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Abstract

Herbicide compounds were prevalent in ground water across Iowa, being detected in 70% of the 106 municipal wells sampled during the summer of 1995. Herbicide degradation products were three of the four most frequently detected compounds for this study. The degradation product alachlor ethanesulfonic acid was the most frequently detected compound (65.1%), followed by atrazine (40.6%), and the degradation products deethylatrazine (34.9%), and cyanazine amide (19.8%). The corn herbicide acetochlor, first registered for widespread use in the United States in March 1994, was detected in a single water sample. No reported herbicide compound concentrations for this study exceeded current U.S. Environmental Protection Agency's maximum contaminant levels or health advisory levels for drinking water, although the herbicide degradation products examined have yet to have such levels established.

The occurrence of herbicide compounds had a significant, inverse relation to well depth and a significant, positive relation to dissolved-oxygen concentration. It is felt that both well depth and dissolved oxygen are acting as rough surrogates to ground-water age, with younger ground water being more likely to contain herbicide compounds. The occurrence of herbicide compounds was substantially different among the major aquifer types across Iowa, being detected in 82.5% of the alluvial, 81.8% of the bedrock/karst region, 40.0% of the glacial-drift, and 25.0% of the bedrock/nonkarst region aquifers. The observed distribution was partially attributed to variations in general ground-water age among these aquifer types. A significant, inverse relation was determined between total herbicide compound concentrations in ground water and the average soil slope within a 2-km radius of sampled wells. Steeper soil slopes may increase the likelihood of surface runoff occurring rather than ground-water infiltration—decreasing the transport of herbicide compounds to ground water. As expected, a significant positive relation was determined between intensity of herbicide use and herbicide concentrations in ground water.

Introduction

Iowa has some of the most intensive applications of herbicides in the United States (Figure 1), with these applications being relatively uniform across the State (Figure 2). Awareness has been growing of the possible deleterious effects that herbicides and their degradation products may have on humans and aquatic ecosystems (Bagchi et al., 1995; Bester et al., 1995; Biradar and Rayburn, 1995; Carbonell et al., 1995; Juttner et al., 1995; Sawicki et al., 1995; Tessier and Clark, 1995; Berkowitz et al., 1996; Ribas et al., 1996). Aquatic ecosystems are a concern in areas where contaminated runoff is transported directly to surface water and where contaminated ground water discharges to surface water.

Although several statewide monitoring studies for herbicides in Iowa's ground water have been conducted previously (Detroy et al., 1988; Cherryholmes et al., 1989; Kross et al., 1990), there are important reasons for continuing this research. First, the statewide patterns of chemical use are constantly changing as the popularity of existing herbicides rise and fall and as new compounds are introduced into farming. For example, acetochlor use has increased (from 0 to 2,815,600 kg/year) and alachlor use has decreased (from 5,451,800 to 347,500 kg/year) between 1985 and 1995 (Hartzler and Wintersteen, 1991; U.S. Department of Agriculture, 1995). The previous statewide studies on the occurrence of herbicides in Iowa's ground water were all conducted in the 1980s. Thus, it is important to determine if the temporal changes in chemical use since the previous investigations were conducted have affected the occurrence of herbicides in ground water. Second, recent research has shown that herbicide degradation products are commonly found in ground water (Kolpin et al., 1996; Potter and Carpenter, 1995; Roy and Krapac, 1994). Few herbicide degradation products were examined in the previous statewide investigations.

To determine the occurrence of herbicide compounds (herbicides and herbicide degradation products) in ground water across Iowa, 106 municipal wells, completed in the major aquifer types across the State, were sampled during the summer of 1995. This study is an extension of the Iowa Ground Water Monitoring (IGWM) Program, a joint effort by the University of Iowa Hygienic Laboratory; the Iowa Department of Natural Resources, Geological Survey Bureau; and the U.S. Geological Survey (Detroy, 1985; Detroy et al., 1988) that has been ongoing since 1982. This study provides the most detailed investigation of the occurrence of several herbicide compounds (acetochlor, alachlor ethanesulfonic acid, cyanazine amide, and prometon) that has been conducted in Iowa to date. The purpose of this paper is to describe the results from a study of 106 municipal wells sampled throughout Iowa during the summer of 1995, and to discuss how the occurrence of herbicide compounds is affected by selected hydrogeologic, soil, land use, and chemical use factors.

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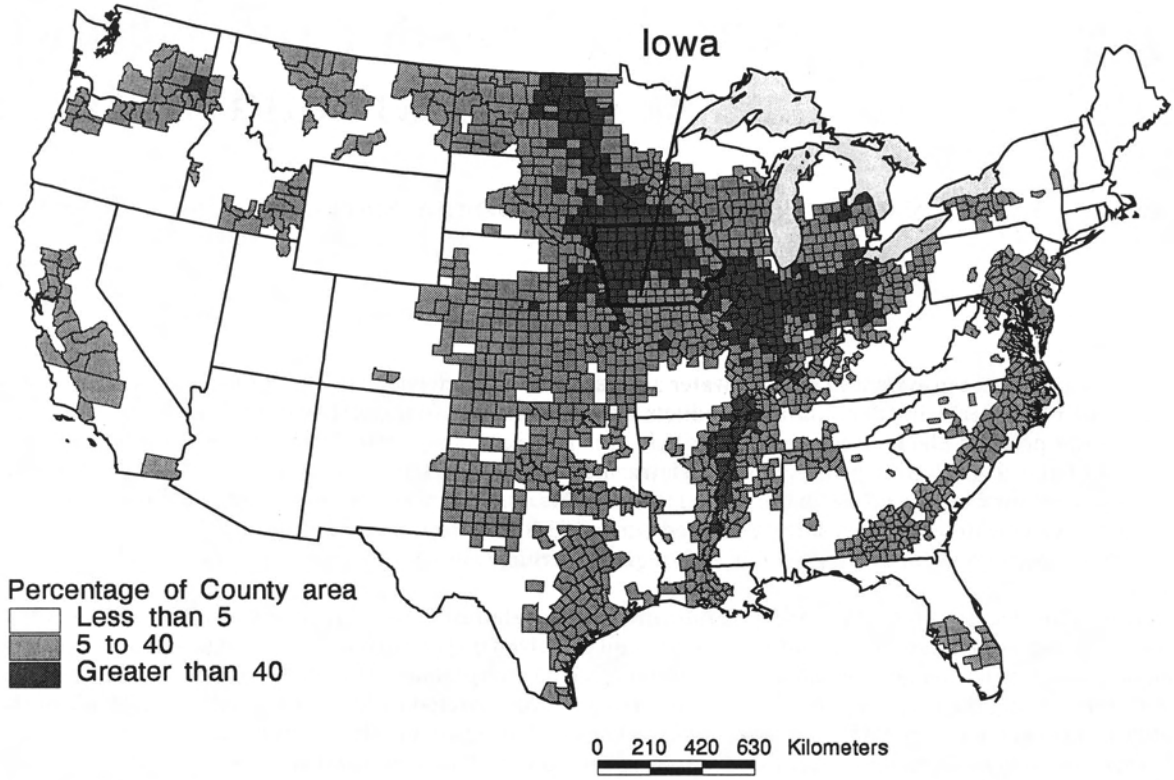

Fig. 1. Percent of county treated with herbicides to control weeds in crops in the contiguous United States during 1992 (U.S. Department of Commerce, 1994).

Methods

The 106 municipal wells (Figure 3) sampled during 1995 were part of the IGWM. These wells were randomly selected within each major aquifer type for the IGWM from a population of over 2000 Iowa municipal wells. The sampling protocol for this study was similar to that used for a previous study of ground water in the midwestern United States (Kolpin and Burkart, 1991). All wells were pumped a minimum of 30 min prior to measurements of dissolved oxygen, pH, specific conductance, and water temperature. Once the values for the above parameters stabilized, the water samples were collected. Water samples were filtered through a 1.0-μm glass-fiber filter into amber baked-glass bottles and immediately chilled. A quality control program (Detroy, 1985) using a series of field blanks, field duplicates, and split samples verified effectiveness of the sampling protocol and the analytical procedures.

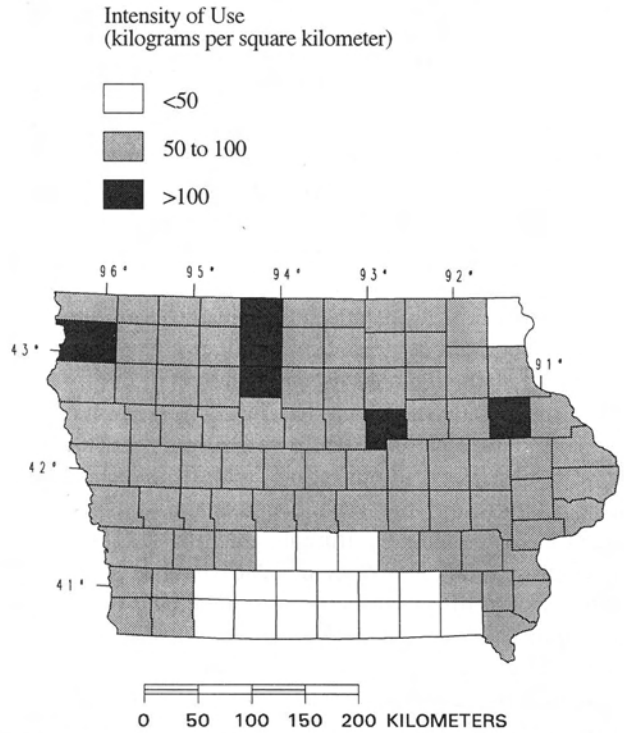

Fig. 2. Intensity of chemical use (kg/km^2) across Iowa, by county, for selected herbicides. Intensity of use was calculated by dividing the summation of county-level use (Gianessi and Anderson, 1996) for five index herbicides (alachlor, atrazine, cyanazine, metolachlor, and metribuzin) by county area.

All water samples were analyzed for 17 herbicide compounds including 13 herbicides, three triazine herbicide degradation products, and one alachlor degradation product (Table 1). The 13 herbicides and three triazine herbicide degradation products were analyzed by gas chromatography/mass spectrometry following solid-phase extraction on C-18 cartridges (Meyer et al., 1993; Thurman et al., 1990; Meyer, 1994). The analytical reporting limit for this method was 0.05 μg/l for all compounds. The alachlor degradation product, alachlor ethanesulfonic acid (alachlor-ESA), was isolated by solid-phase extraction and analyzed by enzyme-linked immunosorbent assay (Aga et al., 1994). The analytical reporting limit for this method was 0.10 μg/l.

A summary of selected ancillary information for the sampled wells is provided in Table 2. Soil information was obtained from 1:250,000 scale digital maps produced by the U.S. Soil Conservation Service (1993). Soil hydrologic group and soil slope were extracted from the dataset and used for this study. Soil hydrologic group is a categorical factor (assigned values from A to D) that incorporates factors such as runoff potential, permeability, depth to water table, depth to an impervious layer, water capacity, and shrink-swell potential (U.S. Soil Conserva-

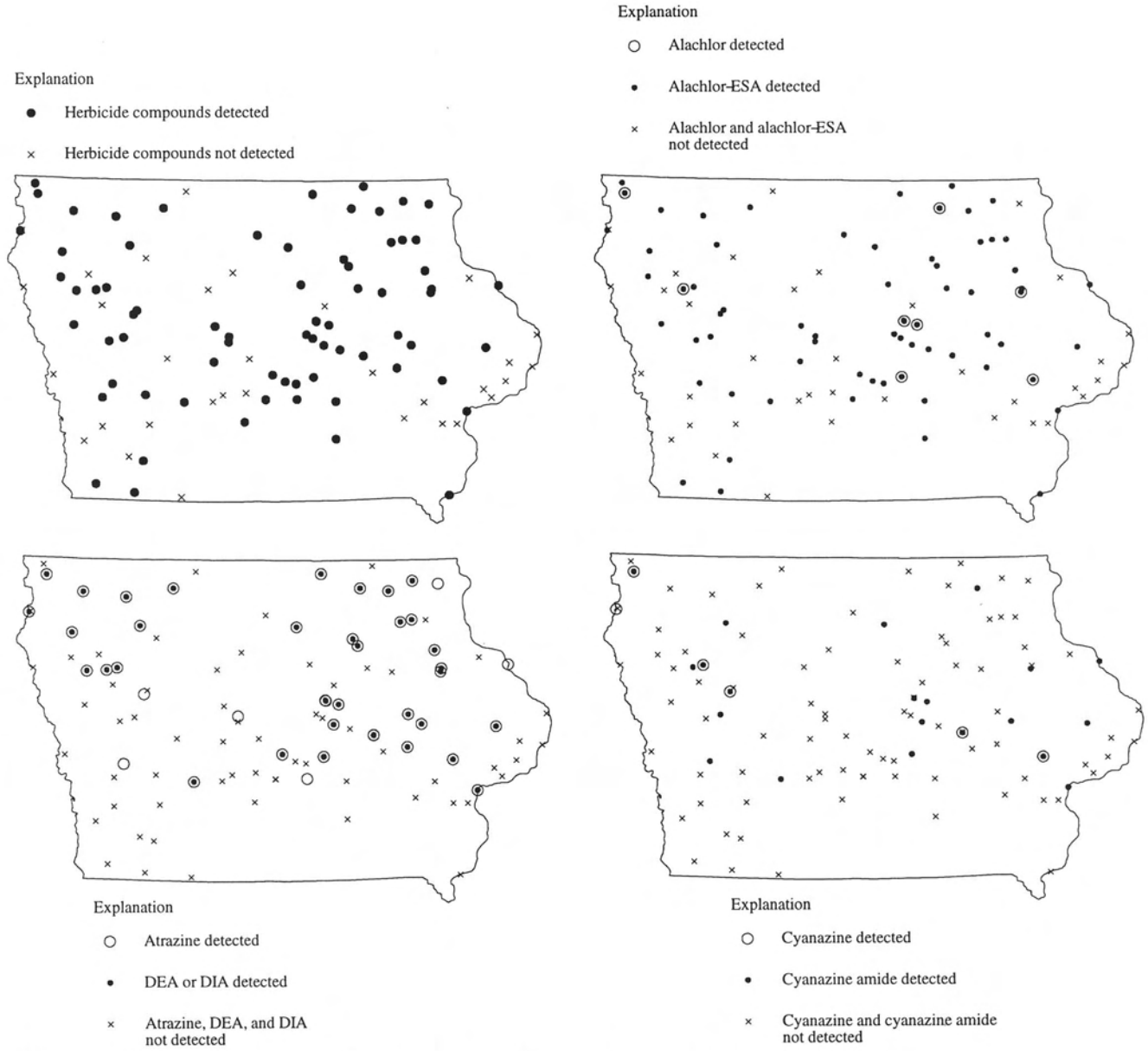

Fig. 3. Selected herbicide-compound results from 106 Iowa municipal wells sampled during the summer of 1995.

tion Service, 1994). To convert to a continuous factor, numerical values were assigned to soil hydrologic group (A = 1, high infiltration rates; B = 2, moderate infiltration rates; C = 3, slow infiltration rates; D = 4, very slow infiltration rates). The two soil factors examined were calculated as an area-weighted mean of the individual soil components in each mapping unit for Iowa (William Battaglin, U.S. Geological Survey, written commun., 1996). To obtain the soil data for areas surrounding the sampled wells, area-weighted means were calculated for a 2-km radius around the well. A 2-km radius was used for consistency with previous work (Harvey et al., 1996).

Land-use data for Iowa were obtained from U.S. Geological Survey's Geographic Information Retrieval and Analyses System; created from aerial photography in the 1970s and mid 1980s (U.S. Geological Survey, 1990) and updated to represent current (1990) land-use patterns using U.S. Bureau of Census census block population data (U.S. Bureau of Census, 1991) and a geographic information systems procedure described by Hitt (1994). Land use was defined into general categories defined by Anderson et al. (1976). These categories include urban, agricultural, forest, water, wetland, and barren land. Land use in a 2-km radius around each well was determined for this study.

Regional agricultural chemical use information is rarely available at other than county-level scale. At present, the most recent regional chemical use data available for this study is county-level information for 1992 (Gianessi and Anderson, 1996). The county-level use data (in kg of active ingredient) was divided by total county area (km^2) to obtain the intensity of use (kg/km^2) for a given herbicide. Chemical use data was only compiled for alachlor, atrazine, cyanazine, and metolachlor (Table 2). These chemicals represent the most frequently detected herbicide parent compounds in Iowa's ground water (Detroy et al., 1988; Cherryholmes, 1989; Kross et al., 1990).

Nonparametric statistical techniques were used for this study. These methods are appropriate because the data did not exhibit normal distributions and because of the presence of censored data (concentrations less than analytical reporting limits). The Kruskal-Wallis test (Helsel and Hirsh, 1992) was used to test for differences in the medians of two or more groups. Because not all relations are linear, the Spearman's rho (Helsel

Table 1. Pesticides and Their Degradation Products in Samples Collected During the Summer of 1995 from 106 Municipal Wells in Iowa

Compound	*Percent detection*	*Reporting limit (μg/l)*	*Maximum concentration (μg/l)*	*Maximum contaminant level*[a] *(μg/l)*	*Health advisory level*[a] *(μg/l)*	*Use or origin*
Alachlor-ESA	65.1	0.10	14.8	—	—	Alachlor degradation product
Atrazine	40.6	0.05	2.13	3.0	3.0	Herbicide
Deethylatrazine	34.9	0.05	0.59	—	—	Triazine degradation product (atrazine, propazine)
Cyanazine amide	19.8	0.05	0.58	—	—	Cyanazine degradation product
Metolachlor	17.0	0.05	11.3	—	70	Herbicide
Prometon	15.1	0.05	1.0	—	100	Herbicide
Deisopropylatrazine	15.1	0.05	0.44	—	—	Triazine degradation product (atrazine, cyanazine, simazine)
Alachlor	7.5	0.05	0.63	2.0	—	Herbicide
Cyanazine	5.7	0.05	0.30	—	1.0	Herbicide
Acetochlor	0.9	0.05	0.77	—	—	Herbicide
Metribuzin	0.9	0.05	0.27	—	100	Herbicide
Ametryn	0.0	0.05	—	—	60	Herbicide
Prometryn	0.0	0.05	—	—	—	Herbicide
Propachlor	0.0	0.05	—	—	90	Herbicide
Propazine	0.0	0.05	—	—	10	Herbicide
Simazine	0.0	0.05	—	4	4	Herbicide
Terbutryn	0.0	0.05	—	—	—	Herbicide

[a] US Environmental Protection Agency (1995).

Table 2. Statistical Summary of Well Construction, Soil, Land Use, Chemical Use, and General Water Quality of Samples from Municipal Well in Iowa During 1995

Constituent	*Mean*	*Median*	*Minimum*	*Maximum*
Well construction				
Well depth (meters below land surface)	47.8	21.3	6.1	501.7
Soil, weighted average, 2-km radius (William A. Battaglin, U.S. Geological Survey, written commun., 1996)				
Area weighted slope (%)	2.4	2.2	0.6	7.9
Soil hydrologic group (see text)	2.5	2.5	2.1	3.5
Land use, as a percent of a 2-km radius (U.S. Geological Survey, 1990)				
Agricultural	77.3	84.7	4.3	100
Urban	14.3	9.8	0.0	76.6
Forest	5.2	0.9	0.0	45.0
Barren	0.4	0.0	0.0	6.0
Wetland	0.7	0.0	0.0	23.5
Water	2.0	0.0	0.0	29.4
County-level chemical use (kg/km^2) (Gianessi and Anderson, 1996)				
Alachlor	3.8	3.9	1.4	5.4
Atrazine	23.6	24.3	11.6	32.6
Cyanazine	18.9	19.3	9.3	25.6
Metolachlor	31.6	32.8	14.8	42.8
General water-quality characteristics				
Water temperature (°C)	11.8	11.5	8.5	21.3
Specific conductance (μS/cm)	717	680	269	1,760
pH (standard units)	7.3	7.3	6.5	7.9
Dissolved oxygen (mg/l)	2.8	2.1	0.1	12.8

and Hirsh, 1992) was used to measure the monotonic relation between two continuous variables. A significance level of 0.05 was used for all statistical tests in this study. This acceptable probability of error ($\alpha = 0.05$) means that there is 1 chance in 20 that the statistical test reported a significant relation when one did not exist. Thus, the smaller the p-value, the greater is the certainty that a reported statistical relation is real.

Results

Herbicide compounds were prevalent in ground water across Iowa (Figure 3), being detected in 70% of the 106 wells sampled. Herbicide degradation products were three of the four most frequently detected herbicide compounds for this study (Table 1). No reported concentrations exceeded current U.S. Environmental Protection Agency's maximum contaminant levels or health advisory levels for drinking water, although the herbicide degradation products examined for this study have not yet had such levels established. This study provided the largest data set on the occurrence of acetochlor, alachlor-ESA, cyanazine amide, and prometon in Iowa's ground water published to date.

More than one herbicide compound was detected in samples from 44 of the 106 wells, with as many as nine compounds being detected in a single sample. The maximum total herbicide compound concentration (sum of all compounds in sample) was 29.0 μg/l. Existing USEPA drinking water standards only take into account the concentrations of single compounds. Research has shown that some combinations of pesticides can have either additive or synergistic toxicity (Marinovich et al., 1996; Thompson, 1996).

The occurrence frequency of herbicide compounds in ground water determined for this study was higher than determined for previous statewide studies (Table 3). To facilitate comparisons between this study and the previous statewide investigations, five index herbicides were used (alachlor, atrazine, cyanazine, metolachlor, and metribuzin). The occurrence frequency for this study was reduced from 70% to 42% when only the index herbicides were used. The occurrence frequency for this study was further reduced to 33.0% if a reporting limit of 0.10 μg/l (the reporting limit generally used in the previous studies) was used for these index herbicides. Thus, much of the increase in chemical occurrence determined for this study was the result of both, data on herbicides and herbicide degradation products that were not analyzed for the previous studies, and the generally lower analytical reporting limits used for this study. Other factors that may have contributed to the higher occurrence frequency for this study over previous statewide studies in Iowa include study design, sampling date, type of well sampled, and number of wells sampled.

Alachlor-ESA was detected almost nine times more frequently than its parent compound, alachlor (Table 1, Figure 3). The large disparities in the frequency of detection between alachlor and alachlor-ESA is similar to that determined by other research of ground water in the midwestern United States (Kolpin et al., 1996; Table 3). Alachlor has been documented to readily degrade in the unsaturated zone (Thurman et al., 1996), with much slower degradation rates occurring under saturated conditions (Potter and Carpenter, 1995; Clay et al., 1995). The water solubility of alachlor-ESA is substantially greater than its parent compound alachlor (Thurman et al., 1996). The greater solubility and apparent stability may contribute to the increased transport to ground water of alachlor-ESA as compared to alachlor.

The similarity of the spatial distributions between atrazine and its degradation products (Figure 3), unlike those of alachlor and its degradation product, is likely related to a slower degradation rate for atrazine (Agertved et al., 1992; McMahon et al., 1992; Klint et al., 1993; Nair and Schnoor, 1992; Widmer and Spalding, 1995), allowing more of the parent compound to be transported to ground water. The relative frequencies of detection between atrazine, deethylatrazine (DEA), and deisopropylatrazine (DIA) determined for this study (Table 1) are similar to previous work (Jayachandran et al., 1994; Kolpin et al., 1996; Kruger et al., 1996).

Cyanazine amide was detected more than three times as frequently as cyanazine (Table 1, Figure 3). The presence of cyanazine amide in ground water is in agreement with the reported greater stability of cyanazine amide after transforma-

Table 3. Results of State-Wide Ground-Water Monitoring Studies for Herbicide Compounds in Iowa[a]

Herbicide compound	*This study (1995)*			*SWIRL[b] (1988-89)*			*IGWM[c] (1982-87)*			*OTT[d] (1986)*			*MHS[e] (1991-94)*		
	%	RL	N	%	RL	N	%	RL	N	%	RL	N	%	RL	N
Acetochlor	0.9	.05	106	—	—	—	—	—	—	—	—	—	0.0	.05	6
Alachlor	7.5	.05	106	1.2	.02	686	4.0	.10	355	2.7	.20	856	7.5	.05	40
Alachlor-ESA	65	.10	106	—	—	—	—	—	—	—	—	—	48	.10	25
Atrazine	41	.05	106	4.4	.13	686	18	.10	355	12	.20	856	28	.05	40
DEA	35	.05	106	3.5	.10	686	—	—	—	—	—	—	32	.05	40
DIA	15	.05	106	3.4	.10	686	—	—	—	—	—	—	18	.05	40
Cyanazine	5.7	.05	106	1.2	.12	686	3.0	.10	355	6.3	.20	856	7.5	.05	40
Cyanazine amide	20	.05	106	—	—	—	—	—	—	—	—	—	20	.05	16
Metolachlor	17	.05	106	1.5	.04	686	5.0	.10	355	2.7	.20	856	20	.05	40
Metribuzin	0.9	.05	106	1.9	.01	686	2.0	.10	355	0.6	.20	856	2.5	.05	40
Prometon	15	.05	106	—	—	—	—	—	—	—	—	—	12	.05	40
Any compound	70		106	14		686	20		355	15		856	45		40

[a]%, percent of wells with detectable concentrations; RL, analytical reporting limit in μg/l; N, number of wells; —data not collected; Alachlor-ESA, Alachlor ethanesulfonic acid; DEA, Deethylatrazine; DIA, Deisopropylatrazine.
[b]SWRL (Iowa State-Wide Rural Well-Water Survey): Kross et al., 1990.
[c]IGWM (Iowa Ground-Water Monitoring Program): Detroy et al., 1988.
[d]OTT (Iowa One Time Testing Program), includes 41 surface-water samples: Cherryholmes et al., 1989.
[e]MHS (Midwest Herbicide Study): Kolpin et al., 1993; Kolpin, Zichelle et al., 1996.

tion from cyanazine (Kolpin et al., 1996; Muir and Baker, 1976). Cyanazine may also degrade to a common atrazine degradation product, DIA, by the loss of a cyanoisopropyl group (Meyer, 1994; Thurman et al., 1994). Although atrazine was always present when DIA was detected, cyanazine or cyanazine amide was detected coincidentally with 69% (11 of 16) of the DIA detections. This suggests that some portion of the reported DIA concentrations could potentially have originated from cyanazine.

The occurrence of metolachlor for this study was substantially higher than the studies conducted during the 1980s, but similar to the study conducted during the 1990s (Table 3). A possible explanation for this increase in metolachlor occurrence is the increase in statewide use of metolachlor that has occurred over the last decade. The statewide use of metolachlor has increased from sixth among all herbicides in 1979; to second in 1985; to first in 1990, 1993, and 1995 (George R. Hallberg, University of Iowa Hygienic Laboratory, written commun., 1996).

The occurrence of prometon in this study was similar to the only other previous statewide investigation for which this compound was examined (Table 3). Prometon is unique among the herbicide compounds examined for this study in that it is used strictly for nonagricultural purposes such as along highways, domestic and commercial applications on driveways, and as an asphalt additive.

The corn herbicide acetochlor, first registered for widespread use in the United States in March 1994 (U.S. Environmental Protection Agency, 1994), was detected in a single water sample (Table 1). This water sample was obtained from an alluvial well having a well depth of 14.6 m below land surface. A U.S. Geological Survey study conducted during 1994 (the first year of widespread acetochlor use in the United States) did not detect acetochlor in ground-water samples collected across eight midwestern states (Kolpin et al., 1996, Table 3).

The occurrence of metribuzin for this study was similar to the previous statewide investigations (Table 3), being detected infrequently. Historically, metribuzin has not been intensively used across Iowa. Metribuzin was ranked seventh in statewide mass of active ingredient applied during 1985, with an estimated 799,700 kg applied (Hartzler and Wintersteen, 1991). Since 1985, the statewide application of metribuzin has progressively decreased to an estimated 10,000 kg/year during 1995 (George R. Hallberg, University of Iowa Hygienic Laboratory, written commun., 1996).

Discussion

The occurrence of herbicide compounds was significantly ($p = 0.002$; Kruskal Wallis test) related to well depth (Figure 4). Well depth provides a rough surrogate for ground-water age (shallow wells generally representing younger ground water). General ground-water age data based on tritium concentrations from a separate study of near-surface aquifers of the midwestern United States (Kolpin et al., 1995), found major differences in the median well depths between pre-1953 (16.2 m) and post-1953 (56.2 m) water (Dana W. Kolpin, U.S. Geological Survey, unpublished data, 1996). Thus, the decreasing occurrence of herbicide compounds with increasing well depth reflects the amount of time for processes such as chemical degradation, dispersion, adsorption, and transport to take place. A significant relation to well depth also was found for the compound alachlor-ESA ($p = 0.003$; Kruskal-Wallis test).

The occurrence of herbicide compounds was significantly ($p = 0.004$, Kruskal-Wallis test) related to the dissolved-oxygen concentration. The occurrence of herbicide compounds was 50.0% in the 28 samples from reducing conditions (dissolved-oxygen concentrations ≤ 0.50 mg/l) compared to 79.2% in the 72 samples from oxidizing conditions (dissolved-oxygen concentrations > 0.50 mg/l). Dissolved oxygen could not be measured in six of the wells sampled. Because some herbicides, such as atrazine, have faster rates of degradation under oxidizing versus reducing conditions (Agertved et al., 1992; Klint et al., 1993; Nair and Schnoor, 1992), this significant, positive relation to dissolved oxygen may initially appear opposite of expected results. However, oxygen tends to be consumed through biotic and abiotic processes as water travels from zones of recharge to greater depths. Thus, dissolved-oxygen concentrations in ground water may provide another rough surrogate for ground-water age (similar to well depth). General ground-water age data based on tritium concentrations from a separate study of near-surface aquifers of the midwestern United States (Kolpin et al., 1995), found major differences in the median dissolved-oxygen concentrations between pre-1953 (0.14 mg/l) and post-1953 (1.46 mg/l) water (Dana W. Kolpin, U.S. Geological Survey, unpublished data, 1996). Thus, the decreased occurrence of herbicide compounds in water from reducing conditions may reflect the amount of time for processes such as chemical degradation, dispersion, adsorption, and transport to take place. A significant relation between the frequency of occurrence and dissolved-oxygen concentration also was found for the compounds atrazine ($p = 0.002$), DEA ($p = 0.001$), DIA ($p = 0.040$), alachlor-ESA ($p = 0.039$), and prometon ($p = 0.008$) using a Kruskal-Wallis test.

The occurrence of herbicide compounds was substantially different among the major aquifer types across Iowa (Figure 5), being detected in 82.5% of the alluvial, 81.8% of the bedrock/karst region, 40.0% of the glacial-drift, and 25.0% of the bedrock/nonkarst region aquifers. The general spatial distribution of these aquifer types across Iowa is shown in Figure 6. The hydrogeological differences among these aquifer types suggests that variations in ground-water age could be an important factor in explaining the results for this study. Using well depth and dissolved-oxygen concentrations as rough indicators of ground-

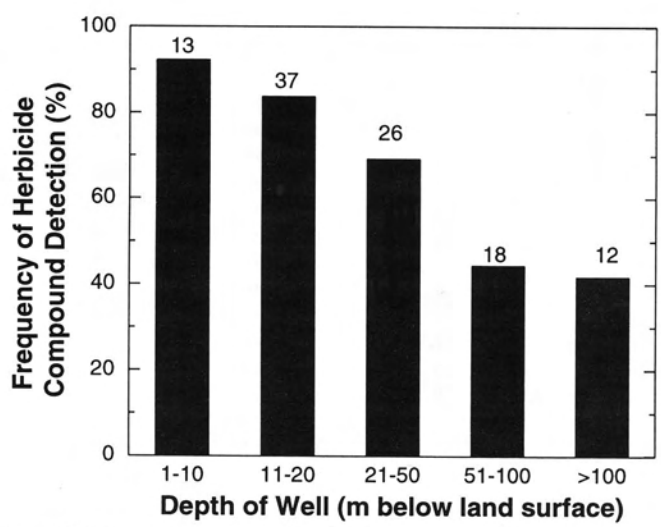

Fig. 4. Relation of frequency of herbicide compound detection to well depth. Total number of wells in category is shown above bar.

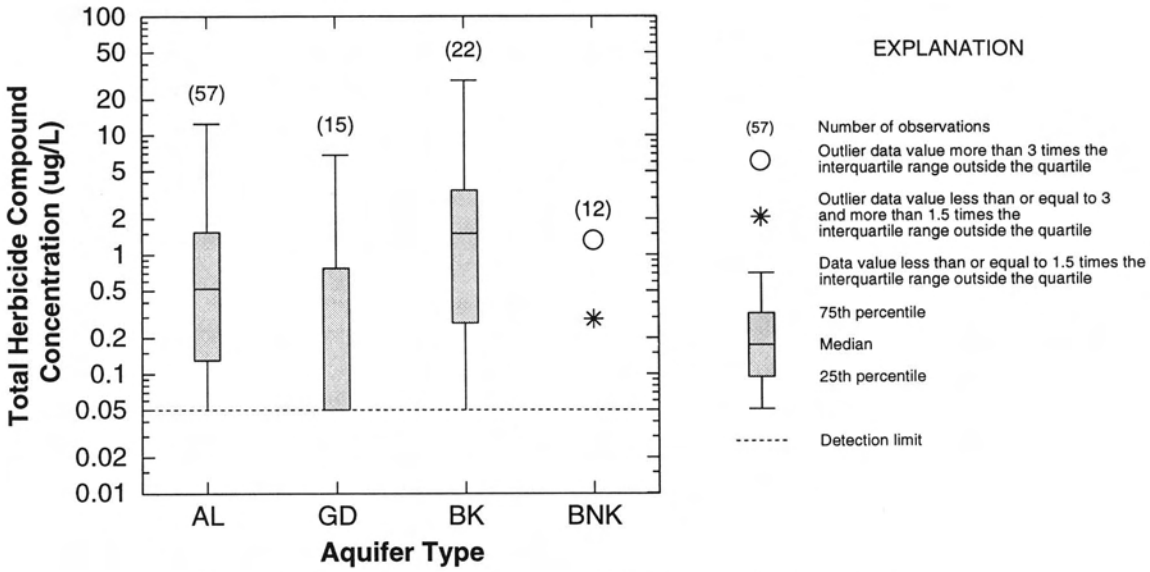

Fig. 5. Total herbicide compound concentration by aquifer type for the 106 Iowa municipal wells sampled during the summer of 1995 (AL = alluvial, GD = glacial-drift, BK = bedrock/karst region, and BNK = bedrock/nonkarst region).

water age (as discussed above) generally supports our hypothesis. The aquifer types having the greatest occurrence of herbicide compounds (alluvial and bedrock/karst region) also were those where median dissolved-oxygen concentrations exceeded 1 mg/l (Figure 7). However, well depth was less reliable in describing the results of this study. For example, the wells sampled in bedrock/karst region aquifers had a deep median well depth, but also had herbicide compounds frequently detected (Figure 7). This shows the importance of examining as many surrogates to ground-water age as possible in the absence of actual ground-water age measurements. A significant difference in the frequency of occurrence among the aquifer types was found for the individual herbicide compounds alachlor-ESA ($p < 0.001$), atrazine ($p = 0.002$), DEA ($p = 0.001$), and DIA ($p = 0.023$) using a Kruskal-Wallis test.

Variations in soil characteristics for areas surrounding sampled wells also may affect the occurrence of chemicals in ground water (Mueller et al., 1995; Ng et al., 1995). No significant relation was determined between the occurrence of herbicide compounds and the soil hydrologic group. The poor relation between hydrologic group and the occurrence of a herbicide compound may be due to the relative uniformity (narrow numerical range) of hydrologic group for this study (Table 2).

No significant relation was determined between the occurrence of herbicide compounds and average soil slope. Although significant relations to average soil slope were found for the individual compounds alachlor-ESA ($p = 0.010$) and DEA ($p = 0.036$) using a Kruskal-Wallis test. However, a significant, inverse relation ($p = 0.004$; Spearman's rho) was determined for

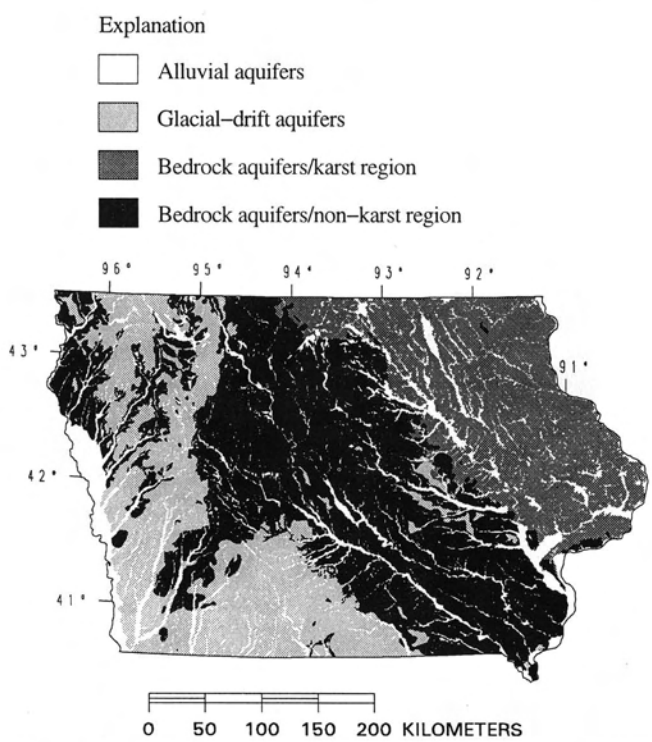

Fig. 6. Location of the major aquifer types in Iowa (Hoyer and Hallberg, 1991).

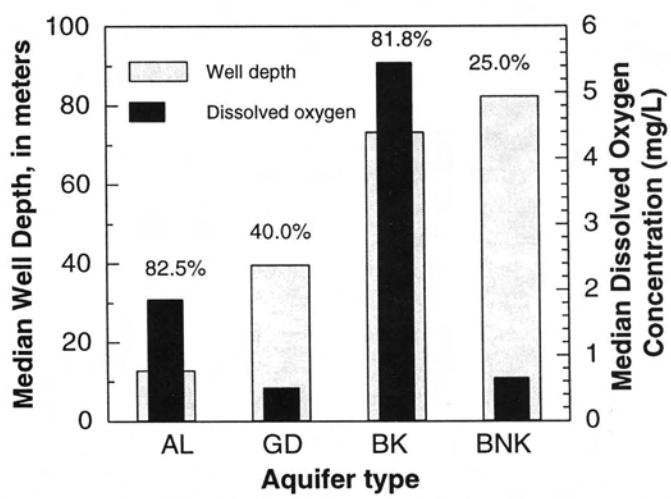

Fig. 7. Median well depth and dissolved-oxygen concentration for sampled wells from the major aquifer types in Iowa (AL = alluvial, GD = glacial-drift, BK = bedrock/karst region, and BNK = bedrock/nonkarst region). Frequency of herbicide compound detection is shown above bar.

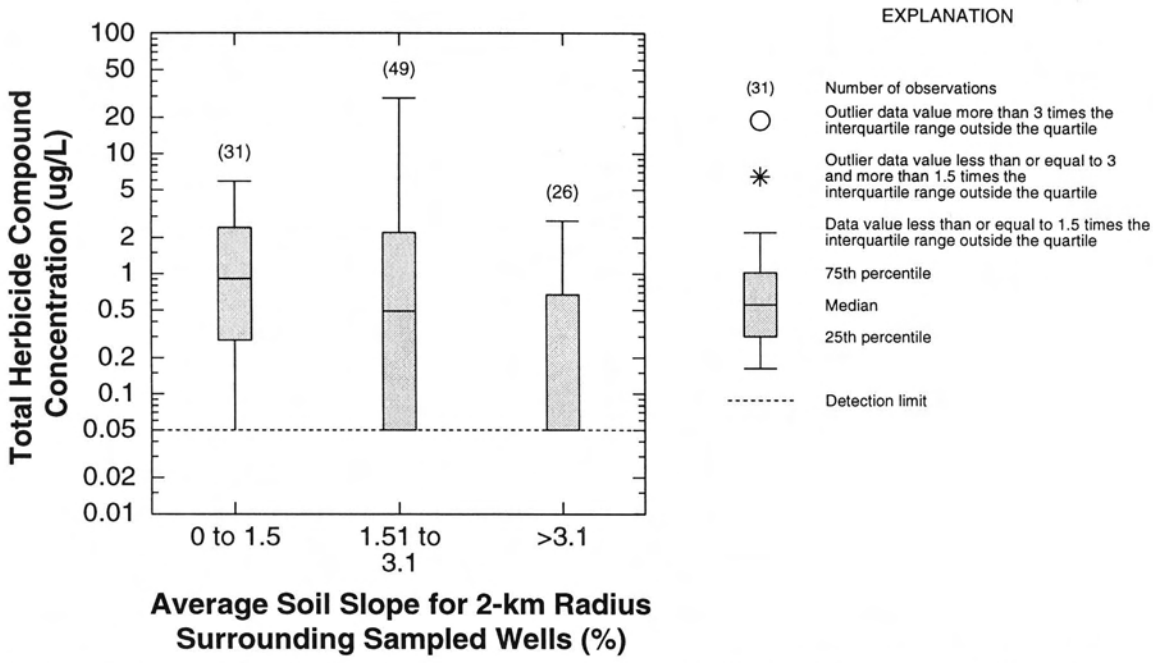

Fig. 8. Total herbicide compound concentration by average soil slope class for the 106 Iowa municipal wells sampled during the summer of 1995.

total herbicide compound concentration and average soil slope (Figure 8). In general, as the average soil slope increases around a well, the less herbicide compounds were transported to ground water. The distribution of soil slopes across Iowa is shown in Figure 9. A decrease in soil slope increases the likelihood of ground-water infiltration, and hence, increases the likelihood of transport of herbicide compounds to ground water. An increase in herbicide transport to ground water by increased recharge has been documented in the literature (Isensee et al., 1990; Gish et al., 1991).

No significant relations were determined between land use (Table 2) and total herbicide compound concentration using a Spearman's rho. However, a significant, positive relation ($p = 0.021$; Spearman's rho) was found between the amount of surface water within a 2-km radius and alachlor-ESA concentration. Because herbicides are not generally applied to surface water, this relation is opposite to the expected result. More research is required to understand this relation between surface water and alachlor-ESA concentration. The general uniformity of land use within a 2-km radius (Table 2), the generalized nature of the available data, and the simple placement of a circular buffer around a well all may have contributed to the general lack of significant relations between land use and concentrations of herbicide compounds in ground water found for this study.

Variations in chemical use for areas surrounding sampled wells also could affect the occurrence of herbicide compounds in ground water (Barbash and Resek, 1996). Significant, positive relations between intensity of use and chemical concentrations in ground water were determined for atrazine ($p = 0.008$), cyanazine amide ($p = 0.039$), cyanazine ($p = 0.012$), DEA ($p = 0.017$), and metolachlor ($p = 0.004$) using a Spearman's rho test. These results suggest that the county-level chemical use data may provide a relative indication of the amount being applied near a sampled well for most of the chemicals examined. Thus, in general, increased use of a herbicide near a sampled well increases the likelihood of transport of that herbicide (or its degradation products) to ground water.

Conclusions

During the summer of 1995, a statewide study investigating the occurrence of herbicide compounds in Iowa's ground water was conducted. This study is an important extension of previous statewide studies because of the changes in chemical use that has occurred since the previous studies, and the addition of herbicides and herbicide degradation products not previously examined by these studies (acetochlor, alachlor ethanesulfonic acid, cyanazine amide, and prometon). Herbicide compounds in ground water were detected in 70% of the 106 Iowa municipal

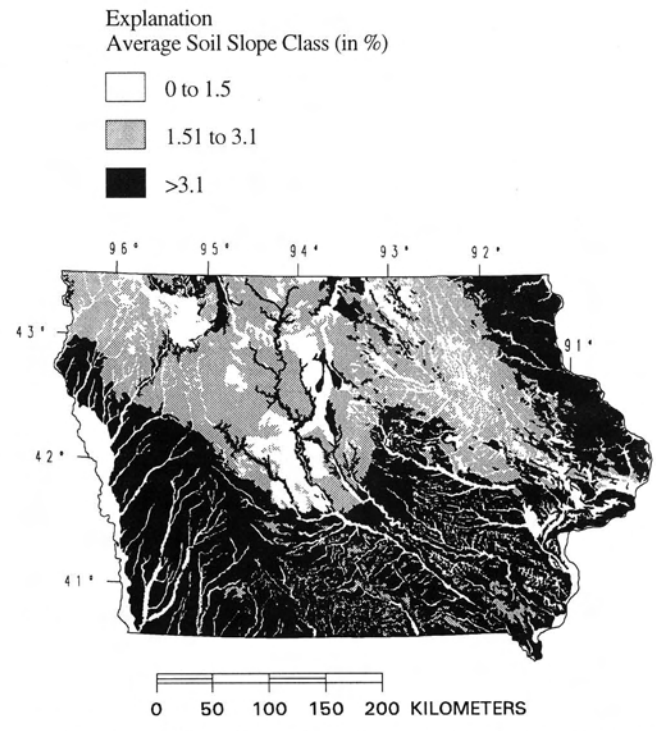

Fig. 9. Average soil slope for major soil associations in Iowa (U.S. Soil Conservation Service, 1993).

wells sampled for this study. The occurrence of herbicide compounds was found to be much more prevalent in this study than determined during previous statewide ground-water investigations. Much of this increase in chemical occurrence was the result of data on herbicides and herbicide degradation products that were not analyzed during previous studies and also the generally lower analytical reporting limits used for this study.

The most frequently detected herbicide compounds for this study were the degradation product alachlor ethanesulfonic acid (65.1%), atrazine (40.6%), and the degradation products deethylatrazine (34.9%), and cyanazine amide (19.8%). No reported herbicide compound concentrations for this study exceeded current U.S. Environmental Protection Agency's maximum contaminant levels or health advisory levels for drinking water, although the herbicide degradation products examined have yet to have such levels established.

The occurrence of herbicide compounds had a significant, inverse relation to well depth and a significant, positive relation to dissolved-oxygen concentration. It is felt that both well depth and dissolved oxygen are acting as rough surrogates to ground-water age, with younger ground water being more likely to contain herbicide compounds as the result of less time for processes such as chemical degradation, dispersion, and adsorption to take place. The occurrence of herbicide compounds was substantially different among the major aquifer types across Iowa, being detected in 82.5% of the alluvial, 81.8% of the bedrock/karst region, 40.0% of the glacial-drift, and 25.0% of the bedrock/nonkarst region aquifers. The observed distribution was partially attributed to variations in general ground-water age among these aquifer types.

A significant, inverse relation was determined between total herbicide compound concentrations in ground water and the average soil slope within a 2-km radius of sampled wells. Steeper soil slopes may increase the likelihood of surface runoff occurring rather than ground-water infiltration—decreasing the transport of herbicide compounds to ground water. As expected, a significant positive relation was determined between intensity of herbicide use and herbicide concentrations in ground water. Thus, the increased use of a herbicide near sampled wells generally increases the likelihood of transport of that herbicide (or its associated degradation products) to ground water.

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