 1.5, and 2.1 m soil depth, and the atrazine concentrations in groundwater samples collected on 36, 53, 82, and 108 DAP

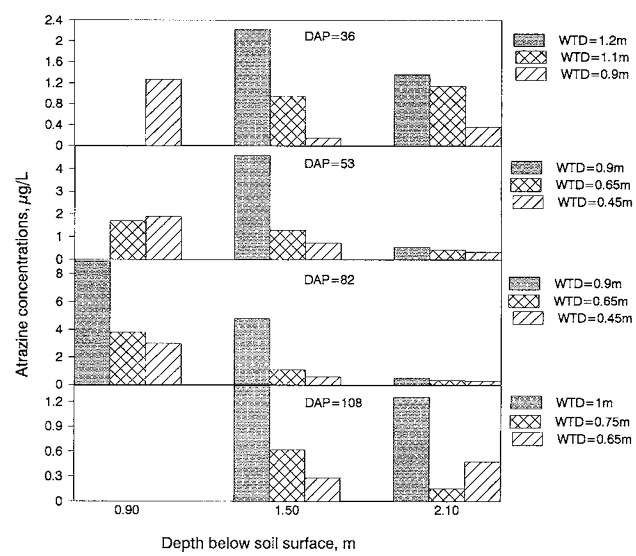

Figure 5–Atrazine concentrations in suction-tube water samples at the Ankeny site in 1991.

are shown in figure 5. Atrazine concentrations at 0.9 and 1.5 m depths increased with time, after subirrigation had started, up to 82 DAP, and then decreased. This might be a result of slow downward movement of atrazine with rain or subirrigation water at the beginning of the season. Atrazine concentrations in groundwater were, however, much lower with shallow WTD than with deep WTD at all soil depths.

A quantitative comparison of atrazine concentrations in groundwater between piezometer and suction-tube water samples is not presented for the Ankeny site, because piezometers and suction tubes were installed at different locations and under different water table depths at this site. Piezometer and suction-tube water samples, however, show identical trends of decreasing atrazine concentrations in groundwater with shallow water-table depths. These concentrations also decreased with increased soil depth, and time, in most cases.

Groundwater Atrazine Data at the Ames Site

Piezometer Water Samples. At the Ames site, water table depths were constantly maintained at treatment depths from the beginning of the treatment until harvest date every year. Atrazine concentrations in piezometer water samples at the Ames site in 1989, 1990, and 1991 are shown in figures 6, 7, and 8, respectively. Figure 6 shows groundwater atrazine concentrations in 1989; at 1.2 m depth, atrazine concentration in groundwater decreased from 3.3 to 1.25, 2.2 to 0.5, and 1.6 to 0.58 μg L^{-1} under 0.9, 0.6, and 0.3 m WTD, respectively, during the growing season. Atrazine concentrations at 1.8 m soil depth also show, on the average, a decreasing trend with shallow WTD. But at 2.4 m depth, the highest atrazine

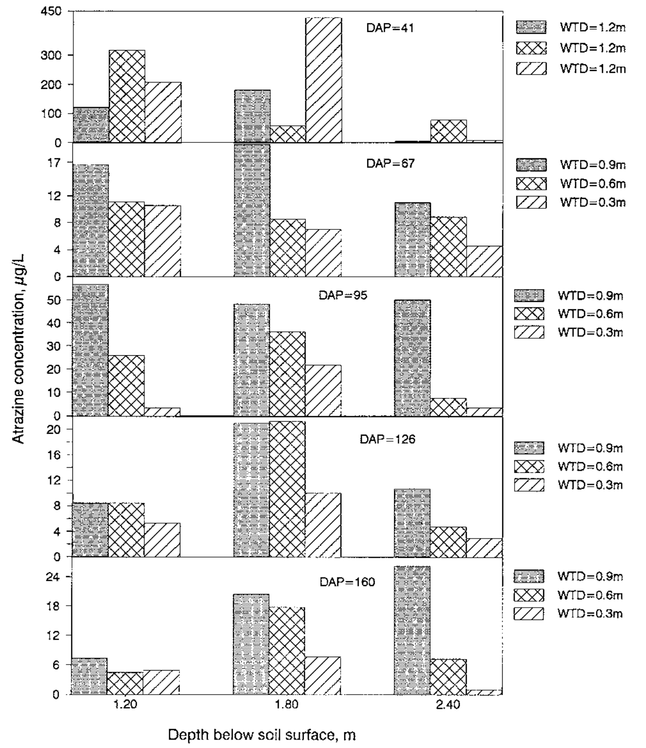

Figure 7–Atrazine concentrations in piezometer water samples at the Ames site in 1990.

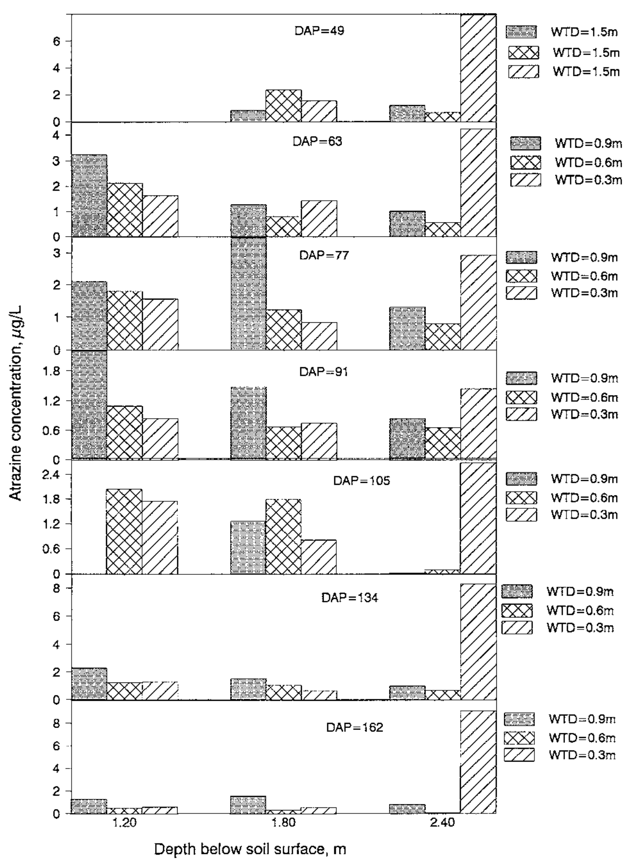

Figure 6–Atrazine concentrations in piezometer water samples at the Ames site in 1989.

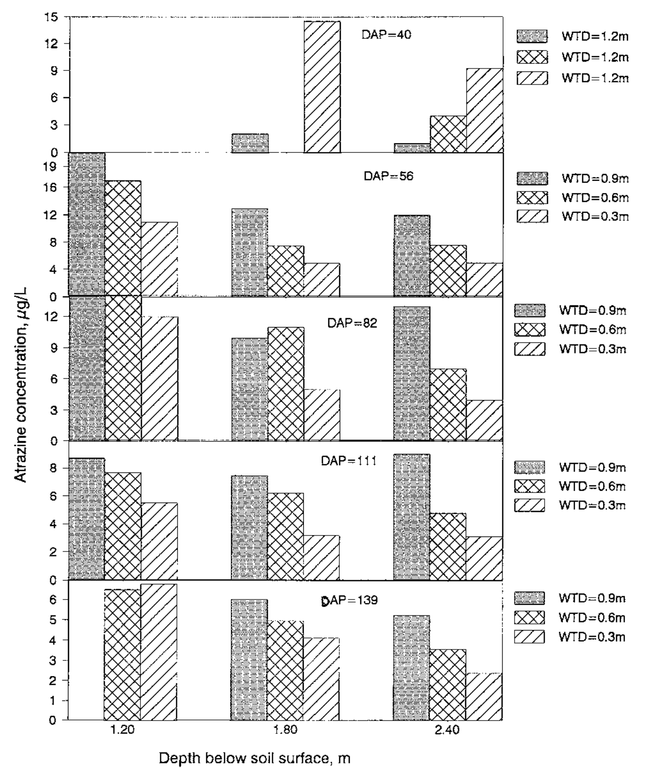

Figure 8–Atrazine concentrations in piezometer water samples at the Ames site in 1991.

concentration in groundwater was observed under 0.3 m water-table depth; atrazine concentrations decreased from 8 to 1.4 μg L^{-1} at 91 DAP and then increased again to 9 μg L^{-1} at the end of the growing season (162 DAP). This uncommon trend might be a result of pesticide leaching through macropores or unseen cracks around the piezometer. Atrazine concentrations at the 2.4 m soil depth, however, remained low (1.2 to 0.8 μg L^{-1}) under 0.9 and 0.6 m WTD, and the lowest concentrations were observed with 0.6 m WTD. In 1989, planting and herbicide application were followed by a heavy rain of 58 mm in 48 h at the Ames site, which probably caused a major portion of applied atrazine to leach down to lower depths through macropores. Although atrazine was degraded with time (at 2.4 m), residual atrazine was probably added at this depth by macropore flow after the peak growing season, and a higher concentration of atrazine was observed at the end of the growing season.

The effect of heavy rainfall during the growing season in 1990 on pesticide concentrations in groundwater is shown in figure 7. Atrazine concentration of as high as 427 μg L^{-1} was observed in groundwater at 1.8 m depth 41 DAP before the water-table treatment was started. But these concentrations reduced to a maximum of 20 μg L^{-1} two weeks after the start of WTM practices (67 DAP). Following another heavy rainfall, atrazine concentrations in groundwater at all three depths increased again (95 DAP), but these increases were very small under shallow water-table conditions. Rainfall had a major influence on atrazine concentrations in groundwater, and the trends of atrazine concentrations in groundwater at all depths followed rainfall pattern. Nevertheless, atrazine concentrations were much lower with shallow than with deep water-table depths, and this trend was distinct throughout the growing season.

Atrazine concentrations in piezometer water samples in 1991 also show that groundwater atrazine residues were lower with shallow WTD (fig. 8). Water samples collected a few days after the start of water-table treatments (56 DAP) showed atrazine concentrations of 21, 13, and 12 μg L^{-1} at 1.2, 1.8, and 2.4 m depths, respectively, with 0.9 m WTD. Under 0.3 m WTD, these concentrations were 11 μg L^{-1} at 1.2 m depth, and 5.0 μg L^{-1} at 1.8 and 2.4 m depths. Atrazine concentrations in groundwater decreased with increases in depth and time during the growing season. The lowest atrazine concentration, 2.4 μg L^{-1}, was observed in groundwater at 2.4 m depth under 0.3 m WTD. Although the rainfall totals during the growing seasons of 1989 and 1991 were similar, atrazine concentrations on an average, under all three water table treatments, were relatively higher in 1991 than those in 1989. This was probably a result of heavy rainfall in 1990 that left a higher residual atrazine concentration in the soil profile by the end of the 1990 growing season and was carried over to the 1991 season.

Suction-tube Water Samples. Figures 9, 10, and 11 show atrazine concentrations in suction-tube water samples in 1989, 1990, and 1991, respectively. At the Ames site, suction-tube water samples were collected from as shallow as 0.3 m depth from plots where a 0.3 m water-table depth was maintained. Figure 9 shows that in 1989, concentration of atrazine at the depth of the water table was less than the concentration at depths immediately below the water table. Under 0.3 m WTD, samples collected on 63 DAP from

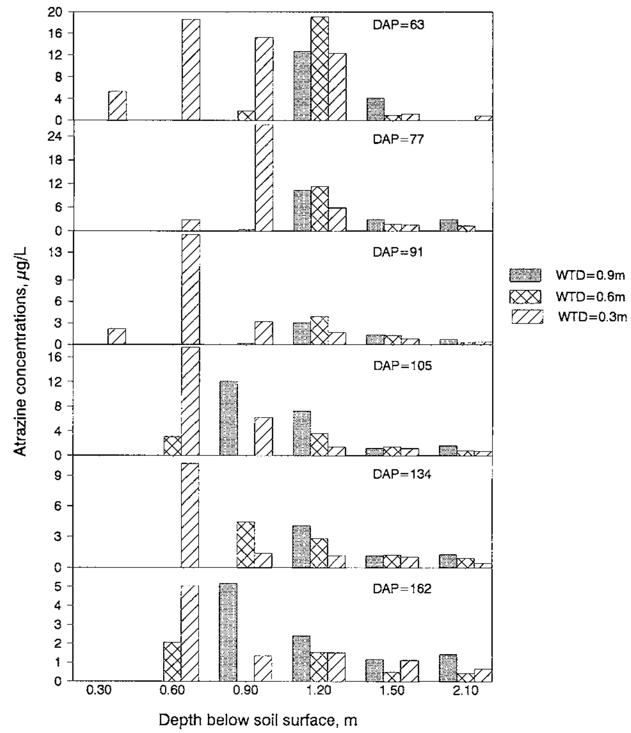

Figure 9–Atrazine concentrations in suction-tube water samples at the Ames site in 1989.

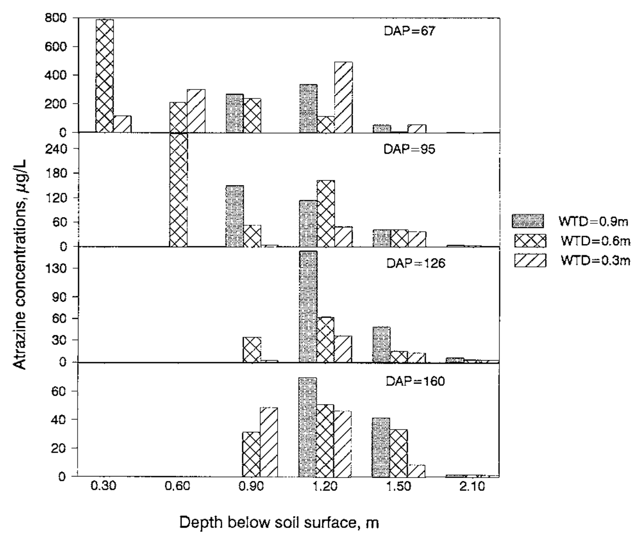

Figure 10–Atrazine concentrations in suction-tube water samples at the Ames site in 1990.

0.3 m soil depth showed an atrazine concentration of only 5.3 μg L^{-1}, but it was nearly 19 μg L^{-1} at 0.6 m soil depth. However, water samples from deeper depths of 0.9, 1.2, 1.5, and 2.1 m always showed a trend of decreasing atrazine concentration with an increase in depth. Similar results were observed from samples collected at 91 DAP in 1989. Another noticeable observation in the 1989 data was that, at depths between 0.3 and 0.6 m, atrazine concentrations in groundwater were higher with 0.3 m than with 0.6 m WTD. But at deeper depths, concentrations of

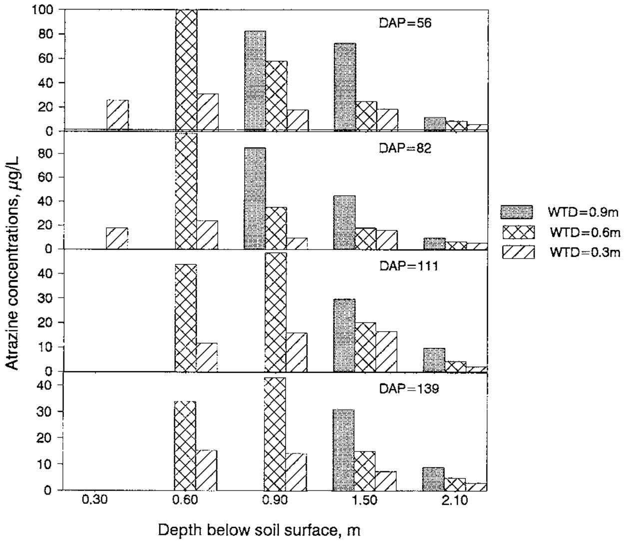

Figure 11–Atrazine concentrations in suction-tube water samples at the Ames site in 1991.

atrazine in groundwater were much lower under 0.3 m than under 0.6 m and 0.9 m WTD.

Suction-tube water samples in 1990 again show the dominating effect of heavy rainfall during the growing season on atrazine concentrations in groundwater (fig. 10). The highest atrazine concentration, 788 μg L^{-1}, was observed in groundwater at 0.3 m depth (unsaturated condition) with 0.6 m water-table depth on 67 DAP. Although atrazine concentrations show, on an average, a decreasing trend with shallow water tables, these concentrations were very high with all three WTD and at all depths except 2.1 m. At 2.1 m suction-tube depth, atrazine concentrations in groundwater varied from 7 to 1.2 μg L^{-1} during the growing season.

The 1991 data also show very high atrazine concentrations in groundwater at the Ames site (fig. 11). An atrazine concentration of 100 μg L^{-1} was observed at 0.6 m depth under a 0.6 m WTD on 56 DAP. These concentrations were much higher than those observed in 1989 suction-tube water samples at the same site. Atrazine concentrations decreased with increased depth, and were very low at 2.1 m depth. These data show that WTM practice had a significant effect in reducing atrazine concentrations in groundwater. At 0.9 m soil depth, atrazine concentrations under 0.9 m WTD were 83 and 85 μg L^{-1} on 56 and 82 DAP, respectively, whereas, these concentrations were only 18 and 10 μg L^{-1} on 56 and 82 DAP under 0.3 m WTD. At soil depths of 1.5 and 2.1 m, similar effects of WTD on groundwater atrazine concentrations were observed. Atrazine concentrations in groundwater on 139 DAP at 2.1 m depth decreased to 3 μg L^{-1} under a 0.3 m water table depth. These results show a positive influence of WTM in reducing atrazine concentrations in groundwater. At the Ames site, however, atrazine concentrations in suction-tube water samples were higher than those in piezometer water samples.

Groundwater Alachlor Data at the Ankeny Site

Concentrations of alachlor in piezometer and suction-tube water samples from the Ankeny site in 1989 and 1991 are shown in table 1. Alachlor was not detected in any samples collected in 1990 from this site. Table 1 shows only the dates when alachlor was detected in groundwater samples in 1989 and 1991. In 1989, alachlor was detected in piezometer water samples only once at the Ankeny site (84 DAP), and twice (34 and 70 DAP) in suction-tube water samples. In the piezometer samples, a maximum alachlor concentration of 0.7 μg L^{-1} was observed in groundwater at 1.2 m depth under 1 m WTD. In the suction-tube water samples, alachlor concentration as high as 27 μg L^{-1} was observed on 34 DAP at 0.9 m depth before subirrigation started, but these concentrations decreased considerably under subirrigation practice.

In 1991, alachlor was detected in groundwater samples collected from piezometers and suction tubes on several days; but, in most cases, these concentrations were very low. Both piezometer and suction-tube samples show a maximum alachlor concentration of 0.7 μg L^{-1} and a minimum of 0.1 μg L^{-1} in groundwater during the growing season. These alachlor concentrations in groundwater in both the 1989 and 1991 seasons were very low, and in most cases were not detected at all, so no definite trend of alachlor concentration with water-table depth was established for the Ankeny site.

Groundwater Alachlor Data at the Ames Site

Table 2 shows data on alachlor concentrations in piezometer and suction-tube water samples at the Ames site during the 1989-1991 growing seasons. In 1989, a very low alachlor concentration was detected in suction-tube groundwater samples collected on 77 and 105 DAP, but nothing at all was detected in any piezometer water samples. This low alachlor concentration was very similar

Table 2. Alachlor concentrations in groundwater at the Ames site, 1989-91

		WTD	Piezometer Depth				WTD	Suction Tube Depth					
Year	DAP	(m)	1.2 m	1.8 m	2.4 m	DAP	(m)	0.3 m	0.6 m	0.9 m	1.2 m	1.5 m	2.1 m
Alachlor (μg/L)													
1989	77	0.9	0.0	0.0	0.0	77	0.9	-	-	-	0.0	0.0	1.1
		0.6	0.0	0.0	0.0		0.6	-	-	0.6	0.1	0.6	0.3
		0.3	0.0	0.0	0.0		0.3	-	1.3	0.2	0.2	0.2	0.1
	105	0.9	0.0	0.0	0.0	105	0.9	-	-	0.0	0.0	0.0	0.0
		0.6	0.0	0.0	0.0		0.6	-	0.0	0.0	0 3	0.5	0.0
		0.3	0.0	0.0	0.0		0.3	-	0.0	0.0	0.0	0.3	0.3
1990	41	1.2	64.3	59.6	1.8	41	1.2	-	-	-	-	-	-
		1.2	60.2	23.1	57.1		1.2	-	-	80.7	420.9	2.4	1.0
		1.2	142.1	226.9	5.9		1.2	-	-	-	259.2	6.8	3.4
	67	0.9	67.7	111.0	28.1	67	0.9	4.1	-	18.5	74.2	8.1	1.3
		0.6	45.5	10.6	4.6		0.6	3.5	41.6	12.3	53.4	7.2	0.3
		0.3	4.3	6.7	1.4		0.3	67.0	4.1	0.8	9.0	1.2	0.3
	95	0.9	28.0	47.0	41.3	95	0.9	-	-	8.2	264.3	9.1	0.4
		0.6	0.6	9.7	0.2		0.6	-	1.8	0.7	33.8	3.0	0.3
		0.3	1.8	3.6	1.9		0.3	-	-	0.0	52.2	0.0	0.4
	126	0.9	10.2	12.5	5.7	126	0.9	-	-	-	40.8	61.8	2.1
		0.6	2.1	5.2	0.6		0.6	-	-	4.2	63.3	16.8	6.4
		0.3	0.0	2.3	0.2		0.3	-	-	0.8	7.9	1.4	0.2
	160	0.9	2.8	2.8	1.7	160	0.9	-	-	-	2.8	0.6	6.8
		0.6	0.6	3.3	0.5		0.6	-	-	1.2	1.9	0.1	0.1
		0.3	0.3	1.9	0.3		0.3	-	-	0.2	0.6	0.2	0.0
1991	40	1.2	-	0.1	0.0	40	1.2	-	-	-	-	-	1.8
		1.2	-	-	0.0		1.2	-	-	-	-	2.0	
		1.2	-	1.7	0.3		1.2						
	56	0.9	4.9	6.2	4.1	56	0.9	-	-	12.0	-	25.0	3.8
		0.6	3.7	3.2	3.4		0.6	-	7.4	4.9	-	5.8	1.8
		0.3	2.8	1.8	1.8		0.3	3.1	5.7	2.7	-	4.7	0.6
	82	0.9	2.7	2.2	2.4	82	0.9	-	-	3.0	-	15.0	5.3
		0.6	2.2	1.9	1.9		0.6	-	4.0	2.4	-	2.9	1.1
		0.3	1.0	1.1	0.7		0.3	1.9	0.8	0.7	-	0.7	0.3
	111	0.9	1.2	1.4	1.4	111	0.9	-	-	-	-	2.5	0.5
		0.6	0.9	0.7	1.0		0.6	-	2.3	2.1	-	0.7	0.3
		0.3	0.4	0.8	0.5		0.3	-	0.3	1.0	-	0.9	0.0
	139	0.9	-	0.9	0.0	139	0.9	-	-	-	-	4.4	0.8
		0.6	1.0	1.1	0.0		0.6	-	2.1	1.5	-	0.7	0.2
		0.3	0.0	0.6	0.6		0.3	-	0.0	0.8	-	0.3	0.0

DAP — days after planting; WTD — water table depth.

to the alachlor concentrations in groundwater at the Ankeny site in 1989. But water samples collected from piezometer and suction tubes in 1990 show very high alachlor concentrations in most of the samples. On 41 DAP, the highest alachlor concentrations were 227 µg L^{-1} at 1.8 m depth in piezometer water samples, and 421 µg L^{-1} at 1.2 m depth in suction-tube water samples. With WTM practices, alachlor concentrations in groundwater, however, decreased. At the end of the growing season (160 DAP), alachlor concentrations in piezometer water samples reduced to a minimum of 0.3 µg L^{-1} at 1.2 and 2.4 m depths under 0.3 m WTD; the suction-tube water samples show a minimum alachlor concentration of 0.2 µg L^{-1} at 0.9 and 1.5 m depths under 0.3 m WTD. On an average, 1990 data show the positive influence of WTM practices on the reduction of alachlor concentrations in groundwater, and these concentrations were minimum with shallow water-table depth.

Alachlor was detected in most of the water samples collected from the Ames site in 1991. In the piezometer water samples, a maximum alachlor concentration of 6.2 µg L^{-1} was observed on 56 DAP at 1.8 m depth under 0.9 m WTD, and it reduced to a minimum of 0.6 µg L^{-1} on 139 DAP under 0.3 m water table depth. Similarly, suction-tube water samples show a maximum of 25 µg L^{-1} on 56 DAP at 1.5 m depth under 0.9 m WTD, and a minimum of 0.3 µg L^{-1} on 139 DAP under 0.3 m WTD. Alachlor concentrations in groundwater at this site were higher in 1991 than in 1989, probably for the same reason that atrazine concentrations at the Ames site were higher in 1989 than in 1991. A very high rainfall in 1990 probably carried most of the alachlor from top soil to deeper depths and remained in the soil profile. A shallow WTD, however, reduced alachlor concentrations in groundwater at all depths.

Alachlor is less persistent in soil than atrazine. In our experiments, alachlor was not detected at all at the Ankeny site in 1989 after about 84 DAP, and most of the alachlor was probably lost without any trace in 1990 groundwater samples. Also in 1991, alachlor was not detected in groundwater samples at the Ankeny site after about 108 DAP. Similar observations were made for alachlor concentrations from the Ames site in 1989.

Over all the site and plot conditions of this study, the observed data on atrazine and alachlor concentrations in groundwater indicate that maintaining a water table at a shallow depth may substantially reduce groundwater concentrations of atrazine and alachlor. The reduction of atrazine and alachlor concentrations at shallow water-table depth was possibly enhanced by increased biodegradation. With relatively higher organic matter content at shallow depth, the biodegradation rate of these two pesticides was possibly high under anaerobic conditions. However, shallow water-tables may also have diluted pesticides concentrations. A statistical analysis was carried out to show the correlation between groundwater atrazine concentrations and DAP, WTD, and soil depth. Only the Ames site data were analyzed for this purpose (because water-table depths were consistently maintained at treatment depths at this site during 1989-1991). The correlation coefficients provide a numerical measure of the strength of the relationship or association between the variables, and is not a good measure of anything but linear correlation. Results of this analysis show that WTD is positively correlated ($R = 0.43$) with atrazine concentrations in groundwater, and that the probability of atrazine concentrations (P-level) being not linearly correlated with WTD is 0.0094. It shows that the relationship between WTD and atrazine concentrations in groundwater is very significant. Atrazine concentrations were also negatively correlated to DAP ($R = -0.23$, P level = 0.0069) and soil depth ($R = -0.56$, P level = 0.0004) with highly significant relationships. Therefore, the fact that atrazine concentrations in groundwater decreased with shallow water-table depth, soil depth, and time is statistically significant.

Conclusions

Water-table management practices had a significant effect on the concentrations of two surface-applied herbicides, atrazine and alachlor, in groundwater during the growing season at the Ames and Ankeny sites, 1989-1991. The results of this study can be summarized as follows.

1. Atrazine was detected in all groundwater samples collected between planting and harvesting time at both the Ames and the Ankeny sites. Alachlor was not detected in many samples, and alachlor concentrations were lower than those of atrazine in groundwater at similar depths and under similar WTM practices.
2. Both atrazine and alachlor concentrations in groundwater were substantially reduced by WTM practices. At the Ankeny site, atrazine concentrations were minimum with shallow water-table conditions. At the Ames site, atrazine concentrations in groundwater were minimum under 0.3 m WTD. Similar results were observed for alachlor concentrations.
3. At the Ankeny site, atrazine concentrations in suction-tube and piezometer water samples were almost similar in 1989 and 1991. But at the Ames site, atrazine concentrations in suction-tube water samples were higher than those in piezometer water samples. Also, the 1991 samples show higher atrazine and alachlor concentrations in groundwater than 1989 samples from the Ames site. A very heavy rainfall during the growing season in 1990 produced very high pesticide concentrations in groundwater in 1990, and may have left a large amount of residual pesticide in the soil profile.
4. Statistical analysis showed that the relationships between atrazine concentrations in groundwater and WTD, DAP, and soil depth were highly significant.

Therefore, water-table management practices may be recommended with other sound agricultural practices to reduce atrazine and alachlor concentrations in groundwater and to protect groundwater quality in agricultural areas.

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