Fate of Alachlor and Atrazine in a Riparian Zone Field Site
Author(s): Kurtis G. Paterson and Jerald L. Schnoor
Source: *Water Environment Research*, Vol. 64, No. 3 (May - Jun., 1992), pp. 274-283
Published by: Water Environment Federation
Stable URL: http://www.jstor.org/stable/25044150
Accessed: 02/07/2014 10:52

Your use of the JSTOR archive indicates your acceptance of the Terms & Conditions of Use, available at http://www.jstor.org/page/info/about/policies/terms.jsp

JSTOR is a not-for-profit service that helps scholars, researchers, and students discover, use, and build upon a wide range of content in a trusted digital archive. We use information technology and tools to increase productivity and facilitate new forms of scholarship. For more information about JSTOR, please contact support@jstor.org.

Water Environment Federation is collaborating with JSTOR to digitize, preserve and extend access to *Water Environment Research.*

http://www.jstor.org

This content downloaded from 137.187.180.215 on Wed, 2 Jul 2014 10:52:45 AM
All use subject to JSTOR Terms and Conditions

Fate of alachlor and atrazine in a riparian zone field site

Kurtis G. Paterson, Jerald L. Schnoor

ABSTRACT: A field site was established and instrumented in Amana, Iowa to investigate the fate and transport of the pesticides alachlor and atrazine in the unsaturated zone adjacent to a drainage lake. The pesticides were applied to a barren plot, a plot planted with corn, and a plot planted with deep-rooted poplar trees (*Populus spp.*) to study the characteristic behaviors of a typical agricultural environment (corn plot) and a novel pollutant interception technique (poplar plot) in comparison to unmanaged land (barren plot). A mass balance model was developed and solved for the pesticides on each of the three plots. While the majority of alachlor and atrazine adsorbed to the soil and eventually degraded or accumulated in the unsaturated zone, portions of the pesticides remained in the aqueous phase and subsequently were transported in the surface runoff and to the water table. Alachlor was found to be more mobile and more quickly transformed than atrazine. Plant uptake was an important process in the fate of the pesticides, and hence, vegetative buffer strips hold promise for protecting water supplies. *Water Environ. Res.*, **64**, 274 (1992).

KEYWORDS: alachlor, atrazine, fate, model, pesticides, plant uptake, transport.

Historically, surface water and groundwater supplies have been contaminated by naturally occurring substances such as organics, salts, or algae. However, with the emergence of modern society, anthropogenic contaminants, some of dangerously high toxicity, have received greater scrutiny by the public and policy makers alike. To address these concerns, the fate of contaminants in the natural environment must be understood.

A widespread concern in Iowa and other farming regions is the transport of agricultural chemicals to groundwater supplies, which are often the sole water source for many rural communities. Iowa ranks second in the nation in use of pesticides, surpassed only by California. Alachlor and atrazine are the most commonly used herbicides in Iowa, where nearly 4.5×10^6 and 3.2×10^6 kg active ingredient, respectively, are applied annually (Goolsby *et al.*, 1991). Consequently, water supply surveys have been commissioned for these contaminants.

The Iowa Statewide Rural Well Water Supply study was initiated by the Iowa Department of Natural Resources in 1987. This large-scale survey of 686 wells, conducted by the University of Iowa's Center for Health Effects of Environmental Contamination, was carried out in 1988 and 1989 and was the first survey to test wells in each of Iowa's 99 counties (Kross *et al.*, 1990). The survey showed that 13.6% of the wells contained detectable pesticides, with 1.2% of the wells higher than federal safety standards. Atrazine was the most commonly detected pesticide and was present in 8% of the wells, with an average concentration of 1.14 μg/L. Alachlor was detected in 1.2% of the wells, which had a 0.67-μg/L average concentration. Northwestern Iowa, however, had approximately 24% of wells test positive for pesticides. Well depth was found to be a significant factor in contamination. Nearly 28% of the wells were less than 15 m (50 ft) deep; and 18% were contaminated with pesticides. The geographic regions that had higher percentages of contamination also had higher percentages of shallow wells. The final results showed that more than 94 000 Iowans drink groundwater that contains one or more pesticides. Underscoring the importance of the problem, the survey warns that these figures may be conservative because 1988 and 1989 were drought years.

Surface water supplies are contaminated principally by contaminant-laden runoff water. Agricultural runoff has been suspected of being a significant nonpoint source of surface water contamination and, subsequently, alternative land management techniques have been investigated and proposed. Complicating these recommendations, though, is the fact that runoff water also transports precious topsoil. Licht (1990) has shown the importance of the riparian zone in reducing nonpoint source runoff. Poplar tree buffer strips planted in the riparian zone have proven effective in reducing nitrate runoff and percolation from agricultural settings (Paterson and Schnoor, In press).

The objectives of this research were to design and instrument a field site for investigation of contaminant fate and transport in the unsaturated zone, identify major fate pathways for alachlor and atrazine in the unsaturated zone field site, quantify the fate pathways through the solution of mass balances, and obtain preliminary information on groundwater and surface water contamination reduction or prevention with the use of poplar tree buffer strips.

Fate Processes

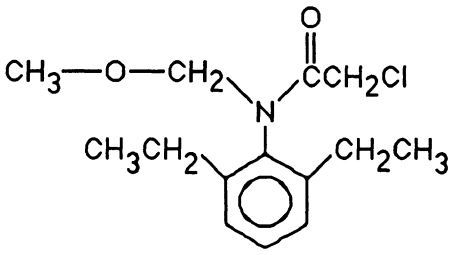
The fate processes that alachlor and atrazine may undergo have been divided into the four basic terms in the mass balance: input, transport, reactions, and accumulation. While there are hundreds of possible interactions within a specific control volume in the natural environment, only the pathways most prevalent within the unsaturated zone control volume are discussed.

Input. Application of pesticides to cropland is the dominant input to the natural environment.

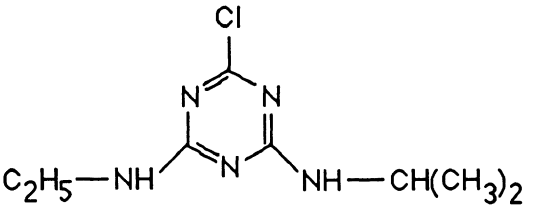
APPLICATION. Alachlor and atrazine are applied in the spring in the Midwest for preemergent weed control (Figure 1, Table 1). In emulsified form, Lasso® is 45.1% alachlor (54.9% inert ingredients), or 0.5 kg/L active ingredient (Scientific Software, 1988). Aatrex® is 49.6% atrazine and 50.4% inerts. Typically, 2–4 L of herbicide are diluted with water and applied to 0.4 ha (1 ac) of cropland via a tractor-pulled applicator or irrigation system.

Transport. Wilson (1987) has estimated that 1–5% of the pesticides applied to Iowa farm fields are transported off the intended land, resulting in a $5–23 million loss annually. Pesticide losses from a specific target area occur by transport in the solid, air,

This content downloaded from 137.187.180.215 on Wed, 2 Jul 2014 10:52:45 AM
All use subject to JSTOR Terms and Conditions



(a) 2-Chloro-2', 6'-diethyl-N-(methoxymethyl) acetanilide



(b) 2-Chloro-4-ethylamino-6-isopropylamino-s-triazine

Figure 1—Chemical structures of (a) alachlor and (b) atrazine.

and water or, more typically, combinations of these media. Drift can be a air–water, air–solid transport process; runoff is a water–solid process; and percolation and plant uptake are principally aqueous phase processes. These four transport pathways constitute the major pesticide losses from the unsaturated zone and are strongly influenced by hydrologic processes, which are driven by precipitation.

DRIFT. Application of pesticides usually involves the dissemination of fine droplets to provide a uniform distribution of a small volume over a large area. Through this process, spray application to agricultural crops releases significant quantities of pesticides to the atmosphere, millions of kilograms each year.

Another major route of entry of pesticides to the atmosphere is through volatilization from treated soils and plants. Volatilization is at a maximum immediately following application, before the pesticide has fully sorbed to the treated surface, and it closely parallels the vapor pressure of the compound. Volatilization from soil increases with temperature, humidity, and wind velocity. However, Starr and Johnsen (1968) found that increased humidity reduced volatilization of pesticides from plants. Inputs to the atmosphere can also be due to pesticides entrained as dust and evaporation from water.

RUNOFF. Howe *et al.* (1989) conducted a 2-year study of a small North Carolina estuary that received runoff water from a 20 230-ha (50 000-ac) farm. In 1987, the peak alachlor concentration in the estuary due to runoff was 14 μg/L. In 1988, the concentration peaked at 47 μg/L. Timing and volume of precipitation are key factors in the quantity of pesticide transported in surface runoff. Also, precipitation patterns determine the maximum pesticide concentrations which aquatic ecosystems receive via agricultural runoff.

PERCOLATION. Percolation of pesticides is dependent on the tendency to bind to the soil; the composition of the soil; and, analogous to runoff, the timing and intensity of precipitation. Both alachlor and atrazine have been detected every month of the year in shallow Iowa groundwater samples (Kelley *et al.*, 1986). The maximum concentration of alachlor detected was 16.6 μg/L compared to 13.0 μg/L for atrazine. However, atrazine was present almost five times more frequently than alachlor in groundwater samples.

PLANT UPTAKE. Root uptake readily occurs in plants, regardless of whether they are resistant or susceptible to the herbicides. Plant uptake increases with increasing concentrations and time of exposure to the chemicals and with higher temperatures and lower humidity. Once inside the plant, pesticides are typically distributed by the xylem to all aerial parts of the plant. Generally, some accumulation is evident in the leaves, particularly in susceptible plants.

Reactions. Transformation of pesticides tends to be most intensive in the unsaturated zone because of its higher organic carbon content, greater microbial population, and fluctuating levels of moisture and oxygen. Hydrolysis, chemical oxidation, biotransformation, photolysis, and other reactions work towards the transformation and mineralization of constituents in the natural environment. The relatively fast rate of alachlor transformation is evident in the half-lives obtained by many researchers. Cohen *et al.* (1984) found a 21-day half-life for alachlor, Rao *et al.* (1985) showed an 18-day half-life, and Howe *et al.* (1989) observed a range of 7–21 days. Half-lives for atrazine disappearance have been observed in a range of 10–100 days in the field (Portnoy, 1989, and Hurle and Kibler, 1976). The range of values demonstrates the unique characteristics of each environment. Generally, however, transformation occurs more quickly in nutrient-rich and moist soils, which enhance microbial activity.

Accumulation. Accumulation of alachlor and atrazine in the unsaturated zone is almost entirely due to soil adsorption and is a significant process for these herbicides. Both are hydrophobic organic chemicals, indicating a tendency to adsorb to soil instead of remaining in the aqueous phase.

Field Site

Location. A field site was established near Middle Amana, Iowa, (approximately 42°N Latitude, 92°W Longitude) on land donated by The Amana Society. The land was part of a hay field along the northeast shore of Amana Lily Lake. The field site was developed adjacent to the lake to produce a shallow but fluctuating water table approximately 1.25–1.75 m below the small plots. Lily Lake is a small drainage lake fed by numerous small streams from agricultural hills to the north and regulated via an outlet canal. No farm chemicals have been applied to the land previously.

Table 1—Physical-chemical properties of alachlor and atrazine (Schnoor *et al.*, 1987, and Cartwright, 1980).

	Alachlor	Atrazine
Molecular formula	$C_{14}H_{20}ClNO_2$	$C_8H_{14}ClN_5$
Molecular weight, g/mole	269.8	215.7
Density, g/mL	1.133	1.187
Solubility in water, mg/L	242	70
Octanol–water partition coefficient, log K_{ow}	2.92	2.68
Vapor pressure, mm Hg at 20°C	2.2×10^{-5}	3.0×10^{-7}

This content downloaded from 137.187.180.215 on Wed, 2 Jul 2014 10:52:45 AM
All use subject to JSTOR Terms and Conditions

A strip approximately 10 m by 30 m was marked for the field site. The terrain was relatively flat with a slight slope ($\approx 1°$) towards the lake and was bordered on the north by a small cluster of trees, on the west by the eroded bank of Lily Lake, and on the east and south by the hay field (Figure 2).

Field site geology. The Amana Lily Lake field site was developed in a Nodaway series soil (Schermerhorn, 1983). Excavation revealed the soil at the Lily Lake site to be stratified (Table 2). The topsoil extended approximately 15 cm in depth and was underlain by till to the 60 cm level. A tight layer of iron-rich clay till extended down to the 1.0 m depth, which was evident by the bright rust coloration of the soil. Below this a clay-rich soil extended down to the water table, which was positioned approximately 1.5 m in depth at the start of the research project.

Field site design. The field site was divided into three plots. A plot planted with poplar trees (*Populus spp.*) to simulate a vegetative buffer strip, a second plot planted with corn to simulate an Iowa agricultural setting, and a third plot left barren to act as a reference for the other two plots.

PLOT LAYOUT. The site was marked off and, initially, a 7.5 m by 15 m area was plowed in midApril 1989. A mechanical trencher was used to cut 1.5-m deep trenches to "deep-root" the poplars and install piezometers for saturated zone samples (Licht, 1990). Poplar cuttings approximately 1.8 m in length were spaced approximately 0.5 m apart in the trenches, which were subsequently backfilled. The poplar cuttings produce a root system along the subsurface part and a canopy above within days after planting. The root systems of poplars planted in this manner extend more than 2.5 m deep and thrive in the unsaturated and saturated zones equally well. Additionally, these trees coppice (that is, regrow after being cut) and grow rapidly (2-m aboveground growth the first growing season). Fourteen rows of trees were planted, each about 1.25 m apart. In midMay an additional area was plowed immediately south of the poplar trees for the corn and barren plots. In early June six furrows approximately 1 m apart were dug by hand and planted with seed corn.

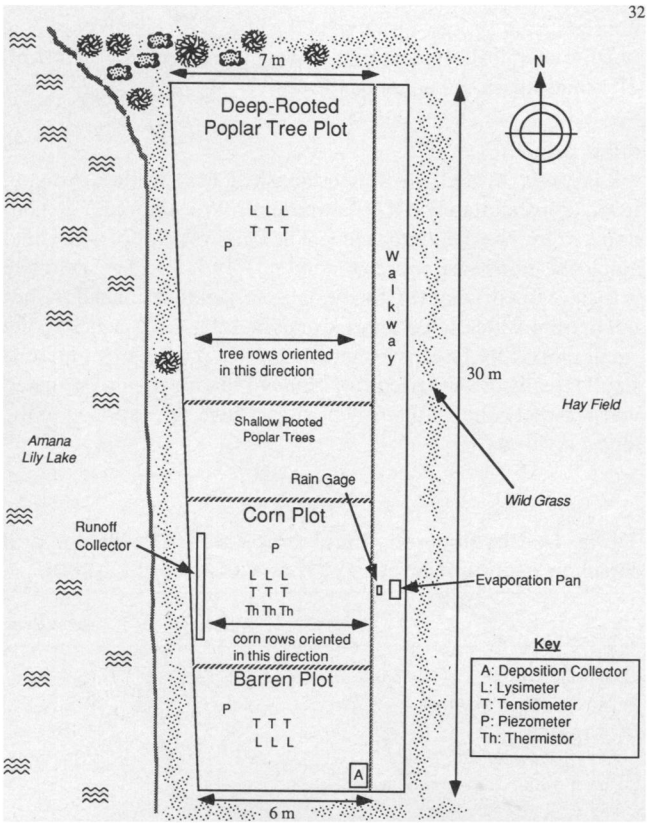


Figure 2—Layout of the Amana Lily Lake field site.

INSTRUMENTATION. All three of the plots (henceforth referred to as the poplar, corn, and barren plots) were instrumented in early June 1989. Installation depths of 30, 90, and 135 cm were selected to obtain a vertical profile of samples within the unsaturated zone. Nested sets of Soilmoisture® suction lysimeters and tensiometers were installed at these depths in each plot. Additionally, the corn plot had a nest of three Omega® thermistors at the same three depths. An aluminum runoff collector was constructed with gravity drainage collection and installed along the western edge of the corn plot because surveying determined it to be in a low-lying area of the plot. A rain gauge and evaporation pan were stationed along the east side of the corn plot. An Aerochem® wet/dry deposition collector was set in the southeast corner of the barren plot.

All three plots had pesticides applied July 31, 1989, using a backpack sprayer. The pesticides atrazine and alachlor were applied at a target rate of 5.5 kg/ha (5 lb/ac) active ingredient over the corn and 11.0 kg/ha active ingredient over the barren plots. Because it was suspected that the poplars were susceptible to the alachlor herbicide, only atrazine was applied to the poplar plot at a target rate of 2.2 kg/ha active ingredient (normal application rate) to avoid harming the trees. The actual rate applied was determined by randomly placing collection jars throughout the plots to obtain samples during chemical application.

Alachlor and atrazine analysis. The procedure used for the determination of alachlor and atrazine concentrations in water samples was solid phase extraction followed by gas chromatography (J&W Scientific, 1989, and Allied Fisher Scientific, 1984). The method enabled analysis of both pesticides simultaneously. Fisher® PrepSep™ extraction columns were used for the extraction phase. The extraction columns were packed with 300 mg of C_{18} bonded-phase silica with a 40-μm pore size. The column was eluted with 2 mL of methanol. A 5-μL elution sample was then injected to a J&W® split-flow capillary column within a Hewlett–Packard® 5890A gas chromatograph for determination of alachlor and atrazine concentrations. Helium was the carrier gas at a flow rate of 3 mL/min. Detection was with a ^{63}N electron capture detector with a makeup gas of 95%/5% argon/methane. Oven temperature was 170°C for 5 minutes then ramped to 200°C at 5°C/min.

Hydrology and Pesticide Mass Balances

To quantify the major pathways of pesticides applied in the environment, a mass balance on alachlor and atrazine was developed. Beginning with the simple relation (equation 1):

$$m_{in} - m_{out} \pm m_{rxn} = \Delta m \qquad (1)$$

the mass balance was accomplished by refining this equation to the specific study of pesticides in an unsaturated riparian zone field setting.

Hydrologic balance. As the concentration and not the mass of the pesticides was measured in this research, it was necessary that the volume of water transporting the pesticide be quantified

This content downloaded from 137.187.180.215 on Wed, 2 Jul 2014 10:52:45 AM
All use subject to JSTOR Terms and Conditions

Table 2—Physical and chemical properties of the Amana Lily Lake field site soil profile.[a]

Soil depth, cm	TOC, % mass	TKN, mg/kg	NH_3-N, mg/kg	NO_3-N, mg/kg	pH, 1:1 in H_2O	Permeability, 10^{-6} cm/s
8	8.85	955.0	5.0	0.80	—	219.20
27	3.10	415.0	3.0	—	7.4	89.70
50	2.10	195.0	3.5	<0.01	—	11.95
75	1.75	155.0	3.0	0.75	7.3	5.18
100	1.45	185.0	2.5	0.15	—	—
135	—	—	—	—	7.4	1.65
200	1.00	120.0	2.0	0.70	6.8	—

[a] TOC, TKN, NH_3, and NO_3 analyses performed by The University of Iowa Hygienic Laboratory.

into respective pathways before the pesticide mass could be balanced. By compartmentalization of the input and output terms, pathways were defined and the water balance was more readily suited to measurement in the field and quantification with the model. For quantification, a control volume was first defined. In this study, the control volume was the area of the field plot in question extended in depth to the water table (that is, the unsaturated zone of each field plot).

Processes leading to an input of water to the control volume include precipitation directly onto the site and overland flow of water from land upgradient of the field plot. The water leaving the control volume was divided into four processes—runoff, evaporation, transpiration, and percolation. The change in soil moisture accounted for the water that accumulated or disappeared from the control volume over the course of the research.

Due to the difficulty in measurement, the volume of water that percolated out of the control volume was calculated by the difference of the inputs, the other three outputs, and the change in soil moisture (equation 2).

$$V_p = (V_i + V_o) - (V_r + V_e + V_t) - \Delta V_{sm} \qquad (2)$$

Precipitation, evaporation, and soil moisture were measured by rain gauge, evaporation pan, and soil samples, respectively. Overland flow and runoff were calculated by the rational method (Chow *et al.*, 1988) and runoff collector, whereas transpiration was determined with the method by Blaney and Criddle (1966).

Alachlor and atrazine mass balances. Following the solution of the hydrologic balance, the mass balances on alachlor and atrazine in the field plots were solved. The control volume used for the hydrologic balance was likewise assigned for the pesticide mass balances. Because alachlor and atrazine possess different characteristics and the influence of the vegetation was of some interest, five mass balances were done—one for each of the following systems: alachlor applied on the barren plot, atrazine on the barren plot, alachlor on the corn plot, atrazine on the corn plot, and atrazine on the poplar plot (alachlor was not applied to the poplar plot).

As implied by the solution of a hydrologic balance, water was the media primarily responsible for transport of the pesticides. Hence, the solution of the hydrologic balance was critical to the solution of the mass balance. Using the acquired data, the mass balance, in terms of measurable quantities, was solved (equation 3).

$$\sum_{i=1}^{m} Q_{in_i} C_{in_i} - \sum_{j=1}^{n} Q_{out_j} C_{out_j} - \sum_{k=1}^{p} m_{rxn_k} = \frac{\Delta(VC_T)}{\Delta t} \qquad (3)$$

Although there are numerous pathways in each of the four terms above, the number of pathways was limited to those thought to have a major role in the mass balance. For the mass of alachlor and atrazine into the control volume, the single, direct application was the only significant source. The pesticide mass out of the control volume was due to runoff, vertical transport by percolation into the saturated zone, and plant uptake. The mass that accumulated in the control volume by adsorption to soil was determined with a linear partitioning relationship (equation 4):

$$S = K_p C \qquad (4)$$

where K_p was the soil–water partition coefficient (a function of the octanol–water partition coefficient), C was the dissolved pesticide concentration in soil–water, and S was the amount of absorbed pesticide per mass of soil. Local sorption equilibrium was assumed. Parameters needed for this mass balance included partition coefficients, soil moisture and organic carbon contents, and pesticide half-lives. The pesticide mass transformed in the control volume soil–water was the last pathway to be calculated from field measurements. The pesticide mass transformed in the soil-bound phase was estimated by difference (equation 5). The soil reaction mass calculation assumed there were no other losses of bound pesticide, such as desorption from the soil.

$$m_{soil\ rxn} = m_{app} - (m_r + m_p + m_{pu}) - m_{acc} - m_{aq\ rxn} \qquad (5)$$

A more detailed description of the mass balance model used to determine the fate of alachlor and atrazine at the field site is presented by Paterson and Schnoor (1990).

Results

Lysimeter samples collected on July 25—6 days before application—were analyzed for alachlor and atrazine concentrations. In all cases, the concentrations present were less than detectable levels (1 μg/L).

Pesticide applications. Alachlor and atrazine emulsions were diluted with water and applied by hand sprayer on July 31, 1989—day 29 of the field research study. The plots were sprayed in order of increasing application rate. Twelve collection jar samples (four per plot) were analyzed to determine mass collected per unit area. An average application was determined for each of the pesticides on each of the plots. The results are presented in Table 3.

Much of the problem with the low pesticide application was attributed to solubility limitations. The fact that actual atrazine

This content downloaded from 137.187.180.215 on Wed, 2 Jul 2014 10:52:45 AM
All use subject to JSTOR Terms and Conditions

Table 3—Intended versus actual application rates for alachlor and atrazine at the Amana Lily Lake field site.

Plot	Chemical	Intended, kg/ha	Measured, kg/ha	Delivered, %
Poplar	Alachlor	0.0	—	—
	Atrazine	2.2	1.34	61.0
Corn	Alachlor	5.5	1.35	24.6
	Atrazine	5.5	0.78	14.2
Barren	Alachlor	11.0	6.97	63.4
	Atrazine	11.0	4.97	45.2

application rates were lower than the alachlor rates was directly attributable to the fact that atrazine is only 30% as soluble as alachlor in water (Table 1). Also, some alachlor and atrazine remained in the sprayer so were not fully delivered to the plots.

Field environmental conditions. *PRECIPITATION.* The most apparent and pervasive problem was the lack of significant rainfall. A severe drought in the summer of 1988 followed by a dry, mild winter produced low soil moisture levels, which were exacerbated by a continued absence of substantial precipitation in the early period of the study. It was difficult to obtain soil–water samples. Additionally, the poplar trees and corn crops competed for and required large quantities of water, which left less for the lysimeters to withdraw from the soil. This limited the sampling frequency to once per week, less than planned, particularly for the first few weeks following application. Another effect that the lack of rain produced was a lowering of Lily Lake and, consequently, the water table in the field site. This resulted in few samples from the piezometers. The dryness in the field was not rectified until significant precipitation occurred in mid–late August (Figure 3). From midSeptember to the end of the study, October 4, 1989, another dry period occurred.

OTHER ENVIRONMENTAL PARAMETERS. Air temperature, soil temperature, soil pressure, soil moisture content, and evaporation rates were also measured to aid in the determination of the hydrologic balance and ultimately the fate and transport of the contaminants at the field site. These data are reported by Paterson (1990).

Pesticide results. *RUNOFF SAMPLES.* Four rainfall events produced measurable runoff events on day 43, day 52, day 60, and day 67, as shown in Figure 4. After this point, the alachlor and atrazine concentrations were undetectable in runoff. Alachlor ran off at higher concentrations than atrazine; the alachlor concentration was nearly double that of atrazine in the first runoff event, but alachlor was applied to the corn plot at nearly double the concentration (1.35 kg/ha active ingredient versus 0.78 kg/ha active ingredient). Because the poplar and barren plots had no runoff collectors, the runoff concentrations were assumed to be proportional to the corn results, based on application rates.

The effect of rainfall was evident in the data collected. Light rain over a long period produced a slowly decreasing concentration of pesticide in the runoff water, as evident in the first two events. Intense rainfall, conversely, resulted in a cleansing of the surface.

LYSIMETER SAMPLES. Soil–water samples were only consistently obtained from three deep lysimeters—the 90-cm depth in the poplar plot and the 135-cm depth in the corn and poplar plots. Samples were obtained from other locations, particularly after the wet period; but, in most cases, the samples provided pesticide concentrations that were not detectable.

Alachlor. The alachlor concentrations obtained over time in the corn plot are shown in Figure 5. The 90-cm depth yielded only three detectable concentrations (the first three), hence the dotted line was used to represent that the exact trend was not evident. Although the rise and fall in the concentration was anticipated, the exact gradient of the trend could only be estimated with the data collected. The trend may have been much different, particularly in the first few days after application, and may have reached a higher concentration at some point before the sample collected on day 52. However this is only speculation and, therefore, the trend shown in Figure 5 was interpolated for use in the mass balance model.

The 135-cm depth lysimeter consistently produced detectable pesticide concentrations. As shown, a small peak appeared in early August, which followed a small rain event. Because the soil was dry before the rain event, some alachlor may have been carried with the soil–water as it quickly percolated. After the peak, a general decrease in concentration resulted because the pesticide was biotransformed over time. The bottom boundary of the control volume was set at the 135-cm depth; therefore, alachlor was transported out of the field plot unsaturated zone.

Samples from the 1.5 m deep piezometers could not be collected until the heavy rains in late August. By this time, however, the alachlor concentration was no longer detectable.

Data collected from the corn plot was instrumental for further alachlor analysis. No detectable samples were collected from the barren plot, and while samples were collected regularly from the poplar plot, alachlor was not applied to that plot. Therefore, in the modeling analysis, data presented in Figure 5 were used; and, as in runoff, all other plots were assumed to follow the same trend, with concentration directly proportional to the application rates.

The standard deviation of three replicate samples was determined for use as the uncertainty in water sample alachlor concentration. Analysis for alachlor samples produced an uncertainty of ±12%.

Atrazine. In a manner similar to the corn plot and alachlor, the poplar plot provided all of the atrazine data. As can be seen

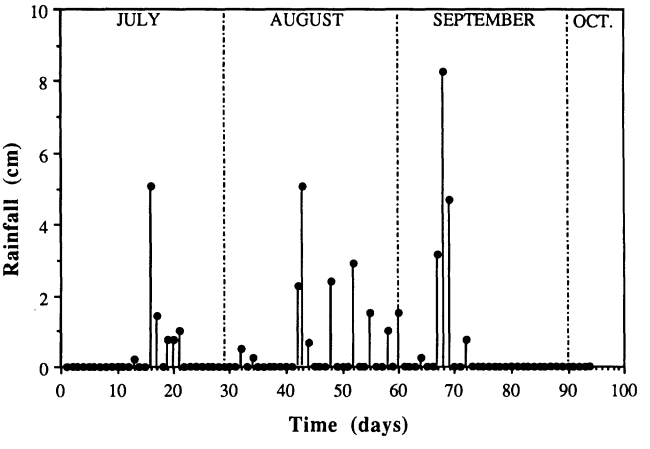


Figure 3—Rainfall at the Amana Lily Lake field site over the period July–October 1989.

This content downloaded from 137.187.180.215 on Wed, 2 Jul 2014 10:52:45 AM
All use subject to JSTOR Terms and Conditions

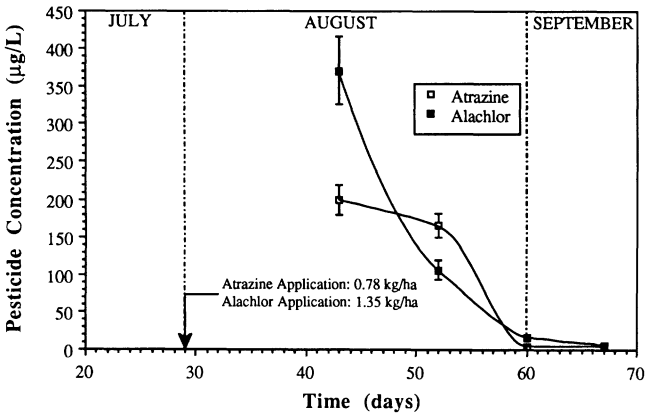


Figure 4—Alachlor and atrazine concentrations in runoff water samples from the corn plot (mean ± standard deviation are represented by data points and error bars, *n* = 3).

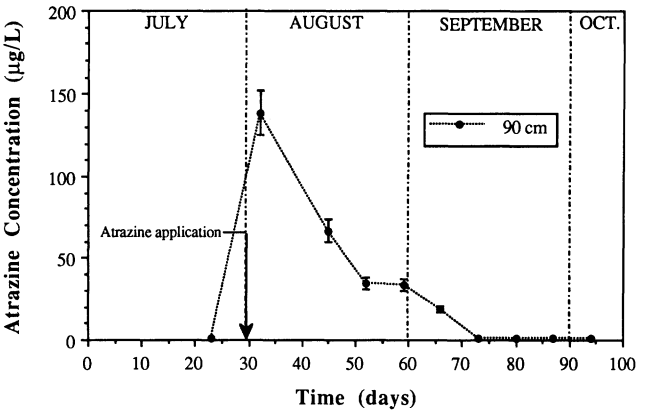


Figure 6—Atrazine concentration in soil-water samples from the poplar plot at a 90-cm depth (mean ± standard deviation are represented by data points and error bars, *n* = 3).

in Figure 6, only the 90 cm deep lysimeters produced soil-water samples with detectable atrazine concentrations. While the 135 cm deep lysimeter consistently collected soil-water samples, no atrazine was ever detected at this depth. The poplar plot data did produce the anticipated trend—a spike shortly after application followed by a decrease. Alachlor in the corn plot probably followed a trend similar to this, although it could not be sampled because of dry conditions. Analysis of replicate samples indicated a sample uncertainty of ±10% for atrazine concentration.

The lack of detectable concentrations of atrazine in the 135 cm deep samples revealed two facts. First, unlike alachlor, no atrazine was transported out of the control volume, which indicated that atrazine was bound more to the soil. Secondly, the decrease in concentration at the 90-cm depth was mainly due to biotransformation because percolation would have transported atrazine to the 135-cm depth.

BIOTRANSFORMATION. Because the calculation of the pesticide mass accumulated in the control volume was important in balancing the mass equation, rates of transformation were estimated based on the disappearance rate in soil-water. The alachlor and atrazine concentrations at the 90-cm depth were used as a representative sampling point for transformation observation. The rates of transformation were calculated by plotting the logarithm of concentration versus time and determining the slope. Half-lives were determined by measuring the elapsed time between maximum concentration and 50% of that amount. The pesticide mass that percolated out of the unsaturated zone control volume was subtracted from the reaction mass to eliminate transport effects from the reaction rate and half-life determinations. The alachlor percolation mass was approximately 5% of the mass that reacted in the control volume, whereas no measurable atrazine percolated out of the unsaturated zone. Hence, the effect of mass transport losses on the reaction rates and half-lives was negligible. The results for alachlor and atrazine are provided in Table 4.

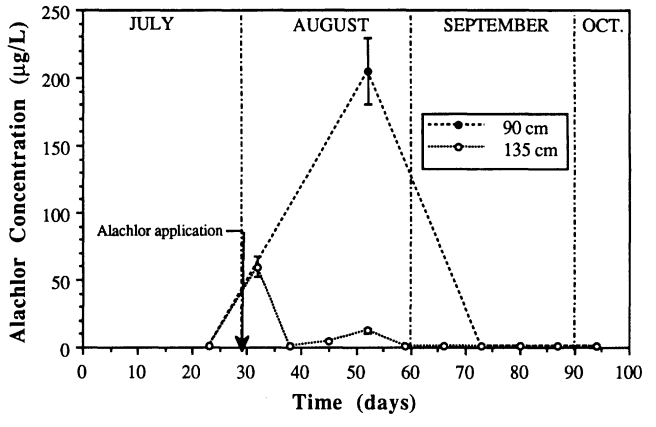


Figure 5—Alachlor concentration in soil-water samples from the corn plot at 90- and 135-cm depths (mean ± standard deviation are represented by data points and error bars, *n* = 3).

Alachlor was transformed almost four times more rapidly than atrazine (0.25 versus 0.06 d^{-1}) because chloroacetanilide pesticides are more readily transformed than *s*-triazines. At the same site, Nair (1991) showed aerobic mineralization of atrazine due to microbial processes, with a rate constant of 0.02–0.03 d^{-1}. Sterile controls indicated a lack of any reaction, thereby excluding abiotic reactions for atrazine. These mineralization rates were approximately 50% of the reaction rate constant determined in this study (0.06 d^{-1}), as expected, because this study includes parent compound transformation only. Half-lives calculated from the data also showed that alachlor disappeared more quickly than atrazine. These values compared well to those in the literature, with ranges of 7–20 days for alachlor and 10–100 days for atrazine (Howe *et al.*, 1989, and Portnoy, 1989). The fact

Table 4—Half-lives and first-order rates of transformation of alachlor and atrazine in the unsaturated zone of the field site.

Pesticide	Half-life, days	Transformation rate, day^{-1}
Alachlor	10	0.25
Atrazine	16	0.06

This content downloaded from 137.187.180.215 on Wed, 2 Jul 2014 10:52:45 AM
All use subject to JSTOR Terms and Conditions

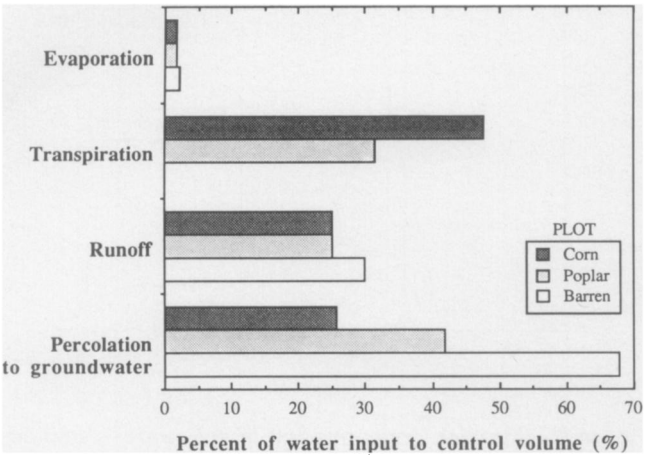


Figure 7—Comparison of hydrologic balances for the poplar, corn, and barren plots for the study period beginning July 31, 1989, and ending October 4, 1989.

that the half-lives in Table 4 were in the low end of these ranges may have been due to the high organic carbon content prevalent in the rich Iowa soil. The organic carbon provided abundant substrate for enhanced biotransformation, whereas many of the half-lives in the literature were determined in much lower organic carbon soil. For the mass balance model, half-lives were assumed constant with time and space to estimate the amount of adsorbed pesticide that accumulated in the control volume during the study period.

Hydrologic balance results. The hydrologic model was a necessary precursor to the mass balance model. The model was driven by precipitation at the field site and, therefore, the measurement of precipitation was critically important. The volume of water between each sampling period was calculated and broken down into each of the four water pathways: percolation, runoff, transpiration, and evaporation.

By dividing each of the pathways by the total volume, the pathways were normalized for comparison and plotted as percentages of the total water volume (Figure 7). For each plot, the change in soil moisture was found to account for less than 1% of the total water within the control volume during the study. Also, soil profile moisture content varied less than 1.5% between samplings. Due to these small values, the change in soil moisture was considered insignificant and was not considered in any subsequent analysis.

Figure 7 shows the variation among conditions in the barren, corn, and poplar plots and shows the relative effects of vegetation on the final distribution of water within the control volumes. The runoff values of 25% for the corn and poplar plots versus 30% for the barren plot demonstrated the retarding effect vegetation had on overland flow. Likewise, the 1.7% evaporation values for the corn and poplar plots versus the 2.2% value for the barren plot revealed the effects of shading and surface wind reduction by the vegetation on the water balance. In all cases, the corn and poplar trees were assumed to have identical transpiration rates, soil surface roughness, and shading because both types of plant were of similar size and leaf area index. Additionally, both plant species were assumed to have uniform root density distributions along the rooting depths. The transpiration and percolation water volume totals were directly linked to the root systems of the plants, or the absence of any root systems in the barren plot case. As shown in Figure 7, the transpiration percentage ranged from nearly zero for the barren plot to more than 45% for the corn plot. Again, poplar and corn plants were assumed to possess equal transpirative capabilities, but research by Licht (1990) showed that only 65% of poplar root systems were in the unsaturated zone (that is, the control volume); hence, the poplar plot transpiration percentage was approximately 30% of the input water volume (that is, 65% of the corn percentage). The effect of transpiration manifested itself most clearly in the percolation percentages. As revealed in Figure 7, percolation was inversely proportional to transpiration. The barren plot without any vegetation had the highest percolation percentage, 68%, of the three plots, while the poplar plot had 42% and the corn plot had 26%, which demonstrated the effect of increasing root concentration in the unsaturated zone control volume.

Alachlor and atrazine mass balance results. The percentage of the pesticide mass in each pathway was determined by dividing each mass by the total mass applied to the plot. Table 5 shows the result of this data transformation to percentages of the alachlor mass applied to the barren and corn plots. The relative importance of each pathway was readily apparent.

Propagation of uncertainties states that the uncertainty for a product is the sum of the fractional uncertainties (Taylor, 1982). In this case, mass = CV, so $\frac{\delta m}{|m|} = \frac{\delta C}{|C|} + \frac{\delta V}{|V|}$, where δx is the standard deviation and $|x|$ is the best estimate, or mean, of x. This approach is conservative and will yield the largest uncertainty possible. As previously stated, the fractional uncertainties of the alachlor and atrazine concentrations, $\frac{\delta C}{|C|}$, were 12 and 10%, respectively. The fractional uncertainties in water volume, $\frac{\delta V}{|V|}$, were calculated by measurement when possible (for example, soil moisture, runoff) and through literature values for transpiration and percolation. The soil retention fractional uncertainty was the summation of fractional uncertainties in the partition coefficient and soil–water pesticide concentration, whereas the uncertainty in the soil reaction term was the summation of the uncertainties in the terms of equation 4 (that is, the uncertainty of a sum is the sum of individual uncertainties).

Table 5—Alachlor mass balance pathways for the barren and corn plots at the Amana Lily Lake field site—percent of total alachlor mass applied to plot.

Pathway	Barren plot	Corn plot
Transport out		
Runoff	11.6 ± 5.2	11.6 ± 5.2
Percolation	0.7 ± 0.2	0.3 ± 0.1
Plant uptake	<0.1	12.5 ± 4.5
Reaction		
Soil biotransformation	67.3 ± 21.5	67.9 ± 21.7
Soil–water biotransformation	17.7 ± 2.1	6.7 ± 0.8
Accumulation		
Soil retention	2.7 ± 0.9	1.1 ± 0.4

This content downloaded from 137.187.180.215 on Wed, 2 Jul 2014 10:52:45 AM
All use subject to JSTOR Terms and Conditions

One large source of uncertainty was the lack of measured pesticide residue in the soil and plants.

The barren plot soil biotransformation accounted for nearly 65% of the alachlor mass and indicated the tendency for alachlor to adsorb to the soil. Aqueous phase biotransformation possessed the next largest quantity of alachlor in the barren plot, followed by runoff. A sizable portion, nearly 3%, of the applied alachlor remained accumulated in the control volume at the end of the research period. A small fraction, less than 1%, was transported by percolation out of the control volume, while there was no plant uptake of alachlor. In the case of the plant uptake pathway in the barren plot and other pathways in other plots, a value of <0.1% was used instead of zero to account for the natural uncertainty and detection limit.

In the corn plot, the large percentage of alachlor in the plant uptake was attained through direct competition with the other aqueous phase pathways: percolation, soil–water biotransformation, and accumulation (runoff occurred independently of the subsurface phenomena). The effect of corn on the plot was to decrease the percentage of alachlor in the percolation, accumulation, and soil–water biotransformation pathways. All three were more than halved by a 12.5% alachlor mass uptake by the corn. As stated previously, runoff remained unaffected by the subsurface competition so was 11.6%. Also, the percentage of alachlor that underwent biotransformation while adsorbed to the soil remained nearly the same.

Table 6 shows the fate pathway percentages for atrazine applied to barren, corn, and poplar plots. Compared to the alachlor results for the barren plot, it was evident that more atrazine was biotransformed in the soil. Similarly, a smaller percentage was in the soil–water biotransformation compartment, which indicated a lower solubility of atrazine and/or a slower biotransformation rate than alachlor. A lower fraction for runoff was obtained, showing that atrazine was slightly less (10% less) mobile in the runoff water. The accumulated atrazine mass fraction was nearly twice as large as the alachlor fraction, which meant atrazine was bound more readily to the soil and transformed more slowly in the soil. No atrazine was transported out of the control volume, an indication of greater adsorption of atrazine, and none was transpired by plants.

From the corn plot results, it was evident that less atrazine (5.5%) than alachlor (12.5%) was taken up by the corn due to the more limited mobility of atrazine in the aqueous phase. The corn did effectively reduce the amount of atrazine that accumulated in the control volume from 5.8% for the barren plot to 2.3% for the corn plot. Likewise, the corn uptake reduced the amount of atrazine that was biotransformed in the soil–water from 7.7% for the barren plot to 2.9% for the corn plot. Unaffected by the subsurface processes, runoff remained at 10.2%. Soil biotransformation reactions comprised almost 80% of the mass applied, which indicated the lower solubility of atrazine in water compared to the 67.9% of the alachlor in the corn plot. As before, no atrazine was transported out of the control volume.

The influence of the poplar trees was to decrease the atrazine mass available for accumulation and soil–water transformation by competing for the water that also contained the pesticide. The soil accumulation fraction was reduced to 3.6%, compared to 5.8% for the barren plot, but was slightly more than the 2.3% for the corn plot. The difference between the corn and poplar plots was directly attributed to the fact that only 65% of the poplar roots were in the unsaturated zone control volume, whereas 100% of the corn roots were. The poplar uptake fraction ($\approx$4%) compares favorably to the laboratory experiments and plant residue analyses by Nair (1991) using lower organic carbon soils and a longer research period ($\approx$10% poplar uptake of atrazine with 2% organic carbon content soil during a 126-day study). For the reasons stated before, runoff remained unchanged for atrazine. However, the soil–water biotransformation fraction was reduced by the poplar uptake in a similar but lesser manner than for the corn. Soil biotransformation accounted for nearly 78% of the atrazine.

The general effect of plant transpiration was to dewater the control volume, which lowered soil moisture and resulted in a greater mass fraction adsorbed to the soil in the control volume. This led to a greater fraction that underwent soil biotransformation (76.3, 77.8, and 79.1% of the applied atrazine mass for the barren, poplar, and corn plots, respectively).

Percentages of the total aqueous phase pesticide mass during the study within the percolation, plant uptake, runoff, and soil–water biotransformation pathways were determined to examine the importance of the aqueous phase (more mobile) pesticide. The differences in aqueous phase pesticides among field plots are illustrated in Figure 8. The results of increasing transpiration were clearly evident again. Plant uptake fractions of the total aqueous alachlor were 0 and 40% for the barren and corn plots, respectively. This manifested a drop in soil–water biotransformation—from 59% for the barren plot to 22% for the corn plot. Additionally, the percolation fraction was reduced from 2.5 to 0.9% for the barren and corn plots. The runoff fraction was not changed by the amount of plant uptake but was decreased by the presence of the corn crop by enhancing the surface roughness, decreasing the runoff water volume.

The aqueous phase atrazine percentages were different than those for alachlor because of the differing chemical properties, primarily water solubility, which resulted in lower atrazine concentrations in the soil–water samples. This resulted in uptake percentages of 0, 19.3, and 29.3% for the barren, poplar, and corn plots, respectively. Likewise, the soil–water biotransformation reactions constituted lower fractions than for alachlor but were still decreased substantially from 43 to 25.7 to 15.8% for the barren, poplar, and corn plots. The lower soil–water concentrations for atrazine resulted in higher runoff percentages for

Table 6—Atrazine mass balance pathways for the barren, corn, and poplar plots at the Amana Lily Lake field site—percent of total atrazine mass applied to plot.

Pathway	Barren plot	Corn plot	Poplar plot
Transport out			
Runoff	10.2 ± 4.4	10.2 ± 4.4	10.2 ± 4.4
Percolation	<0.1	<0.1	<0.1
Plant uptake	<0.1	5.5 ± 1.8	3.6 ± 1.3
Reaction			
Soil biotransformation	76.3 ± 13.0	79.1 ± 13.4	77.8 ± 13.2
Soil–water biotransformation	7.7 ± 0.8	2.9 ± 0.3	4.8 ± 0.5
Accumulation			
Soil retention	5.8 ± 1.9	2.3 ± 0.8	3.6 ± 1.3

This content downloaded from 137.187.180.215 on Wed, 2 Jul 2014 10:52:45 AM
All use subject to JSTOR Terms and Conditions

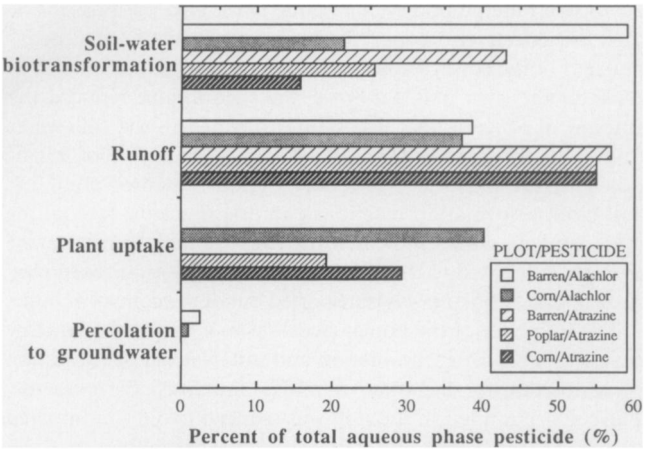


Figure 8—Comparison of aqueous-phase alachlor and atrazine fate in the poplar, corn, and barren plots for the study period beginning July 31, 1989, and ending October 4, 1989.

the aqueous phase—56.9% for the barren and 54.9% for the poplar and corn plots. The higher runoff percentages for atrazine may also have been due to higher soil adsorbed atrazine concentrations, which ultimately were carried along with the runoff water into the runoff collector. No aqueous phase atrazine was transported via percolation out of the control volume.

Sensitivity analysis. A conventional sensitivity analysis of the adjustable parameters was performed by varying the parameters ±10% of their original values. This analysis was used to identify key chemical and hydrologic processes in the fate and transport of the pesticides in the unsaturated zone. The adjustable parameters in the mass balance were modified and the absolute change in each compartment of the mass balance was summed to determine the total absolute change in mass. In terms of the chemical parameters, the pesticide half-life and partition coefficient were the most sensitive parameters. A 10% increase in the half-life and partition coefficient led to a +21 and −8%, respectively, change in the pesticide soil–water concentration. Due to the nonlinear relationship between half-life and concentration, the percentage change given was the average of the changes for alachlor and atrazine half-lives. The hydrologic process with greatest sensitivity was the amount of transpiration, which was a function of plant species and the percentage of their roots within the unsaturated zone control volume.

Conclusions

Percolation, accumulation, runoff, plant uptake, soil–water biotransformation, and soil-bound biotransformation were identified as the major fate pathways of alachlor and atrazine applied to the field site. These processes were quantified by total mass and percentage of mass applied through mass balances and were found to account for 0–1, 1–6, 10–12, 0–12.5, 3–18, and 67–79% of the pesticide mass in the control volume, respectively. The ranges resulted from differing field plot vegetative conditions—barren, corn, and poplar trees.

Adsorption, which accounted for approximately 70% of the alachlor and 80% of the atrazine mass after application, was found to be the dominant process for both pesticides. Alachlor was transformed more quickly in the unsaturated zone than atrazine (0.25 d^{-1} versus 0.06 d^{-1}), and less alachlor accumulated through the course of the study (1.1–2.7 versus 2.3–5.8%). Analysis of soil–water samples showed that the half-life of atrazine was 16 days compared to 10 days for alachlor.

Alachlor was found to be more mobile than atrazine. A greater percentage of alachlor was found in the runoff water (11.6 versus 10.2%) and in the water percolating out of the unsaturated zone (0.3–0.7 versus 0%). Alachlor was nearly three times as soluble in water than atrazine, but the partition coefficient of alachlor was greater than that of atrazine; so, for this case, water solubility was a better predictor of contaminant fate than the partition coefficient.

The runoff events possessed high concentrations of alachlor and atrazine—maximums of 375 μg/L and 200 μg/L, respectively—but the events were short-lived and exhibited a pulse input to the receiving water. The alachlor that percolated to the water table, however, was of lower concentration—maximum of 60 μg/L—but occurred over a longer period of time and was a more continuous input. No atrazine was measured to percolate to the water table throughout the study. Runoff observations indicated a potentially short-term, yet high concentration, contamination of surface water supplies shortly after application of these pesticides on adjacent land. Observed runoff and soil–water concentrations greatly exceeded the maximum contaminant levels for alachlor and atrazine of 2.0 and 3.0 μg/L, respectively (Goolsby *et al.*, 1991). Groundwater supplies may be contaminated through percolation of either of these chemicals. Alachlor is more mobile but is transformed rapidly, whereas atrazine is more persistent but less mobile. Studies in Iowa indicated that atrazine is a more common groundwater contaminant (Kross *et al.*, 1990, and Kelley *et al.*, 1986); hence, persistence is a key parameter. This was also revealed in the mass balance sensitivity analysis of pesticide half-life.

Plant uptake was found to be an influential process on the fate of alachlor and atrazine. The portion of the pesticides taken up was proportional to the water volume transpired by the plants on the plot. The corn plot transpired the most and had the largest percentage of pesticide plant uptake (12.5% for alachlor and 5.5% for atrazine), while the poplar plot had the second most (3.6% of the atrazine), and the barren plot was assumed to have negligible plant uptake. While some of the results for the corn and poplar plots were similar when the uncertainty bounds were considered, the results for these vegetated plots were clearly different than that for the barren plot. Also, the most conservative estimates of uncertainty were used; therefore, the actual bounds are likely to be less than those presented. Regardless of the uncertainty, the calculated mean percentages of pesticide taken up may be conservative because the greatest concentration of pesticides and roots were close to the surface. Similarly, due to the dry conditions preceding the field experiments, the aqueous phase pesticide masses (that is, percolation, runoff, plant uptake, and soil–water biotransformation masses) may be conservative. Lastly, an established poplar tree buffer strip would have greater plant uptake due to its perennial root system and longer growing season than corn and reduce surface runoff throughout the year.

Acknowledgments

Credits. Dr. Louis Licht, Dr. Dhileepan Nair, and Dr. Greg Wilber assisted in the project and The Amana Society provided the land required for the field site established in this research.

This content downloaded from 137.187.180.215 on Wed, 2 Jul 2014 10:52:45 AM
All use subject to JSTOR Terms and Conditions

Although the research in this article has been funded, in part, by the U. S. EPA under assistance agreement R-815709 to The University of Iowa through the Hazardous Substances Research Center for U. S. EPA Regions 7 and 8 headquartered at Kansas State University, it has not been subjected to the EPA's peer and administrative review and, therefore, may not necessarily reflect the views of EPA. No official endorsement should be inferred.

Authors. Kurtis G. Paterson is a Ph.D. candidate in the Department of Civil and Environmental Engineering at the University of Iowa, Iowa City. The work described herein was performed while he was a master's student in the Department of Civil and Environmental Engineering at The University of Iowa. Jerald L. Schnoor is a professor in the Department of Civil and Environmental Engineering at The University of Iowa. Correspondence should be addressed to K. G. Paterson, Department of Civil and Environmental Engineering, The University of Iowa, Iowa City, Iowa 52242.

Submitted for publication October 1, 1990; revised manuscript submitted December 20, 1991; accepted for publication January 27, 1992. The deadline for discussions of this paper is September 15, 1992. Discussions should be submitted to the Executive Editor. The authors will be invited to prepare a single Closure for all discussions received before that date.

References

Allied Fisher Scientific (1984) Fisher PrepSep™ Extraction Columns: Extraction of Organochlorine Pesticides in Water. Bulletin No. 739.

Blaney, H. F., Sr., and Criddle, W. D. (1966) Determining Consumptive Use for Planning Water Developments. Methods for Estimating Evapotranspiration. *Proc. Irrigation & Drainage Specialty Conf.*, Las Vegas, Nev.

Cartwright, K. J. (1980) Microbial Degradation of Alachlor Using River Die-Away Studies. M.S. thesis, Dep. Civ. Environ. Eng., Univ. Iowa, Iowa City.

Chow, V. T., *et al.* (1988) Applied Hydrology. McGraw-Hill, Inc., St. Louis, Mo.

Cohen, S. Z., *et al.* (1984) Potential Pesticide Contamination from Agricultural Uses: Treatment and Disposal of Pesticide Wastes. Am. Chem. Soc., Washington, D. C.

Goolsby D. A., *et al.*, (1991) Distribution of Selected Herbicides and Nitrate in the Mississippi River and its Major Tributaries, April through June 1991. U.S. Geological Survey Water Resour. Invest. Rep. 91-4163. Denver, Colo.

Howe, J. T., *et al.* (1989) Agricultural Runoff in a North Carolina Estuary. Paper presented at Mid-west Environ. Chem. Workshop, Ind. Univ., Bloomington, Ind.

Hurle, K., and Kibler, E. (1976) The Effect of Changing Moisture Conditions on the Degradation of Atrazine in Soil. *Proc. British Crop Protection Conf., Weeds,* 2.

J & W Scientific (1989) Extraction of Triazines using Solid Phase Extraction Cartridges. *J&W Sep. Times,* 3.

Kelley, R. D., *et al.* (1986) Pesticides in Ground Water in Iowa. Paper presented at NWWA Agric. Impacts on Groundwater Conf., Omaha, Neb.

Kross, B. C., *et al.* (1990) The Iowa State-Wide Rural Well Water Survey: Initial Analysis. Iowa Dep. Nat. Resour., Tech. Inf. Series 19.

Licht, L. A. (1990) Poplar Tree Buffer Strips Grown in Riparian Zones for Biomass Production and Non-point Source Pollution Control. Ph.D. thesis, Dep. Civ. Environ. Eng., Univ. Iowa, Iowa City.

Nair, D. R. (1991) Atrazine Fate Modeling and Mineralization Studies in Soil-Plant Systems. Ph.D. thesis, Dep. Civ. Environ. Eng., Univ. Iowa, Iowa City.

Paterson, K. G. (1990) Fate and Transport of Alachlor and Atrazine in Small Plot Field Studies. M.S. thesis, Dep. Civ. Environ. Eng., Univ. Iowa, Iowa City.

Paterson, K. G., and Schnoor, J. L. (1990) Fate and Transport of Alachlor and Atrazine in an Unsaturated Riparian Zone. *Proc. Conf. Hazardous Waste Res.*, Volume 2, Kansas State Univ., Manhattan.

Paterson, K. G., and Schnoor, J. L. (In press) Vegetative Alteration of Nitrate Fate. *J. Environ. Eng.*

Portnoy, C. E. (1989) Disappearance of Bentazon and Atrazine in Silt Loam Soil. Drinking Water Health Advisory: Pesticides. U. S. EPA, Office of Drinking Water, Lewis Publishing, Chelsea, Mich.

Rao, P. S. C., *et al.* (1985) Indices for Ranking the Potential Pesticide Contamination of Groundwater. *Proc. Soil Crop Sci. Soc. Fla.*, **44.**

Schermerhorn, E. J. (1983) Soil Conservation Service. Nodaway Soil Series. Soil Survey of Johnson County, Iowa. U. S. Dep. Agric., Washington, D. C.

Schnoor, J. L., *et al.* (1987) Processes, Coefficients, and Models for Simulating Toxic Organics and Heavy Metals in Surface Waters. Rep. by Dep. Civ. Environ. Eng., Univ. Iowa for U. S. EPA, Office Res. Dev., Athens, Ga.

Scientific Software (1988) The Herbicide Stack, Version 1.01: Demo Disk. St. Louis, Mo.

Starr, R. I., and Johnsen, R. E. (1968) Laboratory Method for Determining the Rate of Volatilization of Insecticides from Plants. *J. Agric. Food Chem.*, **16.**

Taylor, J. R. (1982) An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements. Univ. Science Books, Oxford Univ. Press, Mill Valley, Calif.

Wilson, L. J. (1987) Iowa Groundwater Protection Strategy 1987. Environ. Protection Comm., Iowa Dep. Nat. Resour., Des Moines, Iowa.

This content downloaded from 137.187.180.215 on Wed, 2 Jul 2014 10:52:45 AM
All use subject to JSTOR Terms and Conditions