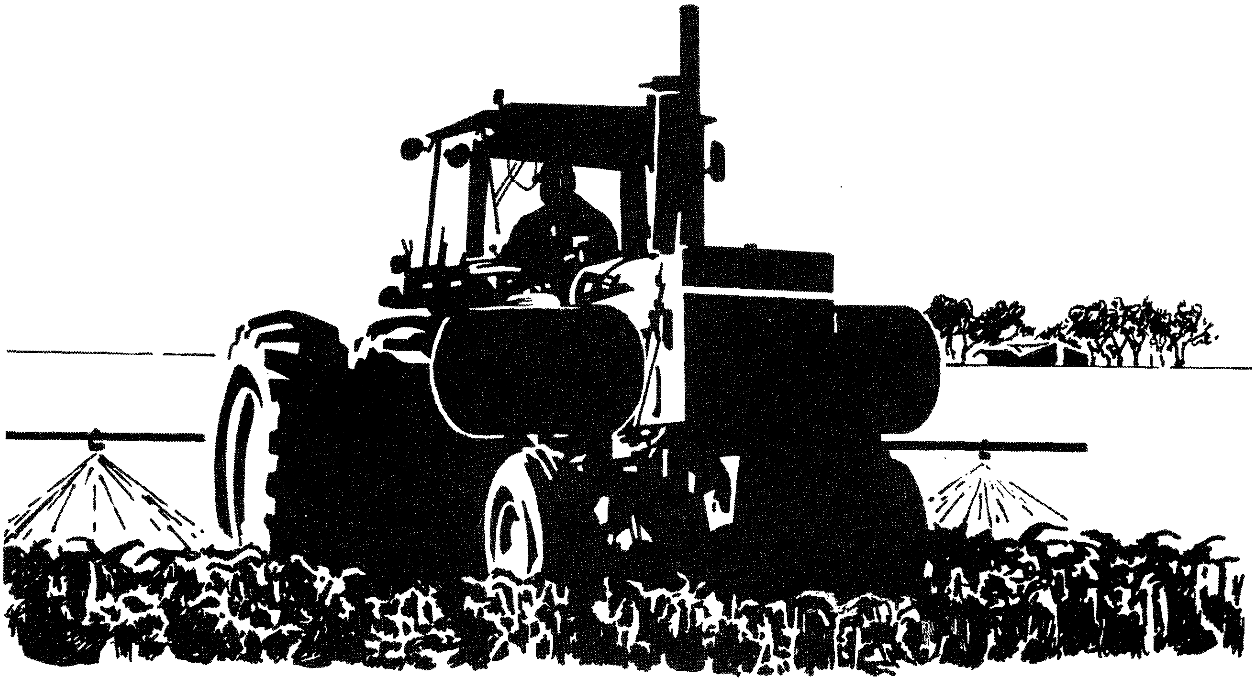
ISGS/ISWS COOPERATIVE GROUNDWATER REPORT 12



AN INITIAL EVALUATION OF THE IMPACT OF PESTICIDES ON GROUNDWATER IN ILLINOIS

Report to the Illinois Legislature

DEPARTMENT OF ENERGY AND NATURAL RESOURCES
Illinois State Geological Survey
Illinois State Water Survey

January 1990

AN INITIAL EVALUATION OF THE IMPACT OF PESTICIDES ON GROUNDWATER IN ILLINOIS

REPORT TO THE ILLINOIS LEGISLATURE

I. EVALUATION OF THE POTENTIAL EFFECTS OF AGRICULTURAL CHEMICALS ON GROUNDWATER QUALITY

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IMPACT OF PESTICIDES ON GROUNDWATER IN ILLINOIS
SUMMARY AND RECOMMENDATIONS

Dennis P. McKenna, Illinois State Geological Survey

At present, data are insufficient to accurately determine what impact pesticides have had on groundwater quality in Illinois. Groundwater sampling in Illinois and other midwestern states indicates, however, that shallow aquifers—current or potential sources of drinking water—are vulnerable to contamination.

In approximately 40 percent of rural Illinois, aquifers lie within 50 feet of ground surface. These shallow aquifers occur throughout Illinois but are most common in the northern and southern parts of the state and along the major river valleys. In about 60 percent of rural Illinois, the aquifers are more than 50 feet deep and apparently protected from pesticide contamination by the attenuation capacity of soils and thick sequences of fine-grained materials. Pesticide use, largely for corn and soybean production, is heaviest in areas of the state where aquifers are generally least vulnerable to contamination.

The agricultural practices most likely to impact groundwater quality are pesticide selection and application rate, nitrogen fertilizer application rate, and crop rotation. Use of less persistent and less mobile compounds can reduce the potential for groundwater contamination. Pesticide and nitrogen fertilizer application rates directly influence the amount available for leaching. Crop rotations usually reduce the need for application of nitrogen fertilizer and insecticides and may reduce the need for herbicides.

Mandate for Action

In this report, the Illinois State Geological Survey (ISGS) and the Illinois State Water Survey (ISWS) have responded to the mandate of the Illinois Groundwater Protection Act that the Illinois Department of Energy and Natural Resources (IDENR) evaluate the impact of pesticides upon groundwater. This preliminary evaluation summarizes data on the extent of groundwater contamination by pesticides, identifies agricultural practices that may contribute to groundwater contamination, and presents recommendations to minimize contamination.

The reasons for concern over the potential for agricultural chemical contamination of groundwater in Illinois include the following:

- Two out of three acres of rural Illinois are treated with pesticides. Each year Illinois farmers apply approximately 50 million pounds of pesticides (Pike et al. 1989) and approximately 1 million tons of nitrogen fertilizer (IDOA 1987).
- In 1988, more than 80 percent of corn acreage and 21 percent of soybean acreage receiving preplant or preemergent weed control was treated with herbicides that pose a potential hazard to groundwater in vulnerable soil and hydrogeologic settings.
- Groundwater is the only source of drinking water for about 97 percent of the rural population in Illinois (Withers et al. 1981).
- Aquifers occur within 50 feet of the surface in about 40 percent of rural Illinois.
- Groundwater sampling by state and county agencies has detected pesticides in shallow aquifers in rural Illinois. Public water supply wells, which generally withdraw water from deep aquifers, have apparently not been significantly impacted.

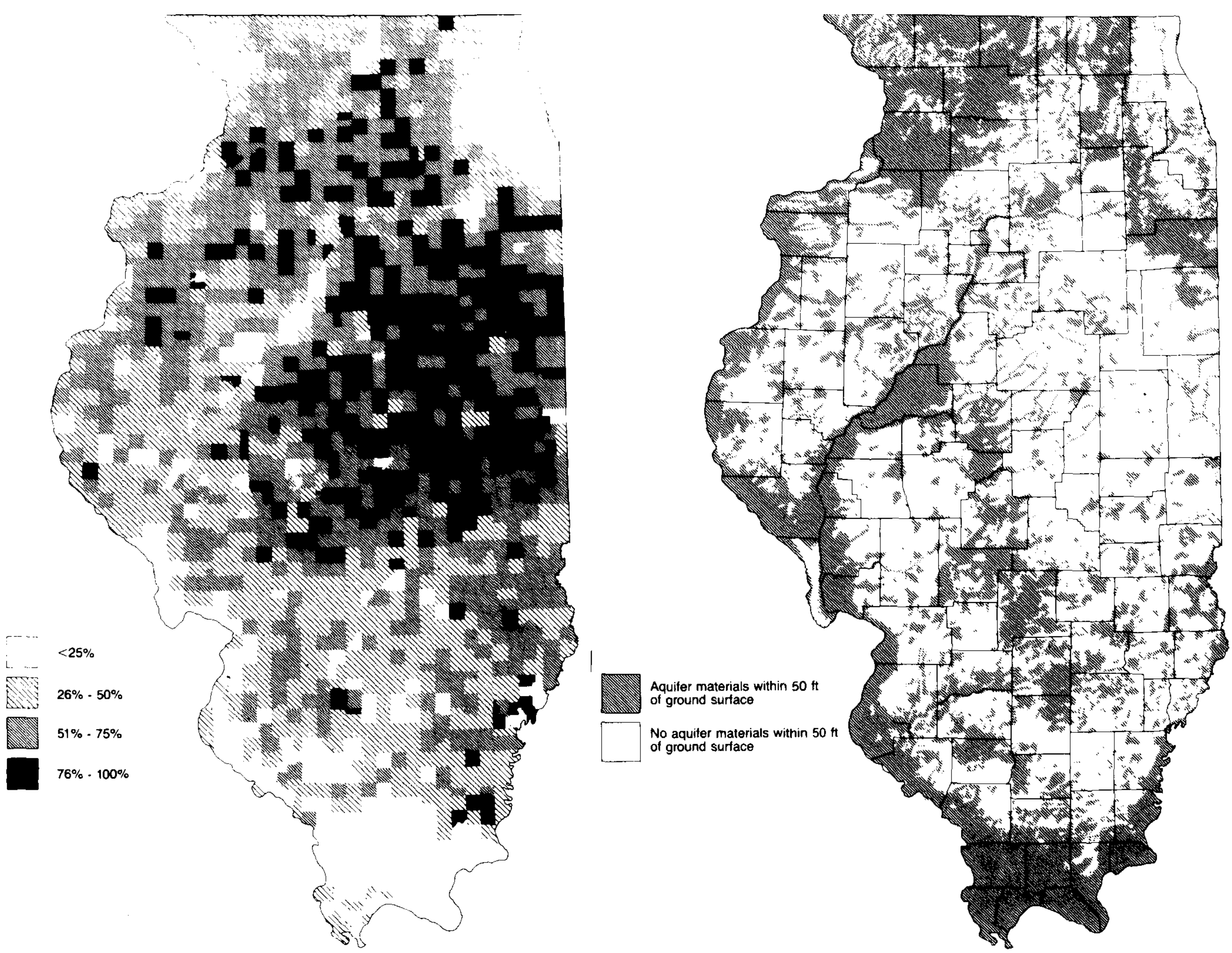
Pesticide contamination of groundwater has been found in neighboring states—particularly Iowa and Minnesota (Kelley 1987, Klaseus et al. 1988). Sampling programs across the country have detected agricultural chemicals in groundwater. The toxicity of many of these chemicals, even at low concentrations, and their widespread ocurrence in drinking water have caused concern over the potential for adverse effects on human health.

To date, federal and state standards for drinking water have only been established for nitrates (10 parts per million NO_3-N) and 12 pesticides (0.1 to 100 parts per billion). Recently, the USEPA released health guidance advisories for another 50 pesticides. Although these standards or advisories provide some reference points against which to evaluate the results of groundwater quality monitoring, how combinations of pesticides or pesticides/nitrates affect the health of humans is largely unknown. How many people are exposed to agricultural chemicals by drinking groundwater is also largely unknown.

POTENTIAL FOR CONTAMINATION OF ILLINOIS GROUNDWATER BY AGRICULTURAL CHEMICALS

Agricultural Chemical Use

Farmland makes up 28 million of the 38 million acres of land in Illinois (IDOA 1987). Distribution of cropland varies across the state: less than 20 percent of Pope and Hardin Counties is cropland compared to nearly 95 percent of Piatt County. In more than 80 percent of the townships in Illinois, more than 50 percent of the total land area is devoted to corn and soybeans (figure below). On average, two of every three acres of land in rural areas of the state are treated with pesticides.



Left Illinois townships: percentage of total land area planted to corn and soybeans (IDOA 1979). *Right* Aquifer materials within 50 feet of ground surface (based on mapping by Berg and Kempton 1988).

In 1988, an estimated 46.9 million pounds of herbicides and 3.7 million pounds of insecticides were applied to the 19.1 million acres of corn and soybeans in Illinois (Pike et al. 1989). Herbicides were applied to 97 percent of the corn and 96 percent of the soybean acreage. Only a small percentage of other cropland or pasture acres received pesticide applications. Consequently, where corn and soybeans are planted is a good predictor of where pesticides are used most intensively.

Aquifer Vulnerability

With current agricultural practices and technology, the leaching of agricultural chemicals, particularly nitrates derived from nitrogen fertilizer, into groundwater (the saturated zone) may be impossible to prevent: more than one-third of the soils in the state have water tables within 5 feet of the surface during the spring and fall (Drablos and Moe 1984). Through most of Illinois, groundwater can occur within 5 to 20 feet of ground surface. However, in about 60 percent of the state, groundwater resources—the aquifers—are more than 50 feet deep and probably not vulnerable to contamination from pesticides (figure, p. 2). Whether deep aquifers are vulnerable to contamination from nitrates is less clear.

The source of groundwater in Illinois is precipitation that infiltrates the soil and percolates downward to the groundwater system. About 10 percent of the precipitation enters the zone of saturation where groundwater is stored in openings ranging from tiny pores between particles of silt and clay, to larger pores in sand and gravel, to large crevices in bedrock. The replenishment of an aquifer, recharge, does not come from a point source or even from small local areas. Some recharge occurs in all unpaved areas except in discharge areas; streams that flow perennially or for most of the year are groundwater discharge areas.

Groundwater can be reached in any of the surficial materials found in Illinois. If these materials transmit water at low rates, it may not be readily available to a well. A large excavation, such as a large-diameter dug well, will fill with water—very slowly—even in materials such as clay. In an aquifer, the interconnected pores, crevices, or fractures are large enough to transmit water readily to a well. In this report, the term aquifer refers to earth materials capable of yielding enough water from a single well to supply at least several residences.

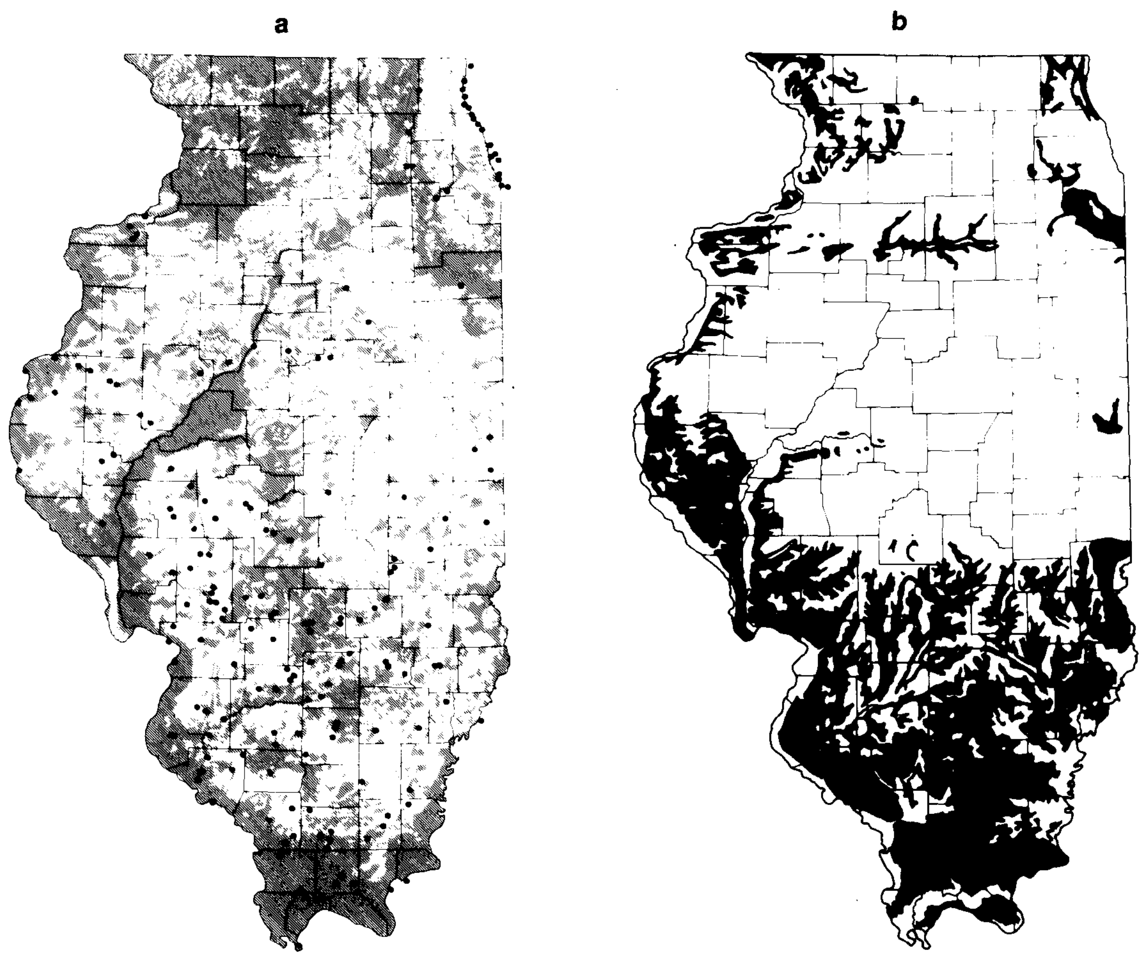
Where aquifers are deeply buried, agricultural chemicals may be found in shallow groundwater, such as the water flowing from drainage tile, while the source of well water, the aquifer, remains unaffected. Making this distinction between groundwater that occurs in fine-grained materials and groundwater in an aquifer is important when establishing compliance points for regulatory monitoring.

Surface Water Vulnerability

For most of Illinois, surface water resources are more likely than groundwater resources to be affected by agricultural chemicals. Although groundwater is the main source of water for most rural residents, surface water is used for drinking by many communities, especially in southern and western Illinois (figure a, p. 4). Thus programs to protect the state's groundwater resources from contamination by agricultural chemicals should also consider the potential effects of agricultural practices on surface water resources.

Contamination of streams by agricultural chemicals has been documented by the Illinois Environmental Protection Agency (Taylor 1989). While shallow groundwater as base flow or discharge from tile drainage probably is the source of some pesticides in streams, the primary source is surface water runoff from cropland. Many erosion control practices significantly reduce runoff, which may increase infiltration and thus increase leaching of agricultural chemicals.

The relative vulnerability of surface water and groundwater to contamination by agricultural chemicals varies across the state. In most of east-central Illinois, erosion control practices should not affect the quality of deep aquifers. In areas of the state where sandy soils overlie shallow aquifers vulnerable to contamination (for example, parts of Mason, Kankakee, and Whiteside Counties), conservation practices to control runoff and erosion are usually unnecessary. In parts of southern, western, and northwestern Illinois, runoff and soil erosion rates are high and aquifers are very vulnerable to contamination (figures a and b, below). Practices to control erosion in these areas may increase infiltration, and thus increase movement of agricultural chemicals to the aquifers.



(a) Aquifers within 50 feet of ground surface (based on mapping by Berg and Kempton 1988); surface water withdrawal points for public water supply systems (ISWS, PICS database); and (b) estimated average annual soil erosion losses for soil associations in Illinois (modified from Soil Conservation Service 1984).

Environmental Fate of Agricultural Chemicals

The processes affecting movement of pesticides into groundwater include plant uptake, volatilization to the atmosphere, chemical or microbial degradation, adsorption by the soil, and transport by water. The amount of a chemical that is stored, transformed, or transported will be controlled by (1) the amount and properties (such as solubility and persistence) of the chemical, (2) soil properties, (3) timing and intensity of precipitation, and (4) hydrogeologic conditions.

The soil properties that most directly affect leaching of pesticides are organic carbon content, which largely determines the adsorption of pesticides, and hydraulic conductivity, the relative ease with which water moves through geologic materials. For example, pesticides are more likely to leach in sandy soils with high hydraulic conductivities and low organic carbon content than in fine-grained soils with low hydraulic conductivities and high organic carbon content. Nitrate is highly water soluble and does not adsorb onto organic matter or clays. Under certain conditions, however, nitrate may undergo denitrification and subsequent volatilization to the atmosphere. The rate of nitrate movement is controlled by the rate at which water moves through the soil. Consequently, leaching of nitrates is also most likely to occur in sandy soils due to their high hydraulic conductivities.

The thickness and character of the geologic materials between the base of the soil and the top of the underlying aquifer greatly affect the potential for contamination of the underlying aquifer. Where aquifers are deeply buried, as in Champaign County, they generally are overlain by deposits of fine-grained materials that are low in permeability. These materials, such as clay and shale tend to restrict contaminant migration; whereas highly permeable materials such as sand, gravel, and fractured bedrock tend to allow rapid migration of contaminants. The thickness of fine-grained materials controls the vulnerability of underlying aquifers to contamination. As the thickness of these fine-grained materials increases, the potential for contamination of an underlying aquifer decreases.

An intensively cultivated area with an aquifer within 50 feet of ground surface is the hydrogeologic setting most vulnerable to contamination, according to our present understanding of pesticide persistence and movement coupled with the results of studies in Iowa (Kelley et al. 1987, Detroy 1987, Thompson et al. 1986) and Minnesota (Klaseus et al. 1987). Shallow aquifers occur throughout Illinois but are most common in the northern and southern parts of the state and adjacent to the major stream valleys (figures, p. 4).

A comparison of the distribution of aquifers within 50 feet of ground surface with the distribution of corn and soybean production shows that the areas where agricultural chemicals are used most intensively are generally not underlain by shallow aquifers. However, a significant part of the state that is vulnerable to contamination is cropped to corn and soybeans. Only in parts of southern Illinois are there vulnerable aquifers, yet minimal land area in corn and soybeans.

General Recommendations

Assessing aquifer vulnerability The USEPA recently proposed a strategy to prevent groundwater contamination by regulating pesticide use. This strategy may largely determine Illinois' approach to protection of groundwater resources. Specifically, the USEPA plans to prevent unacceptable levels of contamination of current and potential drinking water supplies. The proposal includes several key policies:

- use maximum contaminant limits (MCLs) or other criteria set by the USEPA to determine whether contamination is unacceptable,
- manage pesticide use on the basis of differences in groundwater use, value, and vulnerability,

- use groundwater vulnerability as a basis for county- or state-level measures, which may include canceling the use of specific pesticides,
- encourage a strong state role in local management of pesticide use, and require increased responsibilty by the pesticide user,
- increase monitoring for pesticides in groundwater.

Differential protection of groundwater resources, as proposed by the USEPA, is a key concept in the Illinois Groundwater Protection Act. USEPA may restrict or ban pesticides with a high leaching potential from areas where the aquifers are most vulnerable. However, restricting use in areas where such restrictions are not necessary (overprotection) and not restricting use in areas where the aquifer is truly vulnerable (underprotection) must be avoided.

Statewide mapping of Illinois has been used to identify regions with vulnerable aquifers. The predictions of aquifer vulnerability must be confirmed by sampling groundwater. In addition, aquifer vulnerability maps must be prepared at a scale that will allow decisions to be made farm by farm.

Use of soil information The existing information on soil properties is not in a form that can be easily used in a statewide assessment of aquifer vulnerability. The General Soil Map of Illinois has been published at a scale of 1:500,000 (Fehrenbacher et al. 1984). The soil associations shown on that map differ in several important properties, such as organic carbon content and permeability, which affect the potential for leaching of agricultural chemicals. Consequently, the soil association map is not suitable for evaluating leaching potential on a statewide scale.

A much higher degree of accuracy in mapping and characterization of soil properties is available in county soil survey reports prepared by the USDA Soil Conservation Service in cooperation with the Illinois Agricultural Experiment Station. These reports include detailed soil maps at a scale of 1:15,840 and data on the bulk density, clay content, organic carbon content, and permeability for the various horizons of each of the soils mapped. The Soil Conservation Service in Illinois is currently developing a pesticide-soil interaction rating to estimate the potential for leaching for all soils mapped in the state.

State and federal agencies should accelerate programs to digitize the soil surveys for each county in the state. Soil surveys of every county in the state will probably be completed by the mid-1990s. Unfortunately, these maps have not been digitized for computer-aided mapping. With digitization of the soil survey maps and anticipated improvement in models to predict leaching of pesticides, it may be possible in the future to develop computer-generated maps indicating leaching potential at state, county, and farm levels.

Hydrogeologic mapping Aquifer vulnerability to agriculftural chemical contamination is a function of soil properties and hydrogeologic conditions. The increasing body of evidence on the significance of preferential movement of pesticides through macropores in soils (such as root channels and cracks) means that predictions of potential pesticide leaching based solely on the properties of the soil matrix may be misleading. In addition, soils with a high leaching potential may occur in areas where aquifers are deeply buried and not vulnerable. For example, soils formed in windblown sands occur on uplands throughout Illinois. These coarse-textured soils with a low attenuation capacity may overlie thick sequences of fine-grained glacial materials with a high potential to attenuate pesticides.

An accelerated program should be developed to assess the geology and hydrology in the areas of the state where aquifers are most vulnerable to contamination by agricultural chemicals. This information is necessary for state and federal agencies to accurately target educational and monitoring programs, and potentially to implement pesticide use regulations. More importantly, this information is needed by landowners to properly manage their land and minimize effects on groundwater resources. The largest scale of mapping (1:250,000) presently available for most of the state is not suitable for use in making farm-level decisions. Aquifer vulnerability mapping at a scale of 1:62,500 (1 inch = about 1 mile) or larger would be appropriate for these uses.

Pesticide use data Pesticide use surveys should be expanded to provide estimates of pesticide and nitrogen fertilizer usage for counties, or at a minimum, for crop reporting districts. More accurate information on where specific pesticides are used would allow for more informed selection of analytes for groundwater sampling programs and better estimates of the potential for contamination of aquifers in various areas of the state.

POTENTIAL EFFECTS OF AGRICULTURAL PRACTICES ON GROUNDWATER QUALITY

Many farm management decisions potentially affect groundwater quality. Probably no agricultural practice always (inherently) has a negative impact on groundwater, just as no practice—other than non-use—will prevent contamination of groundwater resources by pesticides or nitrogen fertilizers in every soil/hydrogeologic setting in Illinois.

Part I of this report includes a preliminary evaluation of the potential effects of agricultural practices on leaching of pesticides and nitrates (figure, p. 8). The scientific literature is often contradictory and few studies have directly measured the effects of agricultural practices on groundwater quality. Most conclusions are based on inferences. However, this preliminary evaluation of the scientific literature suggests that the practices with the greatest potential to reduce leaching are pesticide selection and application rate, nitrogen fertilizer application rates, and rotation of crops. All of these practices offer the opportunity to reduce loading of agricultural chemicals onto the soil.

Tillage systems and water management practices, including drainage and erosion control, also influence soil properties, water infiltration and runoff, and consequently the movement of pesticides and nitrates. Compared with pesticide selection and rates and nitrogen application rates, however, these practices appear to have only a limited potential for affecting groundwater; they should be of concern only in areas where aquifers are highly vulnerable. Whether a practice will actually affect groundwater quality depends upon many environmental factors and the other agricultural practices in the field.

Pesticide Application

The potential of a pesticide to leach into groundwater depends to a large extent upon the chemical characteristics of the pesticide, especially water solubility, soil adsorption potential, volatility, and soil persistence.

In 1988, more than 80 percent of corn acreage and 21 percent of soybean acreage receiving preplant or preemergent weed control was treated with pesticides that the USEPA has identified as a potential hazard to groundwater in vulnerable soil and hydrogeologic settings. Many of the widely used alternatives for weed control in corn and soybeans also have a high potential to leach (University of Wisconsin 1989). Postemergent weed control programs included fewer herbicides that have a potential to leach. However, postemergent

Agricultural Practices	Pesticides	Nitrates
Pesticide application		
Compound selection	▲	NA
Formulation	◭	NA
Application methods and timing	▲	NA
Application rates	▲	NA
Nitrogen fertilizer app!ication		
Formulation	NA	◭
Application rates	NA	▲
Application methods	NA	▲
Application timing	NA	▲
Tillage practices		
Reduced tillage	◒	◒
Conservation tillage	◒/●	◒/●
No-till	◒/●	◒/●
Crop rotations	○	○
Cover crops	○	○
Tile drainage	●	●
Land-shaping practices		
Land leveling	●	○
Terraces	●	●
Diversions	○	○
Sediment basins	●	●
Grass waterways	◒	◒
Vegetation practices	○	○
Contouring	●	●
Strip cropping	○	○
Ponds	○	○
Irrigation	●	●
Chemigation	●	○
Other Soil Amendments	○	●
Point Sources	●	●

△	no control to low effectiveness
◭	low to medium effectiveness
▲	medium to high effectiveness
NA	not applicable
○	may decrease leaching
◒	no change
●	may increase leaching

Summary Potential effects of agricultural practices on leaching of pesticides and nitrates.

herbicide treatments (applied after crop and/or weed emergence) generally cost more and may not provide adequate control for all weeds in all crops.

Reductions in the amount of pesticide applied will reduce the amount available for leaching. Pike (1989) noted that both the overall quantity of pesticides used in the state (table, p. 9) and the use of many specific pesticides have declined in recent years. This decrease may be attributed to use of newer pesticides that are effective at lower rates; a decrease in corn and

Changes since 1978 in total pounds of active ingredient (AI) of herbicides and insecticides applied in Illinois (modified from Good and Taylor, 1987)

	Herbicides (million lbs AI)	**Change** (%)	**Insecticides** (million lbs AI)	**Change** (%)
1978	57.1		9.3	--
1982	65.4	+12.7	7.3	-21.5
1985	59.8	+ 4.5	5.8	-37.6
1988	45.4	-20.5	3.7	-60.2

soybean acreage; use of integrated pest management (IPM); use of herbicide combinations, sequential and overlay applications; and increasing availablility of postemergent herbicides, which have made it possible to reduce application rates early in the growing season.

In 1988, approximately 83 percent of the total acreage of corn planted after corn (26.4 percent of the total corn acreage) was treated with an insecticide (Pike et al. 1989); 14 percent of the total acreage of corn after soybeans was treated. The total amount of insecticides applied in Illinois decreased significantly between 1978 and 1988. This decrease may have been the result of more widespread use of integrated pest management practices (Good and Taylor 1987).

Nitrogen Fertilizer Application

The potential for contamination of aquifers beneath sandy soils in Illinois is exceptionally high even with careful adherence to recommended fertilizer management practices. Nitrogen loss in coarse-textured, rapidly permeable soils is principally attributed to leaching—primarily a function of the capacity of the soil to store and transmit water added to the surface. Well-drained sandy soils have a high nitrification rate and a very low denitrification rate (Saffigna et al. 1977). Consequently, excess nitrate is lost to leaching during periods of high recharge (fall and spring).

Crop Rotation

The use of crop rotations can significantly reduce applications of pesticides and nitrogen fertilizers. For example, preplant applications of insecticides to corn following soybeans (a common crop rotation in Illinois) are not recommended. Rotations of corn with legumes such as soybeans or alfalfa allow for reductions in nitrogen fertilizer applications. Small grains or hay in a rotation generally do not require applications of pesticides or nitrogen fertilizer, and insecticides are rarely applied to soybeans.

General Recommendations

Targeting educational and technical assistance programs Educational and technical assistance programs by state and federal agencies should be coordinated and targeted to those areas of the state with the highest potential for contamination.

State cost-sharing The state cost-share program for erosion control practices should be modified to include incentive payments to encourage adoption of integrated pest management techniques, such as pest scouting, and soil testing for texture and organic matter content to more accurately determine proper herbicide application rates. Funding for this program could be limited to areas with a high potential for groundwater contamination.

Wellhead protection on farmsteads The storage and handling of pesticides and nitrogen fertilizer as well as septic systems and animal feedlots can be a source of contamination in farmstead wells. County, state, and federal agencies should develop programs to help rural landowners evalute well sites and implement protective measures.

The potential for point source contamination of farmstead wells is particularly high in parts of western and southern Illinois where groundwater for domestic use is supplied by large-diameter dug or bored wells. In these areas, aquifers are not present or the groundwater in the aquifer is naturally of poor quality. There are approximately 100,000 large-diameter wells in Illinois (approximately 20 percent of the total number of wells in the state). These wells are particularly vulnerable to contamination due to their design and generally shallow depth. The source of water for these wells is generally thin sand layers or joints and fractures within low-permeability materials, and only a limited area will contribute water to these wells. In areas where high permeability materials (aquifers) occur, protecting the quality of water in a well may require changes in agricultural practices over a large area.

Developing recommendations for agricultural management A multidisciplinary team representing universities and state and federal agencies should develop recommendations for management practices that meet the needs of farmers attempting to protect vulnerable aquifers below individual fields. For example, specific recommendations are needed for alternative pesticides that will adequately control pests while minimizing leaching. This initial evaluation has identified several research needs:

Soil nitrate testing Soil testing to determine the amount of plant available nitrate in soils has the potential to reduce preplant application rates and thus the amount of nitrates available for leaching. Recent research (Bundy 1988) is encouraging; however, additional research is necessary to develop a diagnostic tool that can be used by farmers.

Evaluation of the effectiveness of cover crops The use of cover crops to remove excess nitrates from soil and prevent over-winter leaching should be investigated in typical soil and climatic conditions in Illinois. In addition, more research is needed to develop specific recommendations for managing cover crops.

Alternative agriculture In areas of the state where aquifers are especially vulnerable to contamination, it may not be possible to maintain water quality and continue to grow corn, soybeans, or other crops that require large inputs of pesticides and/or nitrogen fertilizer. While many of the recommendations presented in Part I of this report will help to minimize leaching, these reductions may not be sufficient to maintain water quality. Consequently, maintenance of both agriculture and water quality may require use of alternative crops or shifting to low input or other sustainable agriculture approaches. The development of effective alternative practices suitable for soils in these areas should be a high priority.

Integrated pest management The use of IPM techniques can substantially reduce the need for pesticide applications. Researchers at the University of Illinois and the Illinois Natural History Survey have developed several successful methods for predicting insect and disease infestations and determining economic thresholds. This program should be expanded and research should be continued on IPM techniques for weed control, including establishing economic thresholds and determining the allelopathic (herbicidal) effects of various cover crops.

EXTENT OF GROUNDWATER CONTAMINATION BY PESTICIDES

To date, Illinois has had no coordinated sampling program to determine the presence of agricultural chemicals in groundwater. In previous programs, the Illinois Environmental Protection Agency (IEPA), the Illinois Department of Public Health (IDPH), and the Illinois State Geological Survey (ISGS) have analyzed groundwater samples for relatively few compounds and/or only sampled public water wells or wells thought to be highly vulnerable to contamination. The IEPA studies (Clarke and Sinnott 1988) indicate that public water supply systems generally have not been contaminated by agricultural chemicals. Where contamination has been detected, the IEPA has attributed it to nearby agricultural chemical distribution facilities. The IDPH (Long 1988) has also identified agricultural chemical distribution facilities as point sources of groundwater contamination by pesticides and nitrates. Agricultural chemical contamination of a shallow aquifer overlain by sandy soils has been reported by the ISGS. The national pesticide survey (NPS) currently being conducted by the USEPA has sampled wells in Illinois; but data appropriate for describing conditions at the state level will not be generated. Several counties have also conducted limited sampling programs; however, the purposes and procedures of the programs have varied considerably and the results should not be used to estimate pesticide impacts on groundwater resources across the state.

General Recommendations

In all of the studies conducted to date, probably more than 1,000 analyses have been performed to determine the presence of pesticides in groundwater. However, knowledge of the statewide extent of agricultural chemical contamination of groundwater is still very limited, especially in rural areas where agricultural chemicals are used most intensively.

Implementatlon of statewide surveys The initial effort to assess the extent of agricultural chemical contamination of groundwater should be focused on private water wells in rural areas of the state. The experimental design recommended by McKenna et al. (1989a) will maximize the acquisition of data on the potential exposure of the rural population of Illinois to agricultural chemicals in drinking water. By sampling existing wells, this approach will minimize sample collection costs.

The simple random survey of rural private wells, currently being planned by the Illinois Department of Agriculture (IDOA), Cooperative Extension Service (CES) at the University of Illinois and the Surveys would provide statistically valid estimates of the overall occurrence of agricultural chemicals in rural private wells. To determine whether some areas of the state are more vulnerable than other areas would require a stratified random survey (McKenna et. 1989a).

Survey of large-diameter wells The proposed IDOA/CES simple random survey would sample large-diameter wells; these wells could be treated as a special class and sampled according to a simple random sampling plan. Dug and bored wells are not distributed uniformly across the state. Therefore, in order to limit the costs of conducting a survey of the occurrence of agricultural chemicals in these wells, the study should be restricted to areas of Illinois where more than 50 percent of the total number of wells are dug wells. Assuming the same conditions for estimating sample size as in the proposed statewide surveys, approximately 380 of these wells would have to be sampled.

Survey of private wells In suburban areas There is growing concern about the potential for groundwater contamination from the use of lawn-care chemicals and household pesticides in urban and suburban areas. Per-acre application rates of lawn-care chemicals have been reported to be much higher than for agricultural uses. Small-scale retrospective studies conducted in several representative suburban areas of Illinois would be the first step to evaluating this potential problem. These studies should include analyses for the most commonly used lawn-care chemicals.

Longterm monitoring The comprehensive long-term groundwater monitoring program mandated in the Illinois Groundwater Protection Act should include, as an integral component, an assessment of potential groundwater contamination by agricultural chemicals. A comprehensive monitoring plan should contain the following elements:

Monitoring rural private wells A long-term monitoring program for rural private wells should be developed. Determination of sampling frequency in various areas of the state should be based on the results of the initial statewide surveys and modified as additional data are obtained during the monitoring program. For example, if private wells in areas of the state where aquifer materials lie at or near ground surface have a significantly higher occurrence of agricultural chemicals than areas where materials lie at greater depths, those areas with a higher frequency of contamination should be sampled every 2 years. Areas where private wells have not been significantly affected by agricultural chemicals might be sampled at 5-year intervals. This long-term monitoring should identify trends in water quality and be useful in assessing the effectiveness of educational or regulatory programs.

Monitoring public water wells The current monitoring program for public water-supply wells should be expanded by (1) conducting an initial random sampling stratified on the basis of the potential for contamination by agricultural chemicals, and (2) bi-monthly sampling over a 1-year period of wells finished at shallow depths in shallow aquifers. Stratified random sampling of these wells will permit more cost-efficient sampling and aid in identifying those classes of public water supply wells most vulnerable to contamination. Frequent sampling of wells finished in shallow aquifers is recommended because greater temporal variability in the occurrence of agricultural chemicals would be expected in these aquifers. In addition, the list of analytes should be expanded to include those recommended for the proposed statewide surveys of private wells.

Research monitoring To increase understanding of the fate of agricultural chemicals in the subsurface, improve predictions of aquifer vulnerability, and evaluate remediation alternatives, investigations should be conducted to determine

- whether the occurrence of agricultural chemicals in groundwater varies over time,
- effects of soil and hydrogeologic conditions in Illinois on the persistence and mobility of pesticides,
- potential for adsorption and degradation of pesticides in aquifers.

These objectives can be met by conducting detailed studies in areas of the state with different soil and hydrogeologic conditions. Particular emphasis should be placed on identifying areas for which anomalous results were obtained in the statewide survey. The studies should include detailed characterization of aquifers and overlying materials and frequent sampling of monitoring wells. Collection of soil cores for pesticide analyses would be valuable in identifying areas where pesticides have leached below the crop root zone but have not yet reached an aquifer.

Database management A comprehensive database on agricultural chemicals in groundwater in Illinois should be developed and maintained in a computerized geographic information system (GIS) format. The database should include results

from routine monitoring by state agencies, special purpose monitoring by state and local agencies, and research by ISGS, ISWS, and university scientists. Information from the database should be used to identify areas for special investigations and to evaluate educational and regulatory programs.

Uniform procedures for data collection and reporting **The value of a database is primarily limited by the comparability and quality of the available data. Therefore, state agencies should develop uniform procedures for groundwater sample collection, analysis, and reporting. While the goals of groundwater sampling programs may differ, minimum reporting requirements should include well location (legal description), well depth and source aquifer, analytes and detection limits, quality assurance/quality control procedures, potential sources of contamination and other information necessary to properly evaluate the data.**

INTRODUCTION

In September 1987, the Illinois Groundwater Protection Act (P.A. 85-863) became law. The act mandates the Illinois Department of Energy and Natural Resources (ENR) to conduct an "ongoing program of basic and applied research relating to groundwater," including an evaluation of the impact of pesticides upon groundwater: "Such evaluation shall include the general location and extent of any contamination of groundwaters resulting from pesticide use, determination of any practices that may contribute to contamination of groundwaters, and recommendations regarding measures that may help prevent degradation of groundwater quality by pesticides. Priority shall be given to those areas of the state where pesticides are utilized most intensively. The Department shall prepare an initial report by January 1, 1990."

This initial report by the Illinois State Geological Survey (ISGS) and the Illinois State Water Survey (ISWS), divisions of IDENR, presents a preliminary evaluation of the impact of agricultural chemicals on groundwater.

Summary and Recommendations:

- The initial evaluation is summarized and programs are recommended to assess more accurately the extent of agricultural chemical contamination of groundwater resources in Illinois and to develop practical solutions to minimize leaching of agricultural chemicals.

Part I, Evaluation of the Potential Effects of Agricultural Chemicals on Groundwater Quality:

- The assessment of the potential for contamination of aquifers by agricultural chemicals, including pesticides (herbicides, insecticides, fungicides) and nitrogen fertilizers is based on hydrogeologic conditions and agricultural chemical usage in the state. Nitrogen is included in the assessment of contamination potential and the evaluation of agricultural practices because nitrogen fertilizers, a potential source of groundwater contamination, are extensively used in Illinois.

- The initial evaluation of the potential effects of agricultural practices on groundwater quality includes preliminary recommendations to minimize groundwater contamination. The evalution, based on a preliminary review of the literature, begins with a brief discussion of the processes and factors affecting the movement of chemicals into groundwater. The agricultural discussion covers selection and application of agricultural chemicals, tillage practices, water management, crop rotation, and erosion control practices.

Part II, initial Evaluation of Agricultural Chemicals in Illinois Groundwater:

- The compilation and interpretation of data from previous programs to sample for pesticides in Illinois groundwater is based on published reports and a survey of more than 400 state, federal, and local agencies representing every county in the state. Information was collected on the location of sampled wells, well depth and source aquifer, analytes and detection limits, quality assurance/quality control procedures, potential sources of contamination and other information necessary to evaluate the available data.

- A stratified random survey has been designed (1) to provide statistically valid estimates of the occurrence of pesticides and nitrates in rural private water wells throughout the state, (2) to determine whether private wells in some areas are more vulnerable to contamination than wells in other areas. Following a description of the proposed statewide survey is a report on the status of a pilot study to evaluate the experimental design.

I. EVALUATION OF THE POTENTIAL EFFECTS OF AGRICULTURAL CHEMICALS ON GROUNDWATER QUALITY

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I. EVALUATION OF THE POTENTIAL EFFECTS OF AGRICULTURAL CHEMICALS ON GROUNDWATER QUALITY

Accurate prediction of the vulnerability of groundwater resources to contamination from agricultural chemicals is one of the most important environmental issues facing farmers, water users, and state and federal agencies. Accurate targeting for education, technical assistance, and detailed monitoring requires identifying the most vulnerable areas. More importantly, regulation of agricultural chemicals to protect groundwater resources must take into account the vulnerability of groundwater resources. Underprotection of the resource will result in contamination and potential damage to water users and the ecosystem. Over-protection may result in economic hardship for the entire state. The optimum level of protection will balance use and protection of the groundwater resource.

POTENTIAL FOR CONTAMINATION OF ILLINOIS GROUNDWATER BY AGRICULTURAL CHEMICALS

With current agricultural practices and technology, the leaching of agricultural chemicals, particularly nitrates derived from fertilizer nitrogen, into groundwater (the saturated zone) may be impossible to prevent: more than one-third of the soils in the state have water tables within 5 feet of the surface during the spring and fall (Drablos and Moe 1984). Through most of Illinois, groundwater can occur within 5 to 20 feet of ground surface. However, in about 60 percent of the state, groundwater resources—the aquifers—are more than 50 feet deep and probably not vulnerable to contamination by pesticides (fig. 1).

Thus agricultural chemicals may be found in shallow groundwater, such as the water flowing from drainage tile, while the source of well water, the aquifer, remains unaffected. Making this distinction between groundwater in fine-grained materials (such as clay) and groundwater in an aquifer is important when establishing compliance points for regulatory monitoring.

The potential for contaminants such as pesticides or nitrates to occur in groundwater at any particular place and time depends upon many factors: (1) contaminant mass and chemical properties (such as solubility and persistence); (2) retardation capacity of the soils; (3) timing and intensity of precipitation (infiltration and recharge); and (4) hydrogeologic conditions. Consequently, a statewide assessment of the potential for agricultural chemicals to contaminate aquifers should be based on patterns of agricultural chemical use, soil properties, climate, and hydrogeologic conditions.

The evaluation in this section is based on hydrogeologic conditions and agricultural chemical usage. It does not consider properties of specific pesticides or soils or climatic factors for which appropriate statewide data are not available. The discussion of hydrogeologic principles and the distribution of groundwater resources in Illinois was modified from Berg, Kempton, and Stecyk (1984) and Berg, Kempton, and Cartwright (1984).

Hydrogeologlcal Principles

Groundwater is defined in the Illinois Groundwater Protection Act (1987) as "underground water that occurs within the saturated zone and geologic materials where the fluid pressure in the pore space is equal to or greater than atmospheric pressure." As this definition of groundwater is independent of the character of earth materials, it is not related to the availability of water to wells. In the zone of saturation, groundwater is stored in openings ranging from tiny pores between particles of silt and clay, to larger pores in sand and gravel, to large crevices in dolomite and limestone. The *porosity* of an earth material is the percentage of the bulk volume that is occupied by pores. In any rock there may be both unconnected pores and dead-end pores through which water cannot flow; the porosity

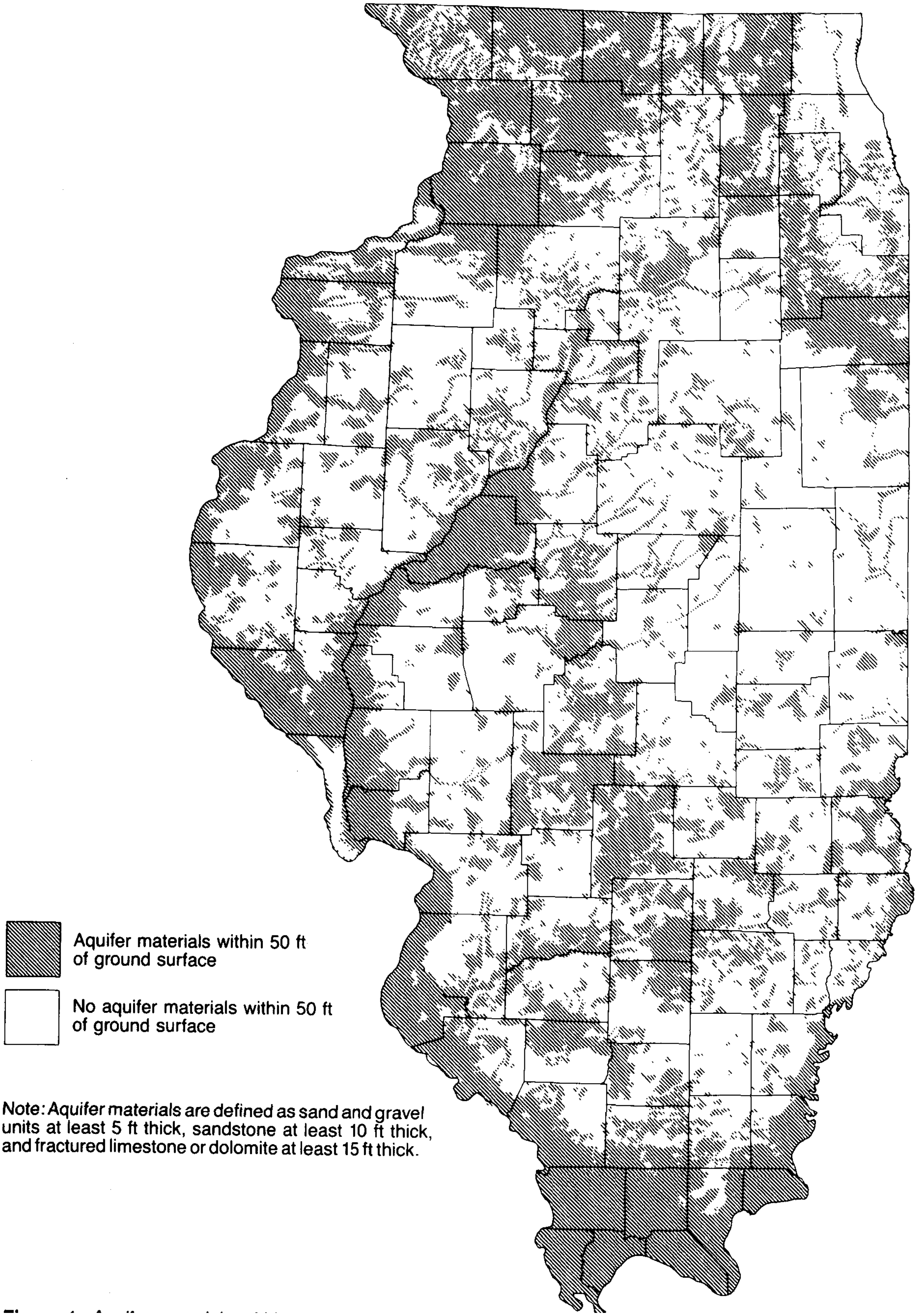

Figure 1 Aquifer materials within 50 feet of ground surface (based on mapping by Berg and Kempton 1988).

available for fluid flow is *effective porosity.* The size and interconnection of the pores and the properties of the fluid determine the *hydraulic conductivity* of the material—the relative ease with which it transmits a fluid under a pressure gradient. *Permeability* refers to the capacity of the earth material to transmit any fluid (Domenico 1972).

The *source of groundwater* in Illinois is precipitation that infiltrates the soil and percolates downward to the groundwater system. About 10 percent of the precipitation enters the groundwater system. *Recharge,* the addition to or replenishment of groundwater, depends upon soil moisture conditions, soil permeability, type and distribution of vegetation, precipitation duration and intensity, and location within the groundwater flow system. Regionally, the interrelationship of surface soils, underlying geologic materials, and configuration of the terrain determine the rate and amount of recharge, and the direction of shallow groundwater flow. (In agricultural areas, tile drainage systems may also considerably alter natural drainage and recharge characteristics.) Recharge does not originate at a point source or even small local areas; some recharge occurs in all unpaved areas except the discharge areas themselves. In Illinois, as in most humid areas, streams that flow perennially or for most of the year are groundwater discharge areas. The entire interstream system forms the recharge area.

The *water table* is the surface at which pore water pressure is atmospheric. Below that point almost all openings (pores) are filled with water. Above the water table, water is held by tension forces and will not flow freely to a well or spring. The water table in humid areas such as Illinois roughly parallels the surface topography, rising under the uplands and intersecting the ground surface along perennial streams, lakes, swamps, and springs. At these points of intersection, groundwater is discharged to surface water bodies by gravity flow from adjacent areas where the water table is higher (fig. 2). The position of the water table and the amount of discharge of groundwater to streams fluctuate from season to season and year to year.

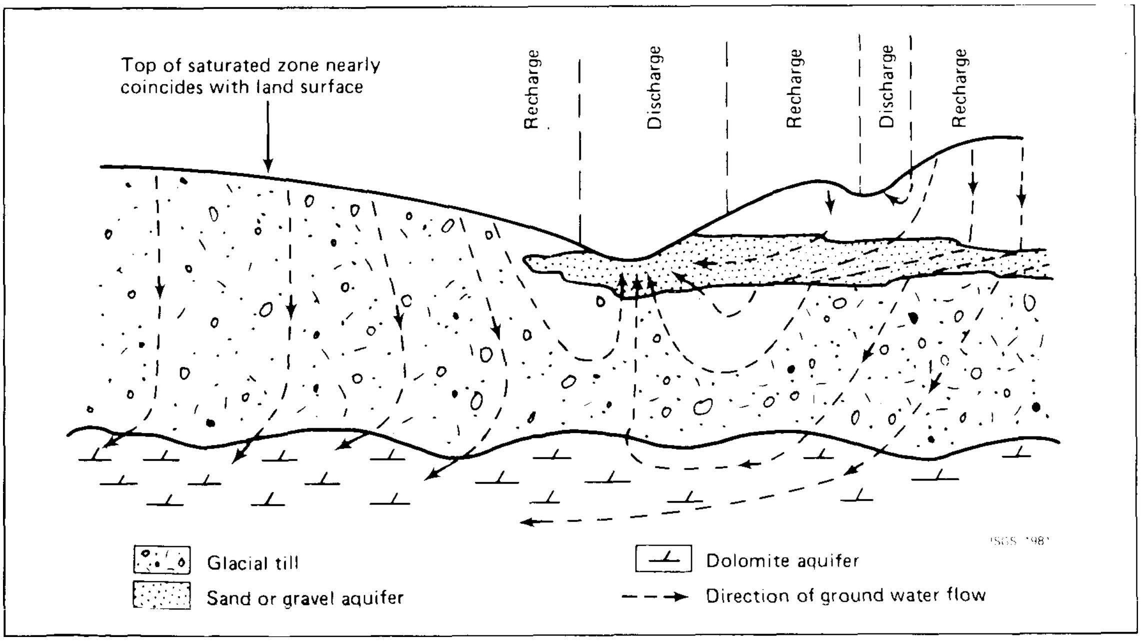

Figure 2 Details of groundwater flow systems (modified from Hughes et al. 1971).

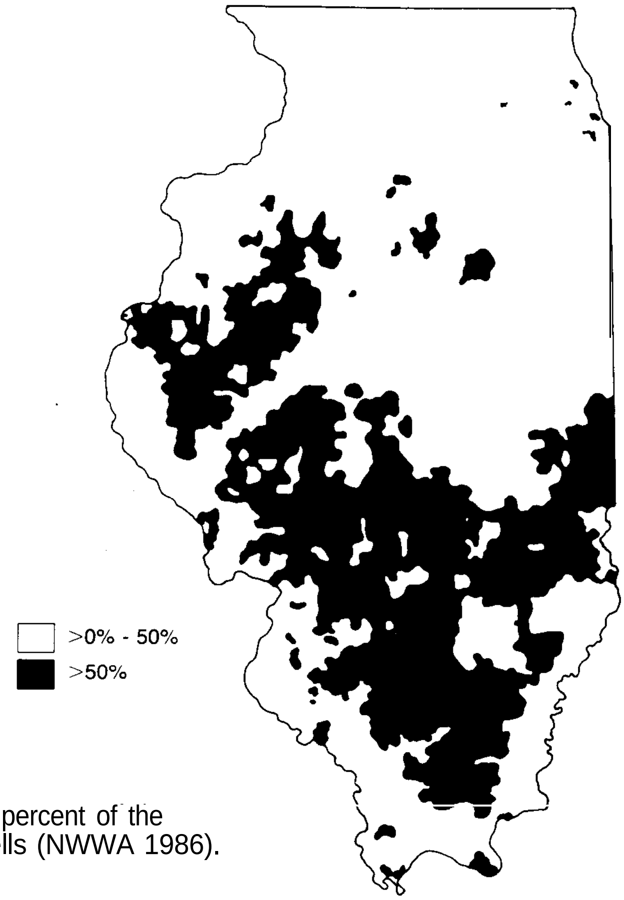

Figure 3 Areas of Illinois where more than 50 percent of the private wells are large-diameter dug or bored wells (NWWA 1986).

The water table occurs at shallow depths in most surficial materials found in Illinois. However, the groundwater present in these materials is not necessarily readily available to a well. Water will be available only if the well encounters material with sufficiently high hydraulic conductivity. A large excavation below the water table, such as a large-diameter bored well, will fill with water—very slowly—even in clayey materials, which have very low hydraulic conductivity.

In large parts of western and southern Illinois aquifers are not present or the groundwater in the aquifer is naturally of poor quality. In these areas (fig. 3) groundwater for domestic use is supplied by large-diameter dug or bored wells. There are approximately 100,000 large-diameter wells in Illinois (approximately 20 percent of the total number of wells in the state; NWWA 1986). These wells are particularly vulnerable to contamination due to their design and generally shallow depth. The source of water for these wells is generally thin sand layers or joints and fractures within bedrock or glacial materials, and only a limited area around a well will contribute water to these wells.

An *aquifer* is a natural material with interconnected openings large enough to transmit water readily to a spring or well in sufficient quantity to satisfy the need for which the well was drilled. An aquifer that produces sufficient water to supply a well for a single residence might not yield enough to serve as an aquifer for a municipal well. (In this report, the term aquifer refers earth materials capable of yielding enough water from a single well to supply at least several residences.)

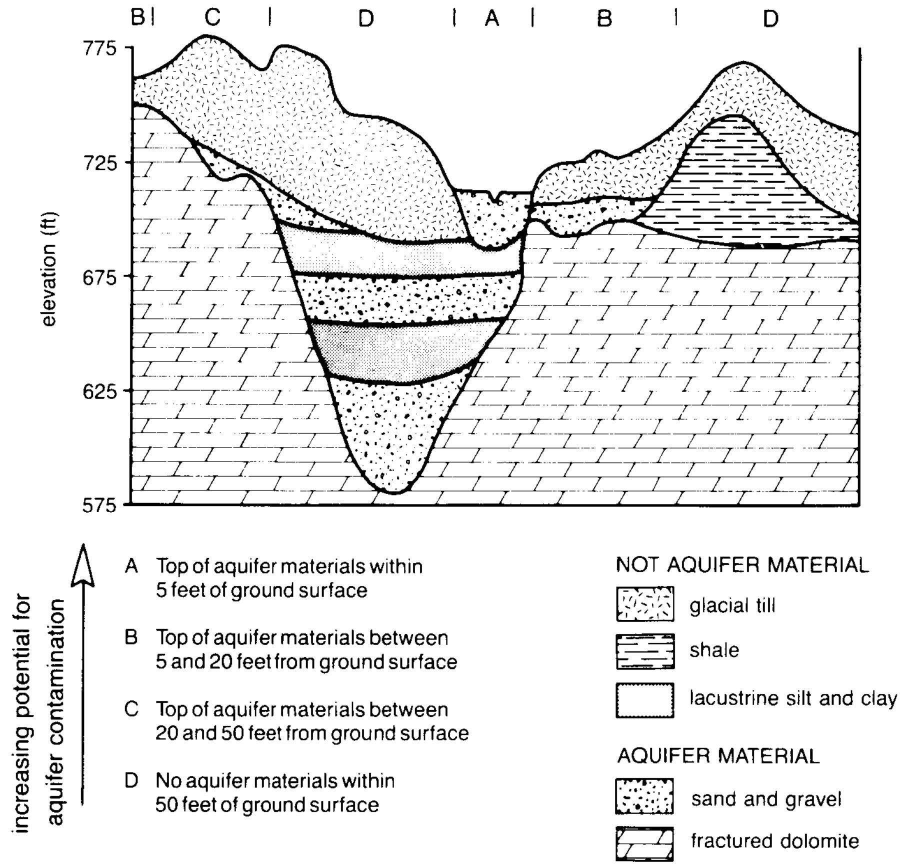

Figure 4 Geologic sequences with ratings for potential for contamination from agricultural chemicals.

Aquifer distribution varies across Illinois, from areas such as Mason County where the aquifer occurs within a few feet of the ground surface, to areas such as Champaign County where aquifers lie more than 100 hundred feet below the surface and are protected by overlying materials of low permeability.

The rate of groundwater movement is directly related to both hydraulic conductivity and hydraulic gradient; relatively rapid infiltration and groundwater movement will occur in areas directly underlain by permeable bedrock or sand and gravel. Conversely, surface runoff may be greater and groundwater movement generally slower in areas directly underlain by silty or clayey materials having a considerably lower hydraulic conductivity. Thus over a given time, these areas provide considerably less recharge than do areas composed of sand and gravel or permeable bedrock at or near land surface.

Estimating the Potential for Aquifer Contamination by Agricultural Chemicals

Where aquifers are deeply buried in Illinois, they are generally overlain by deposits of fine-grained materials that are low in permeability. Materials of low permeability (loess, glacial tills, shale, cemented sandstone, and unfractured dolomite and limestone) tend to restrict contaminant migration; whereas highly permeable materials (sand, gravel, fractured dolomite and limestone, and sandstone) tend to allow rapid migration of contaminants. The thickness of the fine-grained materials controls the susceptibility of the underlying aquifers to contamination. As the thickness of these fine-grained materials increases, the potential for attenuation of a contaminant before it reaches an underlying aquifer increases (fig. 4).

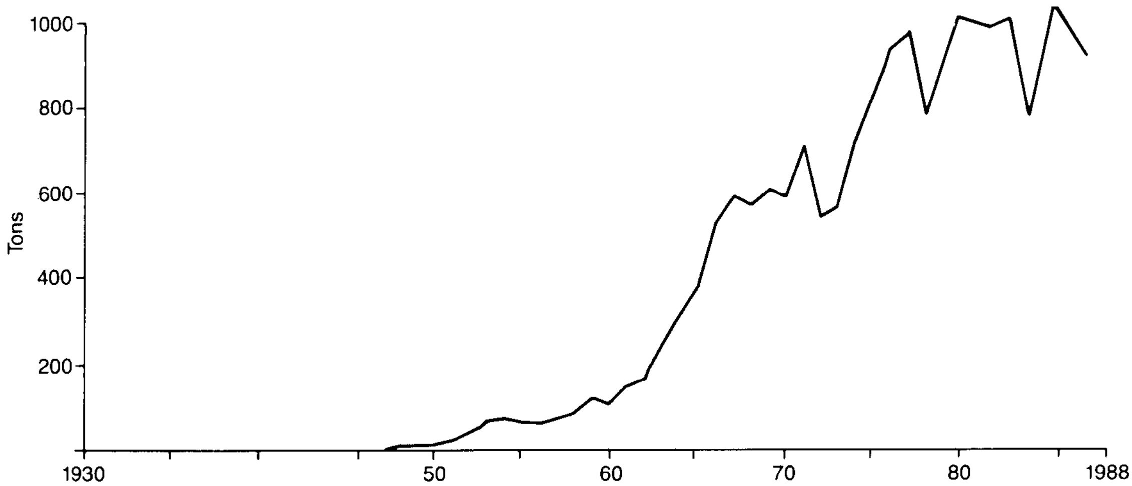

Figure 5 Nitrogen fertilizer usage in Illinois 1938-88 (modified from Westgren et al. 1983).

The time it takes a contaminant to reach an aquifer is affected not only by rate of movement, but also by distance to the aquifer. (Travel time equals distance divided by rate of movement.) Consequently, depth to an aquifer is extremely important for predicting whether aquifer contamination from surface-applied agricultural chemicals has occurred. Most organic pesticides were developed after World War II and not used extensively until the 1950s. The use of nitrogen fertilizers in Illinois has followed a similar pattern (fig. 5).

Agricultural Chemical Usage

Farmland makes up 28 million of the 38 million acres of land in Illinois (IDOA, 1987). Distribution of cropland varies across the state: less than 20 percent of Pope and Hardin Counties is cropland compared to nearly 95 percent of Piatt County. In 1988, more than 19 million acres of corn and soybeans were harvested. In more than 80 percent of the townships in Illinois, more than 50 percent of the total land area is devoted to corn and soybeans (fig. 6). On average, two of every three acres of land in rural areas of the state are treated with pesticides. Corn is produced primarily in northern and central Illinois. Most of the soybeans are grown in the central and south-central parts of the state. The major wheat-growing areas are in the southern part of the state.

In 1988, an estimated 46.9 million pounds of herbicides and 3.7 million pounds of insecticides were applied to the 19.1 million acres of corn and soybeans in Illinois (Pike et al. 1989). Herbicides were applied to 97 percent of the corn and 96 percent of the soybean acreage. Only a small percentage of the small grain and hay or pasture acres received pesticide applications (table 1). Consequently, where corn and soybeans are planted is a good predictor of where pesticides are used most intensively. Insecticides were applied to 37 percent of the corn and only a small percentage of other crops including soybeans. In most years less than 1 percent of the soybean acreas are treated with an insecticide (Pike et al. 1989). (In 1988, 36 percent of the soybean acreage was treated with an insecticide to control a spider mite infestation.)

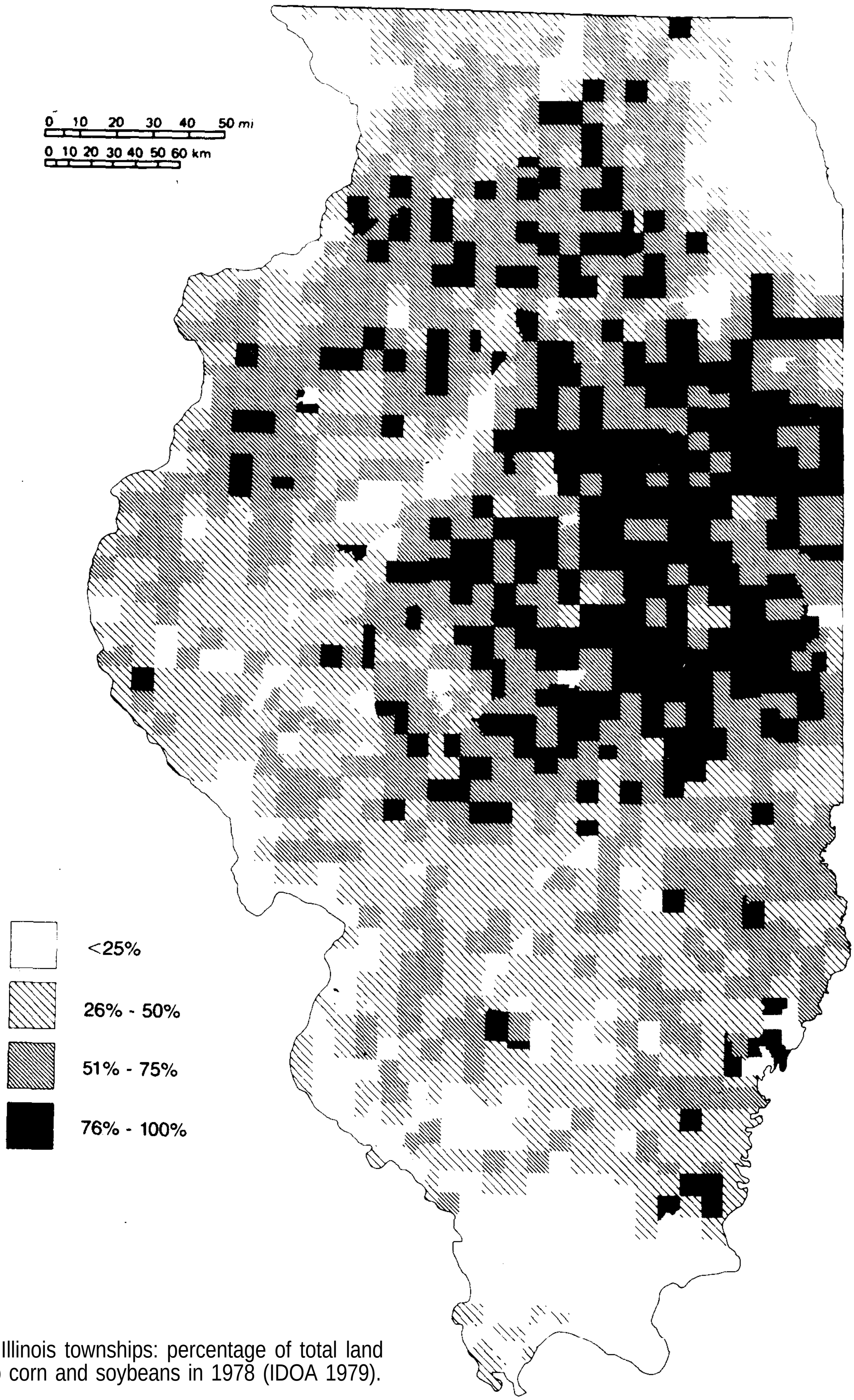

Figure 6 Illinois townships: percentage of total land planted to corn and soybeans in 1978 (IDOA 1979).

Table 1 Pest control practices Illinois in 1988 (Pike et al. 1989)

Crop planted	Total acres	Farms with crop (%)	Acres treated with herbicide (%)	Acres treated with insecticide (%)
Corn	10,041,000	96	97	37
Soybeans	9,089,000	89	96	36
Small grains	1,522,000	43	7	<1**.
Hay	691,000	43	3	4**
Pasture	1,326,000	41	1	<1**

* Small grains include oats, wheat, rye and sorghum.
** Data are for 1984 (Pike 1985).

Each year, Illinois farmers apply approximately 1 million tons of nitrogen fertilizer. Almost all corn acres receive applications of nitrogen: the average application rate is 156 pounds per acre (IDOA 1987). Nitrogen is also applied to most of the wheat acreage in the state, but application rates are much lower, approximately 70 to 80 pounds per acre. Less than 10 percent of the soybean acreage receives nitrogen, and where applied, rates are usually less than 20 pounds per acre.

Since 1980, state and federal agencies in Iowa have documented the extent of groundwater contamination by agricultural chemicals in their state (Hallberg and Hoyer 1982, Hallberg et al. 1983, 1984, Hallberg 1986, Libra et al. 1984, Kelley et al. 1986, Detroy 1986, Thompson et al. 1986). These studies have contributed to a general understanding of the mechanisms by which agricultural chemicals are transported to groundwater; they have also identified hydrogeologic settings vulnerable to contamination (Hallberg 1987). The studies summarized by Kelley et al. (1986) indicated significant differences in the occurrence of pesticides in different hydrogeologic settings (table 2). A much higher percentage of wells withdrawing water from aquifers within 50 feet of the surface had detectable levels of pesticides than wells finished in deeper aquifers. Similar results were reported in Minnesota (Klaseus et al. 1988) where pesticides were most commonly found in karst areas and in shallow sand and gravel aquifers.

Areas with intensive corn and soybean production and an aquifer within 50 feet of ground surface are most vulnerable to contamination. This interpretation is based on our present

Table 2 Pesticide monitoring data from Iowa studies grouped by hydrogeologic setting (modified from Kelley et al. 1986)

Total wells	Wells with detections (%)	Total samples	Samples with detections (%)
Alluvial aquifers (sand and gravel near the surface)			
148	39	181	42
Buried sand and gravel aquifers			
90	14	92	16
Shallow bedrock (<50 ft deep) and karst			
71	62	211	54
Deep bedrock (>50 fl deep)			
47	4	64	9

understanding of pesticide persistence and rates of groundwater movement coupled with the results of studies in Iowa and Minnesota. The rating scheme presented here is based primarily on depth to the aquifer and not on the properties of overlying soils. The depth intervals used are based on currrently available mapping (Berg and Kempton 1988). The validity of the ratings is being evaluated in the ISGS/ISWS/IDOA pilot study and would be fully tested in the proposed stratified random survey (see section, *Proposed Statewide Surveys).*

A comparison of the distribution of aquifers within 50 feet of ground surface (fig. 1) with the distribution of corn and soybean production (fig. 6) shows that the areas where agricultural chemicals are used most intensively are generally not underlain by shallow aquifers. However, a significant part of the state that is vulnerable to contamination is cropped to corn and soybeans. Only in southern Illinois (Union, Johnson, Pope, and Hardin Counties) are there vulnerable aquifers, yet minimal corn and soybean production.

• *Highest potential for contamination from agricultural chemicals* Shallow aquifers are most vulnerable where the top of the aquifer materials lies within 5 feet of ground surface. These areas, about 15 percent of rural Illinois, typically consist of thin loess or bedrock residuum over jointed limestone or dolomite or porous sandstone; or less than 5 feet of loess or silty lacustrine materials over thick deposits of sand and gravel. Principal areas are north-central, northwestern, and extreme southern Illinois and adjacent to the Mississippi River (fig 7).

• *Second highest potential for contamination* Aquifers are also vulnerable where the top of the aquifer materials lies between 5 and 20 feet of ground surface. These areas, about 13 percent of rural Illinois, have continuous deposits of relatively fine-grained materials, such as loess, till, or lacustrine deposits, overlying highly permeable aquifer materials. Principal areas are northern, southern, and extreme western Illinois.

• *Third /eve/ of contamination potential* Areas where continuous aquifer materials lie between 20 and 50 feet from ground surface rank next in vulnerability. These areas, about 11 percent of rural Illinois, have at least 20 feet of fine-grained materials overlying highly permeable deposits. Although these sequences of earth materials occur throughout Illinois, they are concentrated mainly in the western, south-central, and southern parts of the state.

• *Lowest potential for contamination* Areas with no continuous aquifer materials within 50 feet of ground surface are least vulnerable to contamination. These areas, more than 60 percent of rural Illinois, have at least 50 feet of fine-grained glacial deposits or low-permeability bedrock overlying the aquifer. Every county in Illinois contains sequences of earth materials like these, but the greatest areal coverage occurs in northeastern and central Illinois.

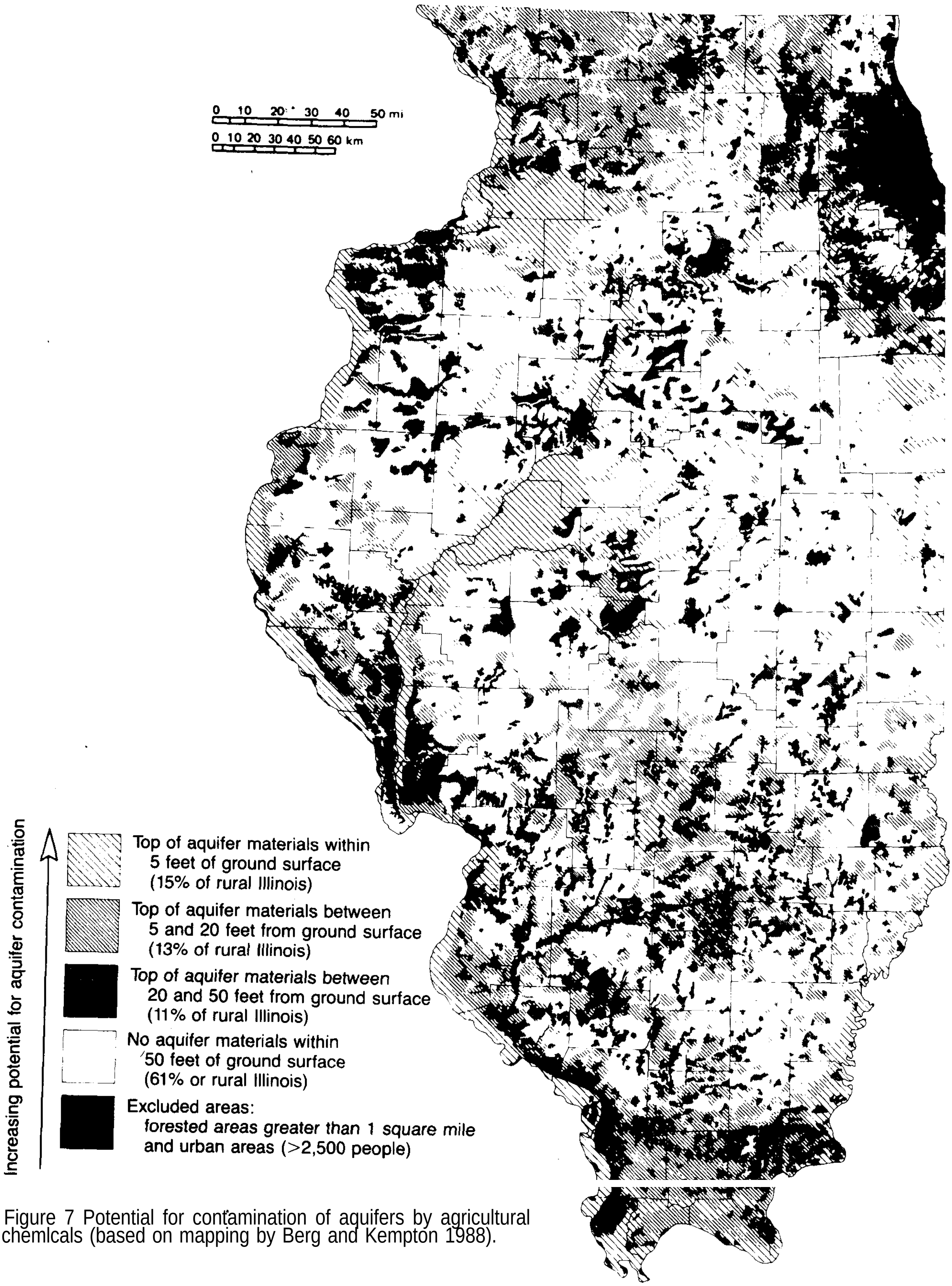

Figure 7 Potential for contamination of aquifers by agricultural chemlcals (based on mapping by Berg and Kempton 1988).

EVALUATION OF THE EFFECTS OF AGRICULTURAL PRACTICES ON GROUNDWATER QUALITY

Many farm management decisions potentially affect groundwater quality. Probably no agricultural practice always (inherently) has a negative impact on groundwater, just as no practice—other than non-use—will prevent contamination of groundwater resources by pesticides or nitrogen fertilizers in every soil/hydrogeologic setting in Illinois. Movement of agricultural chemicals into groundwater is affected not only by agronomic practices, but by various natural processes and environmental factors. Physical, chemical, and biological processes result in the storage, transport, and transformation of a compound. Environmental factors influence which processes are most significant (Ragone et al. 1988).

Processes

A pesticide applied to the soil surface is subject to several processes that affect the potential for movement into groundwater: volatilization to the atmosphere, chemical or microbial degradation, adsorption by the soil, and transport by water (fig. 8). The portion of the applied pesticide that is stored, transformed, or trainsported will be controlled by the properties of the pesticide and by the factors of climate, soil, and hydrogeology.

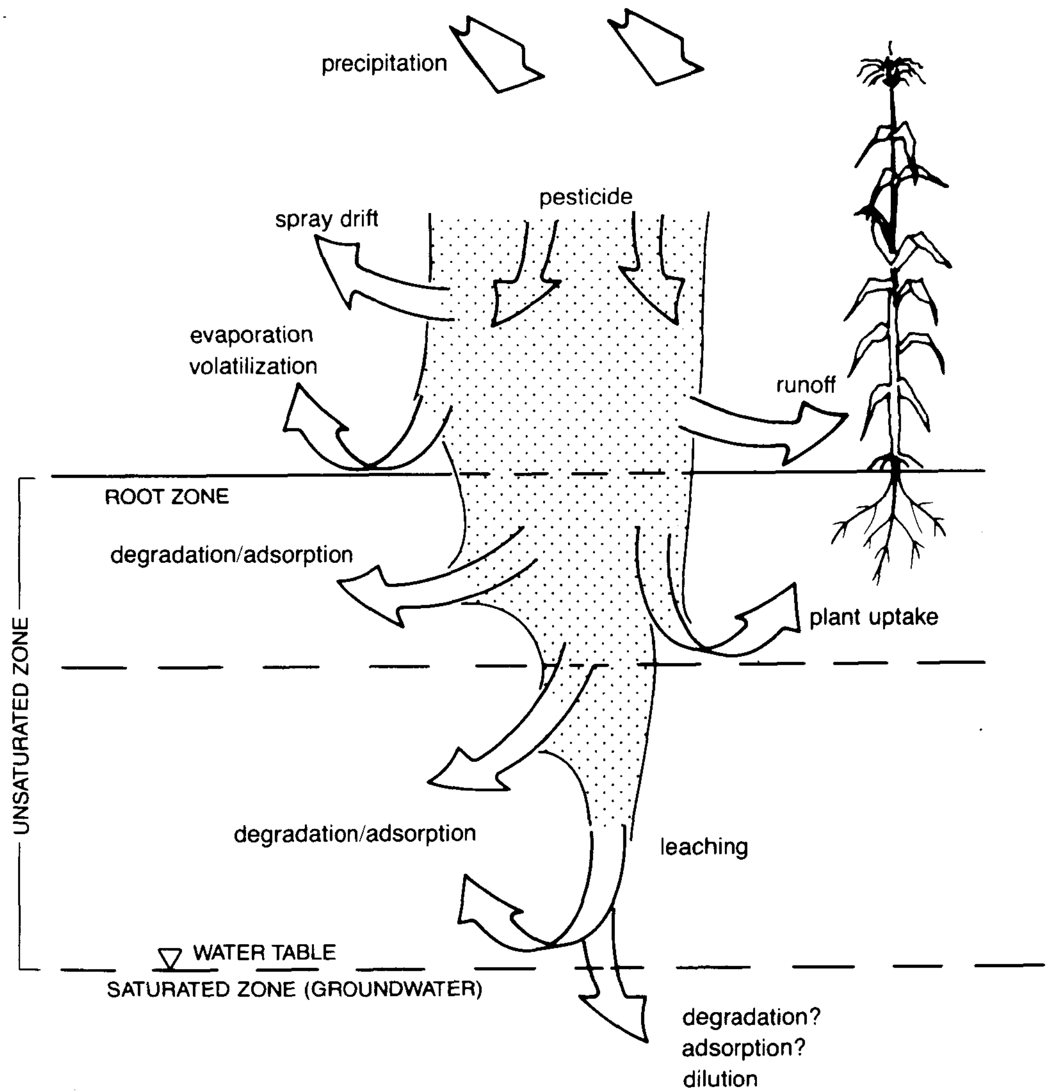

Figure 8 Potential pathways of pesticide loss and transport (modified from Severn 1987).

Volatlllzatlon At the soil surface, rates of volatilization of pesticides are influenced by pesticide concentration and soil water content and temperature, but are primarily controlled by the vapor pressure of the pesticide (McEwen and Stephenson 1979).

Degradation Although primarily the result of biochemical processes carried out by microorganisms, degradation of pesticides also occurs through uptake by plants and subsequent decomposition by plant enzymes, and nonbiologically through photodegradation and hydrolysis. The rate of microbial breakdown depends upon the chemical structure of a pesticide and many environmental factors that affect the growth of microorganisms: pesticide concentration in the soil, moisture content, temperature, pH, availability of nutrients, and the presence or absence of free oxygen (Ashton 1982). Because microbial activity is limited in subsoil environments, pesticides are usually more persistent at depth than in surface **horizons.**

Adsorption The retention of organic pesticides by soil decreases the concentration of pesticides in the soil water and their availability for transport to groundwater. Adsorption is dependent upon both pesticide chemistry and soil properties. Positively charged pesticides are retained on cation exchange sites associated with organic matter or various clay minerals. Most pesticides are nonpolar, however, and adsorption primarily depends on the organic carbon content of the soil.

Transport The primary mode is mass flow in which dissolved pesticides move with percolating water. Within the soil, pesticides are also transported by liquid and vapor diffusion. At the soil surface, pesticides are transported both in solution and adsorbed to soil particles by surface-water runoff.

Cumulative effects The processes of degradation (transformation) and adsorption (storage) significantly reduce the amount of pesticide available for transport either through the soil or in surface runoff. Most research indicates that less than 2 to 5 percent of applied pesticides are transported in runoff water (Wauchope 1978), and that even in vulnerable soil and hydrogeologic settings, less than 5 percent leaches through the soil (McKenna et al. 1989b, Gold and Louden 1982, Hall et al. 1989, Bicki and Felsot 1988).

In most cases, known groundwater contamination due to agricultural use of pesticides at label rates has been at low concentrations-—too low to be considered a health concern. Concentrations have ranged from less than 1 part per billion (ppb) to greater than 10 ppb. Nevertheless, concern is widespread that chronic exposure, even to low levels of pesticides in drinking water, may cause cancer, mutagenesis, teratogenesis, or immunologic-related disorders (Evans 1987). Concerns over excessive nitrate levels in drinking water have focused on methemoglobinemia (“blue baby” syndrome) in infants. Other reports, although disputed, have correlated high levels of nitrates in groundwater to gastric cancer, nervous system impairment, and birth defects (Kovan 1988).

Environmental Factors

Many environmental factors that affect the fate and transport of pesticides in soils are interrelated. Soil temperature is a function of air temperature, soil moisture content, organic carbon content, color, and texture of the surface horizon. Soil properties are partly a function of past and present climate and hydrogeologic conditions, such as depth to the water table. Environmental factors, especially soil properties, can also be modified by agricultural practices.

Climate Temperature, precipitation, wind, and relative humidity influence the fate of surface-applied pesticides. Recharge, the amount of water available to move dissolved chemicals through the unsaturated zone to the water table, depends upon a large number of factors, including climate, soil properties, and agronomic management. The intensity and distribution of rainfall and the extent of evapotranspiration (a function of precipitation, temperature, wind, relative humidity, and soil and crop characteristics) influence the amount of water available for percolation through the crop root zone and the leaching of dissolved chemicals. In Illinois, average total precipitation varies from 32 inches in the north to 46 inches in the south. Higher potential evapotranspiration rates in the south result in higher potential water deficits during the growing season (Bowman and Collins 1987).

Soll properties To a large extent, soil properties control the rate and nature of downward movement of chemicals. In the unsaturated zone, mass flux of a chemical is directly related to the hydraulic conductivity of the soil and indirectly to the texture, water content, bulk density or porosity, and pore-size distribution of the soil.

Environmental factors that affect pesticide transport through soil

Climate
Temperature
Precipitation
Wind
Relative humidity

Soil
Water content
Bulk density or porosity
Pore-size distribution
Saturated hydraulic conductivity
Organic matter content
Depth to water table
Texture
Clay content and type
Surface area
Water retention (field capacity)

Hydrogeology
Depth to water table
Hydraulic conductivity
Effective porosity
Attenuating capacity of earth materials
Depth to aquifer

The soil properties that most directly affect potential leaching of reactive compounds such as pesticides are hydraulic conductivity and organic carbon content. For example, pesticides are more likely to leach in coarse-textured soils with low organic carbon than in fine-grained soils with high organic carbon content (fig. 9). Nitrate is highly water soluble and not subject to adsorption to organic matter or clays. Under certain conditions, however, nitrate may undergo denitrification and subsequent volatilization to the atmosphere. The rate of nitrate movement is controlled by the rate at which water moves through the soil. Consequently, leaching of nitrates is also most likely to occur in sandy soils.

Hydrogeologic factors The thickness and character of the geologic materials between the base of the soil and the top of the underlying aquifer greatly affect the potential for contamination of the aquifer. Once contaminants such as pesticides or nitrates reach the water table, their rate of movement to an aquifer depends upon the hydraulic gradient and conductivity, effective porosity, and attenuating capacity of the materials overlying the aquifer. In general, the rate of movement of a contaminant is controlled by the average linear velocity of the groundwater. However, dispersion causes some contaminant molecules to move faster and others to move slower than the average linear velocity of the groundwater. These processes also cause the contaminant to spread in directions transverse to the groundwater flow path (Freeze and Cherry 1979).

Reactive contaminants, such as dissolved pesticides, are potentially subject to adsorption by the aquifer materials and chemical and microbial degradation. As a result, the movement of the contaminant is slowed and its concentration in solution is reduced. If the adsorption

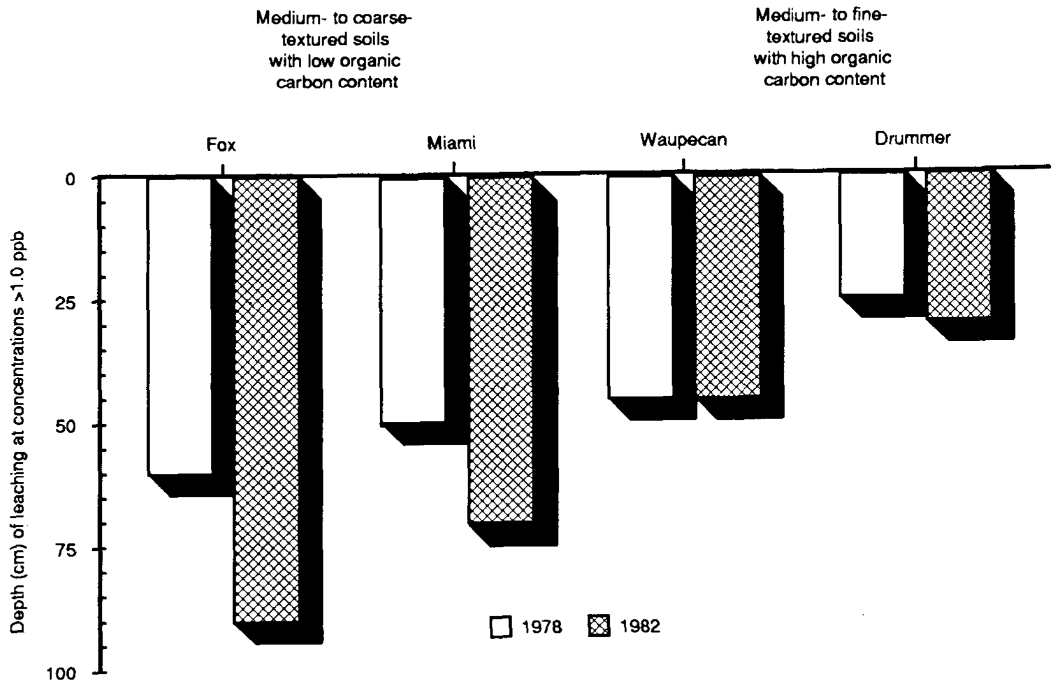

Figure 9 Predicted depth of leaching of a commonly used corn herbicide applied at labeled rates on four soils that differ in organic carbon content and hydraulic conductivity. Predictions developed from simulations using the USEPA Pesticide Root Zone Model (PRZM, Carsel et al. 1984).

reaction between the contaminant and aquifer material is reversible, the adsorbed compound may desorb and re-enter the liquid phase (groundwater). A net transfer of contaminant via desorption into the liquid phase is possible if the concentration of the contaminant in solution decreases due to dispersion, dilution, and/or the cessation of contaminant input.

Dilution is apparently the only significant process affecting the fate of nitrates in deeper aquifers. While it is clear that denitrification occurs in soils and relatively shallow groundwater, the role of denitrification in removing nitrates from groundwater in deeper aquifers is uncertain. Conflicting results from investigations of denitrification suggests that the process may be occurring in some aquifers and not others (Keeney 1986). Denitrification is a biologically mediated reaction; the appropriate microbes and an organic substrate (necessary as an energy source) need to be present. Consequently, environmental conditions conducive to denitrification may not exist in deeper aquifers. Even if all the necessary conditions are present, a large influx of nitrate resulting from the application of nitrogen fertilizer can overwhelm the capacity of a natural system to attenuate the nitrate (Hallberg 1986).

Agricultural Practices

Compound selection and application (rates, timing, and methods), tillage practices, and crop rotation are among the agricultural practices affecting the potential for groundwater contamination by pesticides and nitrates. In addition, water management practices, including irrigation, drainage, and conservation measures influence soil properties, water infiltration and runoff, and consequently the movement of pesticides and nitrates. Agricultural practices with the greatest potential to affect leaching of pesticides and nitrates have been the focus of this initial evaluation (fig. 10). For most practices, only a few studies have directly addressed leaching, the downward movement of dissolved chemicals through soils. Consequently, the evaluation of each practice addresses the following questions.

Does a specific agricultural practice

- require the use of different types or amounts of agricultural chemicals?
- affect the amount of water available for infiltration and recharge?
- change soil properties that affect chemical movement?
- change the processes operating at land surface or in the soil?

Whether a practice will actually affect groundwater quality depends upon all of the environmental factors previously discussed and the other practices used in the field.

Agricultural Practices	Pesticides	Nitrates
Pesticide application		
Compound selection	▲	NA
Formulation	◭	NA
Application methods and timing	▲	NA
Application rates	▲	NA
Nitrogen fertilizer application		
Formulation	NA	◭
Application rates	NA	▲
Application methods	NA	▲
Application timing	NA	▲
Tillage practices		
Reduced tillage	◒	◒
Conservation tillage	◒/●	◒/●
No-till	◒/●	◒/●
Crop rotations	0	0
Cover crops	0	0
Tile drainage	●	●
Land-shaping practices		
Land leveling	●	0
Terraces	●	●
Diversions	0	0
Sediment basins	●	●
Grass waterways	◒	◒
Vegetation practices	0	0
Contouring	●	●
Strip cropping	0	0
Ponds	0	0
Irrigation	●	●
Chemigation	●	0
Other Soil Amendments	0	●
Point Sources	●	●

△	no control to low effectiveness
◭	low to medium effectiveness
▲	medium to high effectiveness
NA	not applicable
0	may decrease leaching
◒	no change
●	may increase leaching

Figure 10 Summary of the potential effects of agricultural practices on groundwater.

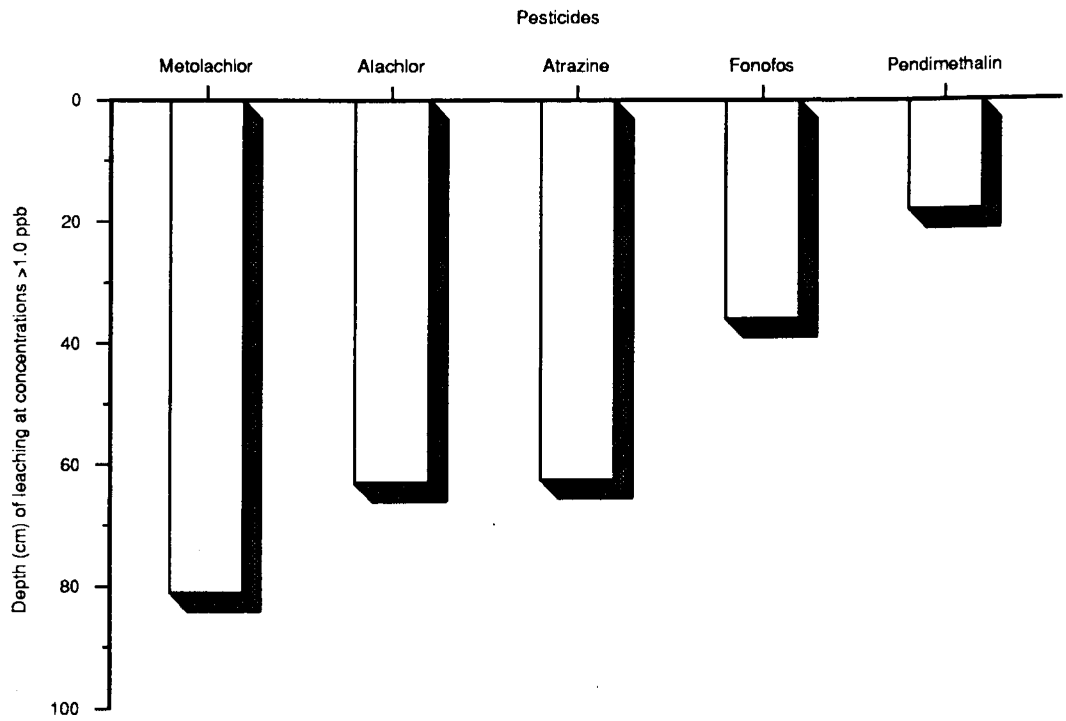

Figure 11 Predicted depth of leaching of five pesticides that differ in chemical characteristics. Predictions developed from simulations using the USEPA Pesticide Root Zone Model (PRZM, Carsel et al. 1984).

Pesticide Application

Compound Selection Pesticide characteristics have been used in several models that evaluate the fate and transport of pesticides in soils (Jury et al. 1984, 1983, Cohen et al. 1984, Helling and Dragun 1981, USEPA 1986). Chemical and physical properties that determine the potential of a pesticide to leach include water solubility, soil adsorption, volatility, and soil persistence (fig. 11). The USEPA (1986) has identified eight specific measurable characteristics that reflect these properties; the agency has estimated target values or limits for each characteristic that can be used to identify compounds likely to leach into groundwater:

- water solubility greater than 30 ppm,
- K_d less than 5, usually less than 1,
- K_{oc} less than 300 to 500,
- Henry's Law Constant less than 10^{-2} atm-m^3/mol,
- speciation negatively charged, fully or partially at ambient pH,
- hydrolysis half-life greater than 25 weeks,
- photolysis half-life greater than 1 week,
- field dissipation half-life greater than 3 weeks.

Although a large number of herbicides are registered for use in Illinois, only a few herbicides are applied to most of the row crop acreage. Many of the herbicides frequently used on row crops in Illinois have an environmental hazard warning regarding potential to leach into groundwater (Pike et al. 1989). Manufacturers are required to include a warning on the product label of pesticides with a high potential to leach into groundwater under certain soil and hydrogeologic settings.

Table 3 Pesticides with labels that contain an environmental hazard warning for potential to leach into groundwater (Chemical and Pharmaceutical Press 1988)

Herbicides common name (trade name)	*Insecticides/nematicides common name (trade name)*
atrazine (Aatrex)	aldicarb (Temik)
alachlor (Lasso)	carbofuran (Furadan)
cyanazine (Bladex)	
metolachlor (Dual)	
metribuzin (Sencor, Lexone)	
picloram (Tordon)	
simazine (Princep)	

In 1988, more than 80 percent of corn acreage receiving preplant or preemergent weed control was treated with pesticides labeled with a warning (table 3); 21 percent of soybean acreage receiving preplant or preemergent weed control was treated with pesticides that pose a potential hazard to groundwater. Postemergent weed-control programs included fewer herbicides that have a potential to leach into groundwater. Of the corn acreage receiving postemergent weed control, 15 percent was treated with atrazine, a herbicide that poses a potential hazard to groundwater.

Pesticide selection and use by farmers is currently based on cost, performance, soil type, pest (weed, insect, or disease), previous crop, tillage, experience, convenience, potential for carryover, and marketing. Cooperative Extension Service weed scientists have suggested that the current pattern of pesticide use is related to cost effectiveness and a history of performance satisfaction (University of Wisconsin 1989). In recent years, Illinois farmers have been urged to include the potential of a chemical to leach into groundwater as an additional factor in pesticide selection and use (Bicki 1988). However, pesticide labels generally provide little or no information on the solubility, persistence, or adsorption potential of compounds.

Formulation Formulations include liquids, water solutions, emulsifiable concentrates (EC), slurrys, water-dispersible liquids, flowables, wettable powders (WP), water-soluble powders, water-dispersible granules, dry flowables (DF), dusts, granules, and pellets. Encapsulated and microencapsulated formulations, where pesticides are enclosed in capsules or beads of material to control rate of release of the active ingredient, are also available for some herbicides and insecticides. The pesticide is applied as formulated, as is the case with some soil-applied insecticides, or the compound is diluted with water or other solutions, as is the **case with most herbicides.**

Pesticide formulation and chemical form have been shown to affect pesticide mobility. Wrucke and Arnold (1985) noted that with 0.1 inches of simulated rainfall, liquid formulations of atrazine and cyanazine were more difficult to wash from wheat straw residue than were WP and DF formulations. At greater than 1-inch rainfall levels, more of the atrazine WP and cyanazine DF were removed than any other formulation. Barnett et al. (1967) noted that 2,4-D esters were lost more readily than 2,4-D amine salts in runoff from fallow soils. Washoff characteristics of herbicides may play a part in preferential flow of pesticides through macropores if rainfall occurs shortly after application. Herbicide transport in rainfall runoff can also result in redistribution of herbicides. Infiltration of runoff water at lower positions on the landscape can result in higher loadings of herbicides and potentially greater leaching.

Some studies suggest encapsulated formulations of herbicides may reduce pesticide movement in the soil. Neuberger and Owen (1985) noted that a microencapsulated formulation of alachlor leached to shallower depth than an EC formulation. Flemming et al. (1989) compared movement of EC and microencapsulated formulations of alachlor, metribuzin DF, and pearl- and borate-starch encapsulated metribuzin formulations in a well-drained sandy soil in Illinois. They noted that starch encapsulation did not always reduce the depth of herbicide movement but generally kept the center of pesticide mass closer to the soil surface. They concluded that extending the release of herbicides from a carrier by encapsulation may help to keep the pesticide in the root zone and reduce the potential for groundwater contamination.

Application methods and tlming Herbicide application methods include preplant, pre-emergent, postemergent, combinations of these methods, sequential or overlay treatments, and band applications. A *preplant herbicide* is applied before planting a crop; it is either a foliar application to control existing vegetation or a soil application, which may or may not be incorporated. *A preemergent herbicide* is applied prior to emergence of a specified weed or crop. Soil-applied herbicides are often incorporated to minimize surface loss from volatilization or photodecomposition, reduce dependence on rainfall, and provide proper placement of the herbicide. A *postemergent herbicide* is applied after emergence of a specified weed or crop. Insecticides are applied in band, furrow, broadcast, or broadcast preplant incorporated soil applications, or as seed or foliar applications depending upon the target pest.

Lower herbicide rates are sometimes specified for preemergent applications than for preplant application. Herbicide rates for combinations and sequential applications are usually lower than rates for herbicides used alone (Anderson et al. 1989, DeFelice et al. 1989, Sterrett 1987, Hopkins and Oliver 1986). Postemergent herbicide application rates may be lower than preemergent rates if the hebicides can be applied at either time. Postemergent herbicides generally have foliar rather than soil action, and rates often vary depending upon the size and species of the weeds and whether or not an adjuvant is used (Anderson et al. 1989). DeFelice et al. (1989) reported that postemergent herbicide rates may be reduced if the herbicides are applied early on very small weeds. Few herbicides currently registered for postemergent weed control pose a significant threat to groundwater quality. However, postemergent weed-control options for some weed and crop combinations are limited and can be more costly than preplant and preemergent applications.

Broadcast application without soil incorporation of some pesticides depends upon timely rainfall shortly after application for incorporation and activation (Anderson et al. 1989). However, several studies (Helling et al. 1988, lsensee et al. 1988, Bicki and Felsot 1988) have reported that high-intensity rainfall occurring shortly after pesticide application has resulted in movement of pesticides into groundwater.

Although models are currently available to evaluate economic thresholds for weed population densities that affect crop yields (Cousens 1985, King et al. 1986, Pannell 1988, Streibig et al. 1989), few farmers have adopted their use. With many herbicide management programs, compounds are applied before a determination can be made regarding the severity of the infestation. For example, early preplant and preemergent herbicide applications are made long before any assessment of weed density can be made. Therefore the decision to treat is based primarily on previous experience and history. Postemergent or foliar-applied herbicides afford some opportunity for assessment of economic thresholds (DeFelice et al. 1989, Streibig et al. 1989).

The use of adjuvants such as surfactants, crop oil concentrates, or fertilizer solutions has been found to improve spray coverage, increase absorption and translocation of foliar-applied herbicides, improve weed control, and in some instances reduce herbicide application rates (DeFelice 1989, Wills and McWhorter 1988). However, damage to crops may increase with use of some adjuvants on some crops (Anderson et al. 1989), and not all compounds are registered for use with adjuvants.

Application of both herbicides and insecticides in narrow bands over the crop row can significantly reduce the mass of pesticides applied to soil. The amount of reduction is related to the width of the band application and the row spacing of the crop. As row spacing of a crop decreases, the amount of pesticide band-applied per acre increases. Recommendations for using many soil-applied insecticides indicate band or in-furrow placement to control most insect pests (University of Illinois 1989).

In 1988, more than 90 percent of corn and soybean acreage received a preplant incorporated or preemergent application of herbicides. Postemergent applications of herbicides were applied to 40 percent of corn acreage and 37 percent of soybean acreage (Pike et al. 1989). Band application of herbicides to both corn and soybean acreage has decreased significantly over the last 20 years and account for only 6 percent or less of acres treated in 1988. The reduction in band application of herbicides was in part related to adoption of erosion-control practices that exclude cultivation and use of more volatile herbicides requiring soil incorporation.

Application rates The product label specifies herbicide application rates, which vary according to time and method of application, tillage, and type and severity of the weed infestation; however, the rates are based primarily on soil organic matter content, pH, and textural class and increase as organic matter increases and texture becomes finer.

Jury and Valentine (1986) noted that the amount of pesticide applied to soil can influence its fate and transport. They indicated that unless adsorption of the pesticide varies as a function of concentration, increasing the total amount of the chemical should give a nearly proportional increase in the solution concentration and thus proportionally affect mass flow, vapor diffusion, and liquid diffusion. Karickhoff et al. (1979) reported that adsorption of most pesticides is linear for a broad range of concentrations frequently found in soils and sediments.

Typical application rates for commonly used corn and soybean herbicides range from 0.04 to 4.0 pounds of active ingredient per acre. In 1985, the average application rate for corn herbicides was 3.7 pounds per acre, and for soybeans, 1.83 pounds per acre (Pike 1985). From 1978 to 1988, the total volume of herbicides applied (table 8) decreased by 42.2 percent. Pike (1989) noted that the overall quantity of pesticides, particularly pesticides, used within the state and the use of many specific pesticides has declined in recent years.

Table 4 Changes since 1978 in total pounds of herbicides and insecticides as active ingredient (Al) applied in Illinois (modified from Good and Taylor 1987)

	Herbicides (million lbs Al)	Change (%)	Insecticides (million lbs Al)	Change (%)
1978	57.1		9.3	---
1982	65.4	+12.7	7.3	-21.5
1985	59.8	+4.5	5.8	-37.6
1988	45.4	-20.5	3.7	-60.2

This decrease may be attributed to use of newer pesticides that are effective at lower rates, a decrease in corn and soybean acreage, use of integrated pest management (IPM), use of combinations, sequential and overlay applications, and increasing availablility of postemergent herbicides, which have made it possible to reduce application rates early in the growing **season.**

In 1988, insecticides were used to treat approximately 83 percent of the total acreage of corn planted after corn (34 percent of the total corn acreage) (Pike 1989) and 14 percent of the total acreage of corn after soybeans. Application rates, also specified on the product label, depend upon the target insect and crop. Typically, application rates for corn rootworm control are 1.0 to 1.4 pounds of active ingredient per acre. The total amount of insecticides applied in Illinois also decreased between 1978 and 1988 (table 4). This reflects a drop in the total acres of corn treated from 65 percent in 1978 to 44 percent in 1988 (Pike 1989). This decrease may be due to more widespread use of integrated pest management (IPM) practices (Good and Taylor 1987).

Proper calibration, operation, and maintenance of sprayer equipment is necessary to achieve uniform and accurate application of pesticides. Improper calibration and operation of equipment can result in non-uniform distribution, over- or under-application, ineffective weed control, and possibly the need for re-application. A study by the University of Nebraska found that more than 60 percent of users incorrectly applied an intended application rate by more than 10 percent (Doersch et al. 1982).

Recommendations Changes in pesticide selection and application rates, methods, and timing can significantly reduce leaching of pesticides.

- Select pesticides with low potential to leach into groundwater, especially in vulnerable hydrogeologic settings.

- Base herbicide application rates on accurate information on soil organic carbon content and texture. General information is available in county soil surveys; detailed information can be obtained through soil testing services.

- Expand use of integrated pest management (IPM) such as scouting and application of economic thresholds for insects, weeds, and disease pests. Herbicide management programs should be used that facilitate an assessment of economic thresholds.

- Use reduced herbicide input strategies such as sequential applications, combinations, banding, cultivation, and applications of postemergent herbicides in areas where the potential for contamination of aquifers is high and potential for erosion is low.

- Use mechanical methods of weed control to replace all or part of chemical weed control in vulnerable hydrogeologic settings and where erosion is not a potential problem.

- Select herbicides on the basis of their effectiveness in controlling the target weed so that only the necessary amounts are applied.

- Use compounds less dependent on rainfall for activation and delay pesticide applications when rainfall is predicted.

- Use adjuvants for foliar-applied herbicides and for herbicides applied with conservation and no-till systems to improve weed control.

- Operate, maintain, and calibrate sprayer equipment properly to improve pesticide performance and reduce the risk of overapplication and non-uniform application as well as reduce the need for reapplication.

Nitrogen Fertilizer Application

The amount of nitrogen used by growing plants represents only 0.001 percent of the total amount of nitrogen on earth. Most nitrogen in soils is present in living and decaying organic matter. Bacteria are primarily responsible for the con version of N_2 to usable oxides and other compounds (e.g., gaseous nitrogen to ammonia to nitrate in soil. Nitrogen must be fixed (made part of a chemical compound) to be used by living organisms; the association of terrestrial microorganisms (symbiotic bacteria) with plants is the most Important natural source of fixed nitrogen. The processes involved in making it available to plants and animals include ammonification, ammonia assimilation, nitrification, nitrate assimilation, and nitrogen fixation. Nitrogen may also be fixed artificially for the production of fertilizer through the use of a high-temperature reduction process.

There are five major pathways of loss for nitrogen applied as fertilizer to soils: plant uptake, microbial utilization, runoff/erosion, volatilization, and leaching. Harvesting crops results in the depletion of these elements from the soil, and production of crops is limited by the availability of nitrogen compounds. Loss of these compounds to dentrification (conversion of fixed nitrogen to gaseous nitrogen) results in loss of nitrogen to the atmosphere. Significant loss of nitrogen, primarily nitrate, to leaching may lead to widespread contamination of groundwater resources (Brinsfield et al. 1988, Pryor 1988, Randall et al. 1988, Saffigna and Keeney 1977, Hallberg et al. 1984).

Soil morphology, geomorphology, and climatic conditions are important factors affecting the potential for nitrogen loss in soil. Alexander (1987) developed a nitrogen potential-loss rating system for Illinois soils based on natural soil drainage class, soil permeability, slope class, slope configuration, subsoil texture, and warm season rainfall. Ratings were attributed to denitrification and leaching losses with no distinction as to the cause of loss. Using individual soil potential-loss ratings and acreages estimates for each soil series in a county, nitrogen potential-loss ratings were determined for each county in the state. Thirty-five counties were rated as having a high potential for nitrogen loss, 42 were rated as medium, and 25 were rated as low.

Nitrogen loss in coarse-textured, highly permeable soils is principally attributed to leaching. Leaching of nitrates is primarily a function of the capacity of the soil to store and transmit water added to the surface. Well-drained sandy soils have a notably high rate of nitrification (conversion of ammonia to nitrate) and a very low denitrification rate (Saffigna et al. 1977). Consequently, excess nitrate is lost to leaching during periods of high recharge (fall and spring). An example of such contamination is reported by Saffigna and Keeney (1977) in the sand plain province of central Wisconsin. The study showed a relatively rapid transit time of more than 15 feet per year for nitrates through the sandy soil. Nitrate-contamination levels in the groundwater were greater than the drinking-water standard. The potential for contamination of aquifers beneath sandy soils in Illinois is exceptionally high, even with careful adherence to fertilizer-management practices.

In dark-colored, fine-textured soils with low permeability, nitrogen is primarily lost through denitrification. The amount lost depends upon forms of nitrogen present, moisture content of the soil, soil and soil-water temperature, soil pH, and the amount of organic matter. Nitrate leaching is generally considered to be significantly lower in fine-textured soils than in coarse-textured soils (Wild and Cameron 1981). Olsen et al. (1970) found that nitrates in a silt loam soil moved downward at a rate of approximately 1 foot per year. However, Priebe and Blackmer (1984, 1989) and Cerrato et al. (1985) reported that substantial amounts of nitrogen were lost from the upper 40 inches of some soils within 2 to 8 weeks after spring application. Rapid movement of nitrogen through the soil was attributed to preferential flow through macropores.

Formulation Nitrogen for crop production is available in both organic and inorganic forms. Organic forms include nitrogen derived from animal manure, sludge, nitrogen fixation, and plant residues. Illinois farmers have never produced enough manure to meet the nutrient requirements of all crops, but now that farming is mechanized, even less manure is available (Welch 1979). Sludge derived from municipal sewage treatment provides another source of nitrogen but application rates are limited by heavy metals that occur in sludge (see section, *Other Soil Amendments).* Anhydrous ammonia, ammonium nitrate, urea, and urea-ammonium nitrate (UAN) solutions are common forms of commercial nitrogen fertilizer. In Illinois, farmers primarily apply anhydrous ammonia, which is readily sorbed onto soil-clay particles and organic matter. Fifty percent of the nitrogen in ammonium nitrate and 25 percent in UAN is in the nitrate form, which is susceptible to loss immediately after application when conditions favor leaching and denitrification.

Application rates Recommended nitrogen application rates for corn are based on yield goals determined primarily by soil productivity and agronomic management. Recommended rates under a high level of management range from 80 pounds per acre for the light-colored claypan soils of southern Illinois to 205 pounds per acre for the highly productive, deep loess, prairie soils of central and northern Illinois (Anderson et al. 1989). Average nitrogen application rates have been constant over the last 5 years (IDOA 1987).

The recommended amount of nitrogen fertilizer applied to a field depends on the crop and the yield goal, which is soil and climate dependent. Recoveries of nitrogen in the field are as low as 50 to 60 percent of the total amount applied as fertilizer; most of the losses can be attributed to denitrification (loss to the atmosphere) and leaching (loss to groundwater). The Illinois Agronomy Handbook (Anderson et al. 1989) suggests that optimum application rates range from 1.22 to 1.32 pounds of nitrogen per bushel of corn. The nitrogen requirement is less when soybeans are rotated with the corn crop. The requirements of wheat, oats, and barley can be based on soil color, which is a function of the organic-matter content of the soil.

In many cases, rates applied are higher than crop requirements (Randall et al. 1988). Overestimation of need occurs because farmers underestimate nitrogen, such as that available from alfalfa and manure, by as much as 50 percent (Kaap 1986). Another reason for overapplication is overestimation of yields. In a Nebraska study of 158 farmers, only 10 percent reached their yield goal (Schepers et al. 1986).

Increases in application rates increase the potential for nitrogen to leach into groundwater. A Minnesota study demonstrated that when nitrogen was applied at rates greater than needed by crops, a significant amount was lost to deep percolation (Randall et al. 1988). A model simulation study based on 7 years of data to calibrate the model, found greater leaching losses associated with higher application rates (Kanwar et al. 1984). Reichman (1986) found that the percentage of nitrogen taken up by crops, or nitrogen uptake ratio, decreased with increasing application rates, suggesting that higher application rates increase nitrogen leaching. When applied at rates above that usable by the crop, nitrogen accumulates in the soil and becomes available for leaching into groundwater (Randall et al. 1988).

Applicatlon methods Kanwar (1985) found that more nitrate was retained in the upper 30-centimeter layer when surface-applied versus soil-incorporated. He concluded that inverting the plow layer during incorporation allowed the nitrogen a 4- to 6-inch head start in leaching to deeper soil layers.

Application timing Nitrification during winter/spring can increase leaching losses of nitrogen applied during the fall (Jackson et al. 1987). Applications after planting (side dress) are considered more efficient than the spring applications before planting. Splitting applications may also reduce leaching potential. Kanwar (1984) found that multiple applications versus a single application of the same amount of nitrogen can increase plant uptake of nitrogen by 7 percent and reduce the amount of nitrogen leached by 9 to 13 percent.

Recommendations Loss of nitrogen fertilizer can be minimized by determining proper application rates, timing of application, placement, tillage methods, and type of fertilizer.

- Base nitrogen fertilizer application rates on realistic yield goals.

- Use nitrogen fertilizer in forms (e.g., ammonia) that are easily sorbed onto soil panicles.

- Credit nitrogen contributions from legumes in rotation, manure, and other sources. Keep track of all sources of nitrogen and account for residual soil nitrate.

- Do not apply nitrogen fertilizer in the fall to soils that are coarse-textured or underlain at shallow depths by fractured bedrock or sand and gravel.

- Use nitrification inhibitors on soils that have high leaching potential. Nitrification inhibitors are effective in sandy soils where leaching may be a significant problem, as well as in poorly drained soils.

- Use cover crops to reduce nitrogen loss in winter and early spring.

- Maintain adequate levels of phosphorous (P), potassium (K), and calcium in the soil. When inadequate levels of these nutrients are available, the efficient use of nitrogen by the crop decreases and the potential for losses to leaching increases.

- Follow the nitrogen application rates recommended in the Illinois Agronomy Handbook (Anderson et al. 1989). There is a point where crop recovery of nitrogen decreases as application rates increase. Beyond this point, additional nitrogen increases the likelihood of groundwater contamination.

- Use split applications on sandy soils to promote more efficient use of nitrogen by crops.

Tillage Practices

Soil and climatic conditions, crop planted, production costs, and labor and equipment availability form the basis for selecting tillage systems. Illinois farmers use moldboard plowing, mulch tillage (chisel plowing, disking or use of sweeps, field cultivators, or blades), ridge-till, strip-till, and no-till, or combinations of these systems. Some farmers vary tillage operations on different tracts and for different crops. For example, some farmers chisel-plow corn residue before planting soybeans and plant corn without tillage into soybean residue, a conservation tillage practice currently recommended in Illinois (Anderson et al. 1989).

The *moldboard plow* system, often referred to as conventional tillage, is a two-part operation: primary tillage by moldboard plowing in the spring or fall is followed by secondary tillage of one or more passes with a disk, field cultivator, harrow, or similar implement. Moldboard plowing turns over the soil surface, so little crop residue is left on the surface. *With mulch tillage,* a heavy or tandem disk or chisel plow is used for primary tillage followed by secondary tillage with a light disk or field cultivator. *Ridge tillage* is a one-pass tillage planting system. Ridges, constructed during cultivation of the previous crop, are prepared for planting with sweeps, disk openers, coulters, or row cleaners. Residue is left on the soil surface between ridges until cultivation.

Strip tillage is a one-pass, tillage-planting system that confines seedbed preparation to a narrow strip. Generally, the seedbed is prepared with a rotary tool and restricted to one-third of the distance between rows.

Any tillage system in which at least 30 percent of the soil surface is covered with crop residue after planting is classified by the Soil Conservation Service as a conservation *tillage system* (Pierce 1985). *No-till* is a system using no primary or secondary tillage before planting. The seedbed is prepared with a coulter, single chisel, or similar tool, and the soil is disturbed only in the immediate area of the crop seed row. Tillage practices that leave 15 to 30 percent of the soil surface covered with crop residue after planting are considered *reduced tillage systems* (conservation Technology Information Center [CTIC] 1989).

Over the last decade, farmers shifted from intensive to conservation and reduced tillage as they attempted to reduce soil erosion and production costs. In 1983, conservation tillage *acreage* in Illinois amounted *to* 6.6 million acres or 34 *percent* of all cropland (CTIC 1989). In 1989, 8.2 million acres or 37 percent of cropland was farmed with conservation tillage practices (fig. 12). Reduced tillage practices were applied to another 37 percent of planted cropland in 1989. Mulch tillage (chisel plowing and disking) accounted for the largest percentage of conservation and reduced tillage acres. Since 1983, Illinois has led the nation in no-till acreage: more than 1 million acres were farmed without primary tillage. In 1989, nearly 2 million acres (9 percent of all cropland) were managed with no-till (CTIC 1989).

Physical, chemical, and biological properties and characteristics of soils change when production changes from intensive tillage operations that disturb soils to reduced tillage systems. The amount of change depends upon how much tillage is reduced, how much residue is retained on the soil surface, and how long the tillage system is used (Blevins et

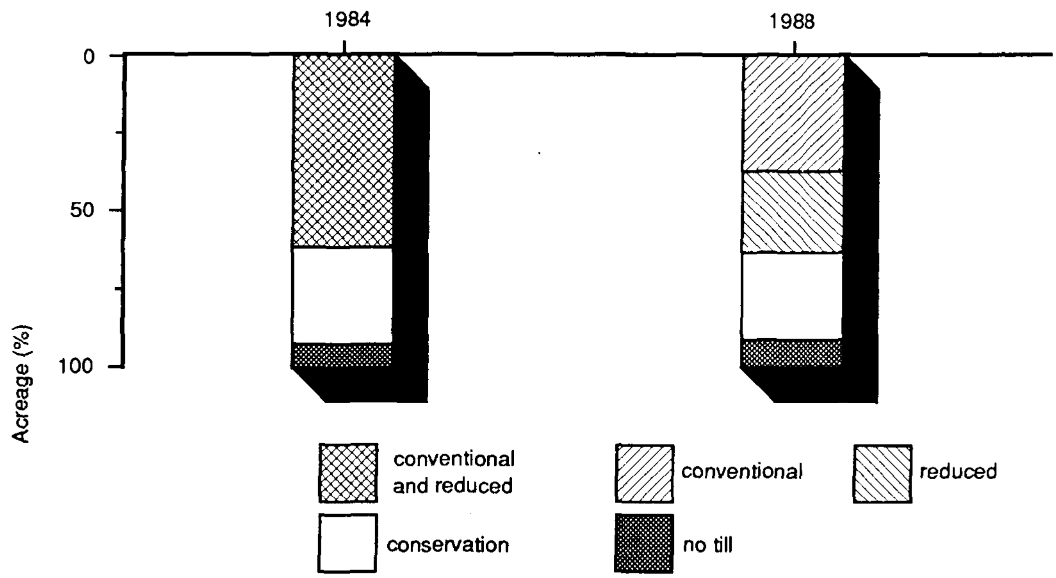

Figure 12 Tillage practices used in Illinois: proportion of total cropland.

al. 1985). Conservation tillage can increase crop residue and organic carbon content near the soil surface, increase water infiltration rate, decrease surface runoff and soil evaporation rates, and thus increase the quantity of water in the soil profile (Wagenet 1987, Koskinen and McWhorter 1986, Baker 1987, Dick and Daniel 1987, Glotfelty 1987, Helling 1987). The most extreme differences in soil properties are observed when no-tillage planting into a sod or cover crop is compared to moldboard plowing with multiple secondary tillage operations. Other primary tillage operations such as chisel plowing or disking are intermediate in tillage intensity and intermediate in how they affect soil properties (Blevins et al. 1985).

Use of pesticides Weed control in moldboard plow, mulch, ridge, and strip tillage may be accomplished with chemical (herbicide) and mechanical (cultivation) methods. Weed seed germination may be reduced significantly when seeds are deeply buried as a result of tillage. Similarly, insect and disease outbreaks can be reduced if crop residue is incorporated into the soil. Controlling weeds in no-till is typically restricted to herbicides. However, if erosion is no concern and conservation compliance is not warranted, mechanical cultivation of no-till is possible, using rolling-basket-type or rotary hoe cultivators (Siemens 1989).

Hinkle (1985) noted that because standard herbicide treatments may be less effective due to interception of the applied herbicide by crop residues on the soil surface, more herbicide may be needed as tillage is reduced. Christensen and Norris (1983) reported an increase in herbicide usage when tillage was switched from moldboard plowing to no-till. Anderson et al. (1989) also noted that for satisfactory weed control in conservation tillage systems, a higher application rate of surface-applied herbicides may be required, especially in fields with considerable weed infestation or crop residue. Estimates for increased herbicide use with reduced tillage range from 15 to 60 percent (Baker and Laflan 1983, Baker et al. 1982, Crosson 1981). However, Fawcett (1987) suggested that reduced tillage has led to changes in the kinds of herbicides applied but not total amounts used. Increased use of knockdown or burndown herbicides on no-till should have minimal impact on groundwater because most compounds used for this purpose are not likely to leach. Whether insecticide use increases with reduced tillage systems is less clear (Wagenet 1987, Wauchope 1987).

Use of nitrogen fertilizer Nitrogen cycling, metabolism, and availability to plants are greatly influenced by amount and type of tillage (Doran 1980a and b). Indications of nitrogen deficiency and/or yield limitations in crops planted with no-till have led several researchers to conclude that more nitrogen is required for untilled than for tilled soils (Bakerman and deWit 1970, Bandel et al. 1975). Blevins et al. (1983) reported that, at low application rates of nitrogen fertilizer, corn yields were greater under conventional tillage than under no-till; but at higher nitrogen rates, no-till produced equal or higher yields.

Reasons for the lower nitrate-nitrogen content of soils managed with reduced tillage include rapid downward movement of nitrate, lower rates of nitrification and mineralization, greater rates of nitrogen immobilization, and more anaerobic conditions that increase losses of nitrate through denitrification (Gamble et al. 1952, Campbell et al. 1976, Dowdell and Cannell 1975). For these reasons, Doran (1980a) indicated that application rates of nitrogen fertilizer for no-till should be greater than those for moldboard plowing. However, split applications of nitrogen fertilizer to soils under reduced tillage can improve efficiency of nitrogen use and often offset the need for higher nitrogen-fertilizer application rates (Anderson et al. 1989).

Injection of anhydrous ammonia is the most prevalent form of nitrogen application in Illinois (Anderson et al. 1989). Siemens and Bicki (1989) noted that pulling an anhydrous applicator through the soil can decrease bulk density and compaction in soils. Similarly, use of an anhydrous applicator to apply nitrogen to no-till soils may effectively disrupt pore continuity and reduce preferential flow.

Soil temperature Near the surface of no-till fields, the temperature of the soil is lower and soil moisture content is higher, at least early in the growing season. Crop residue left on the surface with conservation tillage moderates fluctuations (Unger 1978) and reduces the rate of changes (Gupta et al. 1982) in soil temperature. Pesticide degradation may slow as a result of cooler temperatures in soils managed under reduced tillage, but rates are also affected by microbes and soil moisture content.

Organic carbon As tillage decreases, residue cover and organic carbon content increase at the soil surface. Organic carbon content of the whole soil does not change, but vertical distribution of organic carbon becomes stratified (Hendrick et al. 1988, Blevins et al. 1983, Dick 1983, Mielke et al. 1986, Unger 1989). As tillage intensity increases, residue incorporation and organic carbon content become more uniform.

Because organic carbon is the principal component affecting pesticide adsorption (Wagenet and Rao 1985), changes in amount and distribution of crop residue and organic carbon can affect pesticide adsorption and leaching. In a soil column leaching study, Clay and Koskinen (1989) reported the upper 4 inches of soil managed under no-till retained significantly greater alachlor than the upper 4 inches of soil tilled conventionally. The potential increase in pesticide adsorption in soils with a high organic carbon content at the surface, as a result of conservation tillage, may be offset by increases in infiltration and macropore flow under saturated conditions.

Soil pH Research confirms that soil pH decreases with conservation tillage (Dick 1983, Blevins et al. 1983). Bailey et al. (1985) indicated that large quantities of organic matter in the upper part of soils under conservation tillage, combined with increased biological activity, may produce acidic conditions that require increased lime and adjustments in nitrogen application. As a result, pesticides in the surface horizon of soils under conservation tillage will probably be subjected to a wider range in pH than soils under moldboard plowing.

Biological activity In general, tillage increases microbial populations (Sommers and Biederbeck 1973) but microbial biomass of the surface horizon of no-tilled soil is typically greater than that of tilled soil. Doran (1980a) noted that counts of aerobic microorganisms, facultative anaerobes, and denitrifiers in the surface horizon of no-till soils were 1.14 to 1.58, 1.57, and 7.31 times higher, respectively, than in the surface of moldboard-plowed soil. However, maximum aerobic activity in moldboard-plowed soils extended to greater depth than with no-till. At a depth of 3 to 6 inches, counts of aerobic microorganisms and nitrifiers were 1.23 to 1.77 times higher for no-till soils. He concluded that the biochemical environment of no-till soils is less oxidative than that under moldboard plowing. Degradation of surface-applied, non-incorporated pesticides may accelerate under no-till production because of the increase in microbial activity near the soil surface. However, the more oxidative environment in the moldboard-plowed soil should promote pesticide degradation at greater depth in the soil. Reduced and conservation tillage systems such as mulch, strip, and ridge tillage systems should have pesticide degradation attributes intermediate between no-till and moldboard plowing. Bailey et al. (1985) concluded that overall, pesticide degradation processes should accelerate with conservation tillage systems.

Soil density and porosity Soil density and porosity influence air and water movement in soils, and therefore, potential pesticide and nitrate movement in the soil. Long-term effects of different tillage systems on bulk density and porosity are related to soil type and climatic conditions (Blevins et al. 1985, Benjamin and Cruse 1987).

Soil compaction has been an often-cited concern in conservation tillage, but research results have been contradictory. Many studies have reported greater bulk density and mechanical impedance in the surface horizon under no-till as compared to conventional tillage (Gantzer and Blake 1978, Hill and Cruse 1985, Kladivko et al. 1986, NeSmith et al. 1987, Raines and Bicki 1987, Lal and Van Doren 1989, Roth et al. 1988, Mielke et al. 1986). In contrast, Blevins et al. (1983), Hill and Cruse (1985), and Benjamin and Cruse (1987) reported no difference in bulk density between conventional tillage and no-tillage in Kentucky and Iowa studies. These conflicting data may be partly related to where bulk density samples were obtained relative to wheel traffic.

In general, soil porosity decreases as bulk density increases. Several studies have reported decreased total or air-filled porosity with decreased tillage (Pidgeon and Sloane 1977, Gatzner and Blake 1978, Douglas et al. 1980, and Lindstrom and Onstad 1984). Lindstrom and Onstad (1984) reported that total porosity was lower in no-till than in a moldboard plow system; values were intermediate for chisel plow-disk systems. Van Ouwerkerk and Boone (1970) hypothesized that no-till not only reduces total pore space but also changes pore-size distribution: larger capillary pores disappear and the smaller pores predominate. Hill et al. (1985) found that moldboard-plowed soil had a larger proportion of its total pore volume in large pores (>15µm radii) compared with soils under conservation tillage. Conservation-tilled soil appeared to have a larger portion of pores in the 0.1- to 15-µm pore-radius interval. They implied that moldboard-plowed soils would drain more rapidly than conservation-tilled soils and that conservation-tilled soils would retain more plant-available water than conventionally tilled soil. Mielke et al. (1986) noted that the water-filled pore space in the upper 6 inches of no-till soils was 6 to 28 percent higher than plowed soil.

Infiltration Roth et al. (1988) noted that as residue cover increases, development of surface-sealing crusts is reduced and infiltration is higher. McSweeney et al. (1988) also reported that residue cover provided an effective barrier against early-season surface sealing. Jones et al. (1989), noting that soil crusts reduced infiltration by as much as 50 percent on tilled soils, found crusting did not influence infiltration in no-tilled soil.

Many investigators have reported significantly higher infiltration rates for untilled soils than for tilled soils (Triplett et al. 1968, Ehlers 1975, 1976, Edwards 1982, Edwards et al. 1988, Germann et al. 1984, Edwards and Norton 1985, Bertsch et al. 1988, Golabi et al. 1988, and Edwards et al. 1989) but lower infiltration rates have also been reported (Lindstrom et al. 1981). In Illinois, Raines and Bicki (1987) reported no significant difference in infiltration rate for a well-drained silt loam soil that was managed under moldboard plow, chisel plow, and disk tillage; however, the infiltration rate was significantly lower for no-till than for other tillage treatments. They indicated that the lower infiltration rate for the no-till treatment was due to a significantly higher bulk density, lower total porosity, and lack of earthworm activity in the no-till treatment. Golabi et al. (1988) reported that infiltration rates for soils that were mulch tilled were intermediate between moldboard plow and no-till.

Infiltration in no-till increases, according to Dick and Daniel (1987), because without tillage, continuous channels are not interrupted. Studies of water flow in earthworm channels indicate that infiltration rate is governed by diameter and depth of channels as well as by the number of channels per unit area (Edwards et al. 1979, Edwards et al. 1989). Edwards et al. (1989) noted that water movement in worm holes greater than 5 millimeters in diameter was 13 times greater than their areal distribution would suggest.

Surface-maintained crop residues increase populations of earthworms and other soil invertebrates involved in modifying the soil physical characteristics and nutrient cycling processes (Stinner et al. 1989). Increased earthworm activity has been observed under no-till systems compared to tilled systems (Ehlers 1975, 1976, Boone et al. 1976, Barnes and Ellis 1979, Mackay and Kladivko 1985). Heard et al. (1988) reported little difference in the number of earthworm channels for moldboard plow, chisel plow, ridge-till, and no-till systems at a depth of 4 inches but a significantly greater number of channels at depths of 8 and 12 inches in no-till. Their results suggest that despite a similar number of channels under no-till and other tillage treatments, the channels in no-till were more continuous with depth. Gantzer and Blake (1978) noted that a high level of channel-formation activity in the spring may compensate for destruction of continuous pores by tillage.

Runoff Baker and Laflen (1983) reported that runoff occurring with conservation tillage is generally about 25 percent less than that occurring with the moldboard plow system. They indicated that runoff from a no-till system is usually similar to that from a moldboard plow system and that chisel plowing usually produces less runoff than no-till. However, Edwards et al. (1988) reported the rainfall-runoff record for a small watershed in Ohio managed under long-term continuous no-till corn showed less runoff and significantly higher sustained water infiltration than a comparable, spring-plowed watershed.

The impact conservation tillage has on chemical concentrations in runoff depends upon where the chemical is applied and also on the amount of infiltration and runoff, particularly during the first storm after application, when most soluble losses occur (Baker and Lafien 1983). Increased infiltration and decreased runoff with conservation tillage can also result in a greater amount of pesticide and nitrogen being retained at the target site of application. Ritter et al. (1974) found that atrazine losses from a ridge-till-planted watershed were only 24 percent of those from a conventionally tilled watershed. Glenn and Angle (1987) studied the effect of tillage systems on runoff of atrazine and simazine in the Chesapeake Bay watershed. They reported less runoff of atrazine and simazine from untilled fields than from tilled fields in each year that a major rainfall occurred during the growing season. Baker and Johnson (1978) reported in an Iowa study that alachlor and atrazine losses in sediment and water runoff were less for ridge-till and strip-till systems than for moldboard plowing.

Baker et al. (1978) studied six different tillage systems subjected to large, intense simulated rains shortly after pesticide application and found that conservation tillage was not effective in reducing losses of alachlor or cyanazine. They believed conservation tillage systems were ineffective in reducing pesticide runoff losses because of the interception of herbicides by the crop residue and subsequent washoff. Martin et al. (1978) indicated that 50 to 75 percent of the propachlor, alachlor, atrazine, and cyanazine applied to corn residue washed off with the first centimeter of applied water. If substantial amounts of pesticides are intercepted by residue, little adsorption by soil organic matter will occur. If high intensity rainfall occurs shortly after application, pesticides may be washed from the residue and carried through macropores to considerable depth in the soil.

The effects of tillage practices on nitrogen runoff after application of anhydrous ammonia were examined in western Illinois by Mclsaac et al. (1988). Concentrations of sediment nitrogen in runoff decreased as tillage intensity decreased. Concentrations of aqueous nitrogen in runoff decreased in the order of moldboard plow > no-till > chisel plow > ridge-till. Hill et al. (1989) monitored nitrogen runoff for moldboard plow and no-till treatments under simulated rainfall in Maryland. Greater rates of runoff and sediment loss were reported for the moldboard plow treatment than for no-till but aqueous nitrogen losses were greater in the no-till.

Soil moisture storage Soils managed with no-till typically have higher volumetric moisture content than soils managed with moldboard plowing (Doran 1980b). Mielke et al. (1986) reported that a volumetric water content to a depth of 3 inches was 2 to 11 percent greater in no-tilled than in plowed soils. Bailey et al. (1985) noted that elevated soil-moisture levels may increase mass transfer and diffusion rates of pesticides in the soil.

Saturated hydraulic conductivity (K_{sat}) Preferential flow through macropores occurs under saturated flow conditions or when free water is present (White 1985). Beven and Germann (1982) suggest that rainfall rates between 1 and 10 millimeters per hour may be sufficient to initiate macropore flow; the exact rate depends primarily upon the saturated hydraulic conductivity of the peds that make up the soil matrix.

Research results on the effect of tillage on K_{sat} are varied. Blevins et al. (1983) reported no significant difference in K_{sat} for soil managed under no-till and moldboard plowing. Heard et al. (1988) reported no significant difference in K_{sat} for a prairie soil managed under moldboard plow, chisel plow, ridge-till, and no-till; but K_{sat} for a forest soil was significantly higher for the moldboard-plowed soils as compared with other tillage treatments. Mielke et al. (1986) reported higher K_{sat} at depths of 0 to 3 and 3 to 6 millimeters for tilled than for no-tilled soils. Klute (1982) reported that where reduced tillage created an increase in bulk density, K_{sat} might decrease by two- to more than five-fold. The K_{sat} of non-tilled soils can be significantly affected by macropores formed by earthworms, soil insects, or roots, but these macropores are often destroyed in tilled soils.

Leaching Although tillage practices may significantly affect soil properties that control leaching of pesticides and nitrates (fig. 13), the cumulative effect on leaching is not certain, and research results have been contradictory. Increased infiltration and permeability in soils managed under conservation tillage may increase the potential for agricultural chemicals to leach into groundwater (Gebhardt et al. 1985, Donigan and Carsel 1987). Baker et al. (1987) concluded that environmental effects of moldboard plowing and no tillage differ; however, the effects of intermediate forms of tillage (about 85 percent of conservation tillage acreage, [CTIC 1989]) more resemble moldboard plowing with regard to pesticide and nitrate behavior.

Several monitoring studies have indicated greater leaching of pesticides and nitrogen fertilizer in soils managed with no-till than in soils under conventional tillage, but exceptions have been reported. Tile drainage monitoring in Ohio recorded higher concentrations of atrazine and dicamba in water from no-till plots than from moldboard-plowed plots (Schwab et al. 1973). Gold and Loudon (1982) reported atrazine concentrations ranging from 20 to 170 ppb in tile drainage water from a storm 4 days after planting. Of the 1.4 kg/ha applied at planting, 1 .0 and 2.2 percent was lost in tile flow from conventional and conservation tillage, respectively. In Kentucky, McMahon and Thomas (1976) found that leaching of chloride and nitrate was greater in a soil that was no-till planted into sod than in the soil when moldboard plowed. Hall et al. (1989) monitored the leaching of atrazine, simazine, cyanazine, and metolachlor by analyzing soil fractions and pan lysimeter percolates collected from a depth of 4 feet in soil managed under moldboard plow and no-tillage. They noted that maximum concentrations detected and mean total amounts were greater under no-till than under moldboard plow treatments. In 1985, mean areal losses were 3.4 percent (simazine, atrazine) and 1.6 percent (cyanazine, metolachlor) under no-till. Respective losses from the moldboard-plow treatment ranged from 0.4 to 1.0 percent.

In Illinois, Bicki and Guo (1989) reported no significant difference in leaching of a tracer, potassium bromide (KBr), in a silt loam soil managed under moldboard plow, chisel, disk, para-till, and no-till systems at low simulated-rainfall rates. Under high simulated-rainfall rates, significantly greater leaching of KBr was found in the soil that was no-tilled. They concluded that adoption of conservation tillage systems such as chisel plowing, disking, and para-tilling would not have any more adverse effects on groundwater quality than moldboard plowing. Disruption of pore continuity was thought to be the key factor in restricting KBr movement.

Property/process	Reduced	Conservation*	No Till
Use of insecticides	◒	◒/●	●
Use of herbicides	◒	◒/●	●
Use of nitrogen fertilizers	◒	◒/●	●
Soil temperature			
Surface	◒	◒/○	○
Rate of change	◒	◒/○	○
Organic carbon			
Surface	◒	◒/●	●
At depth	◒	◒/○	○
Soil pH	◒	◒/○	○
Microbial activity			
Surface	◒	◒/●	●
At depth	◒	◒/○	○
Invertebrate activity	◒	◒/●	●
Soil density and porosity			
Surface	◒	◒/●	●
At depth	◒	◒/●	◒/●
Infiltration	◒	○	◒/●
Runoff			
Sediment	◒	○	○
Water	◒	○	◒/○
Soil moisture storage and retention	◒	◒/●	●
Saturated hydraulic conductivity	◒	◒	◒
Leaching	◒	◒/●	◒/●

○ decrease
◒ no change
● increase

*Conservation tillage systems other than no-till.

Figure 13 Effects of reduced, conservation, and no-till systems on soil properties and processes compared to the effects of the moldboard-plow system.

White (1985) noted that the effect of macropores on nitrate and pesticide leaching is complex not only because of uncertainty about the relative contribution of different pathways to water flow but also because of variations in nitrate and pesticide concentrations over short distances. Thomas and Phillips (1979) and Wagenet (1987) suggest that if pesticides and nitrates are held within soil aggregates, they may be protected from leaching when macropore flow occurs because the water flowing in macropores does not interact with the soil matrix. Barraclough et al. (1983) observed that if nitrate fertilizer was recently applied to the soil, or if soil-generated nitrate was held on the surface of aggregates, then macropore flow would cause it to leach faster than uniform flow through the soil.

Leaching of atrazine, alachlor, and cyanazine to groundwater in fine-textured, well-structured soils managed under no-till has been reported (Gish et al. 1988, Helling et al. 1988, Isensee et al. 1988). The authors suggested that leaching was due to macropore flow resulting from rain shortly after application. Hall et al. (1989) also implicated rainfall occurring shortly after application as a factor contributing to pesticide leaching. Atrazine applied to a well-drained sandy soil under irrigated, no-till management was detected at a depth of 6 to 9 inches in the soil, 1 week after application (Kazemi and Anderson 1989). Working with large undisturbed soil monoliths, Shipitalo et al. (1989) reported that low-intensity, simulated rainfall (0.2 inches) applied 2 days prior to a high-intensity event (1.2 inches) reduced bromide and atrazine transport to 14 and 50 percent, respectively, of that which occurred when only 1.2 inches of rainfall was applied. They concluded that the small rainfall moved solutes into the soil matrix, thereby reducing the potential for transport during larger rainfall events that occurred afterward.

Different tillage systems produce no significant differences in leaching of agricultural chemicals, according to several recent studies. A 5-year tile-drainage monitoring study in Minnesota revealed no significant difference in nitrate concentration of drainage water from moldboard plow and no-till treatments (Randall et al. 1988). In Illinois, Bicki and Felsot (1988) reported no significant difference in leaching of alachlor and cyanazine to groundwater in an irrigated, well-drained sandy soil managed with either no-till or chisel plowing. Czapar et al. (1989) monitored alachlor, cyanazine, bromide, and rhodamine in tile drainage water in plots managed under no-till and rotary tillage. In the first year of the study, herbicides and bromide were more frequently detected in tile drainage water from tilled plots than from untilled plots. However, results of this study may not be extrapolated to a system that has been in production for several years and has well-developed macropores. Also Fawcett (1989) indicated that soil morphological differences between the tillage plots may have, in part, influenced pesticide and bromide leaching more than did the tillage practices.

Recommendations Selection and use of tillage practices or systems should take into account not only production costs, yield, and erosion control, but also the potential impact of tillage practices on surface- and groundwater quality.

- For soils with shallow depth to an aquifer and low erosion potential, select tillage systems that rely more on mechanical cultivation and less on herbicides for weed control.

- Limit use of tillage systems, such as no-till, that rely solely on herbicides for weed control to highly erodible land or to soils where the aquifer is at considerable depth.

- Use tillage systems, such as chisel plowing and disking, that reduce runoff and retain pesticides and fertilizer at the target site of application.

- Use conservation or reduced tillage systems to promote organic carbon retention in the surface horizon and increased microbial populations.

- Avoid long-term use of no-tillage systems that enhance macropore development, pore continuity, and preferential flow in areas with vulnerable aquifers. On erodible land, rotate tillage systems that vary in intensity, such as alternating reduced and no-till systems. Leaching has been greater in soils managed under no-till than in soils that have been moldboard plowed wherever the no-till system has been maintained continuously for several years. Management systems that utilize more than one conservation tillage system may reduce the development of macropores and preferential flow found in long-term no-till systems. A tillage program that includes chisel plowing or disking of corn residue in one year followed by no-till planting in the subsequent year may be a viable conservation tillage system in Illinois (Anderson et al. 1989). Dickerson (1989) estimated that perhaps less than 40 percent of Illinois farmers who currently use a no-till production system, use that system exclusively for several years.

- Develop, evaluate, and use tillage systems that leave the soil surface and crop residue relatively undisturbed, yet disrupt subsurface pore continuity.

Crop Rotation

Crop rotation is an agronomic practice in which a planned sequence of crops is grown on a given plot over 1 to 6 years. It can incorporate double cropping (wheat and soybeans) or cover cropping practices. Crop rotation practices increase crop yield (Nafziger 1989, Crookston and Kurle 1989, Peterson and Varvel 1989a and b), overall yield per acre (when combined with double cropping), soil tilth and structure (Fahad et al. 1982), soil fertility, erosion control, and pest and disease control.

In Illinois, crop sequences range from continuous soybeans or corn, to corn-soybean rotations, to multiple-year combinations of corn, soybeans, small grains (wheat, oats), and meadow planted to a legume and/or grass (table 5). In general, hay and grass meadows are only grown in areas of livestock production. Some variation of a corn and soybean rotation is the most widely used sequence (Nafziger 1989). In 1988, 39 percent of the total 26 million acres of cropland was planted to corn; 26 percent of this acreage follwed corn and 66 percent followed soybeans (Pike et al. 1989).

Table 5 Common crop rotation sequences in Illinois (Scott, 1989)

Continuous soybean
Corn-soybean
Corn-corn-soybean
Continuous corn
Corn-corn-soybean-small grain
Corn-soybean-small grain
Corn-soybean-small grain-meadow
Corn-corn-soybean-small grain-meadow-meadow
Corn-soybean-small grain-meadow-meadow-meadow
Corn-small grain-meadow

Use of pesticides The potential for soil insect problems in corn after soybeans is generally low, and the use of soil-applied insecticides is not recommended (Steffey and Gray 1989). In 1988, however, 14 percent of acres planted to corn after soybeans received insecticide applications (Pike et al. 1989). Seed treatments with insecticides are commonly recommended for corn after grass sod, corn after sorghum, corn after small grain, and corn after clover or alfalfa. The potential for rootworm damage is moderate to severe whenever corn follows corn, necessitating the use of soil-applied insecticides when economic thresholds are exceeded.

Usually herbicide applications are the same whether corn or soybeans are grown continuously or in rotation (Pike et al. 1989). Herbicides are rarely applied to small grains or hay crops. Some cover crops may produce a herbicidal (allelopathic) effect on weeds the next spring, so herbicide applications may be reduced (Weston 1989, Curran 1989). However, the use of cover crops for their allelopathic effects is not yet common in Illinois.

Use of nitrogen fertilizer Crop rotations generally result in decreased use of nitrogen fertilizer. This reduction is due to both the reduced nitrogen requirement of crops other than corn and wheat, and the fixation of gaseous nitrogen by legumes. The recommended rates for application of nitrogen fertilizer in a crop rotation sequence depends upon the productivity of the soil and the specific cropping sequence (Anderson et al. 1987).

Continuous corn requires approximately 1.22 to 1.32 pounds of nitrogen per bushel. Recommended application rates for wheat are 50 to 110 pounds of nitrogen per acre. Corn or wheat planted after soybeans or other legumes will require less nitrogen fertilizer (table 6). Legumes provide a nitrogen credit to the soil as a result of nitrogen fixation; the amount of nitrogen produced depends upon the type of legume and the number of years since legumes were grown.

Soybean yields have not shown a significant response to applications of nitrogen fertilizer, so none are recommended (Anderson et al. 1987). As legumes do not benefit from nitrogen fertilizer, applications to legume-grass mixtures with more than 30 percent legumes are not recommended (Anderson et al. 1987).

Table 6 Factors resulting in reduced nitrogen requirement (from Anderson et al. 1987)

Crop to be grown	After soybeans	1st year after alfalfa or clover plants/sq ft			2nd year after alfalfa or clover plants/sq ft	
		5	2-4	<2	5	< 5
	nitrogen reduction, lb/acre					
Corn	40	100	50	0	30	0
Wheat	10	30	10	0	0	0

Effects on soll properties and processes No significant changes in soil properties occur with a rotation of only corn and soybeans, other than a nitrogen surplus after soybeans (Fahad et al. 1982, Anderson et al. 1987). With a rotation that includes 1 or more years of legumes and/or grasses, however, some properties such as soil structure show changes. Root characteristics of legumes and grasses, which include increased root density and depth, improve soil aggregation and tilth (Sumner 1982, Abdou et al. 1967). The effect is more noticeable when 2 or more consecutive years of forage are included in the sequence. The changes in tilth and structure result in a decrease in bulk density and increases in infiltration capacity, organic matter, and microbial activity. Increases in microbial activity and organic matter indicate a possible increase in biodegradation and adsorption.

In corn-soybean rotations, which produce few changes in soil properties, little change can be expected in surficial processes that affect the fate of nitrogen fertilizer and pesticides. In rotations that include 1 or more years of meadow, the increased soil structure and infiltration capacity of the soil will tend to decrease runoff and erosion, with a resulting increase in cumulative infiltration. In rotation sequences that include double cropping or a cover crop, the total duration of crop cover and growth increases, and an increase in transpiration and associated decrease in evaporation can be expected.

Any increase in infiltration may increase the potential for recharge, and thus the potential for leaching of pesticides. With any reduction in nitrogen fertilizer applications, a net long-term decrease in leaching of nitrates can be expected. Because insecticides are generally not used in rotations, a net long-term decrease in leaching of insecticides can be expected. Similarly, for crop rotations that include a small grain or meadow, less herbicide can be applied for a net long-term reduction in herbicide leaching.

Recommendations The use of crop rotations can significantly reduce leaching of pesticides and nitrates.

- Do not apply corn rootworm insecticides to corn in rotation unless the infestation problem exceeds the economic threshold.

- Rotate crops to increase yields and reduce fertilizer and pesticide application rates, particularly in areas where aquifers are near ground surface.

- Reduce nitrogen fertilizer application rates to account for nitrogen fixation by legumes in a rotation.

Cover Crops

Close-growing grasses, legumes, or small grains are used to cover the soil during part or all of the year. Cover crops are primarily used to control wind and water erosion in the winter and early spring, and to improve soil properties. Cover crops may increase soil organic matter content, infiltration capacity, and tilth; decrease soil bulk density; reduce evaporation losses; and reduce nitrogen leaching in the winter and early spring (Zhu et al. 1989, Worsham 1989). Rye and wheat are common winter cover crops. Rye is the most widely planted because of low seeding costs, vigorous growth in early spring, ease of control with herbicides, and allelopathic effects (Worsham 1989).

The allelopathic (herbicidal) effect of some cover crops on weeds may allow for reduced herbicide application rates for the following crop. Rye and wheat have been found to have allelopathic effects on giant foxtail and velvetleaf. Some legumes have also been found to have allelopathic effects on certain weeds. In addition to allelopathic effects, cover crops suppress weeds by shading. More research is needed regarding the specific effects of different cover crops on various weed populations (Worsham 1989).

Most herbicides commonly used to kill cover crops readily adsorb onto soils, so their use should not result in significant leaching. However, some triazine herbicides that are occasionally used to kill legumes have a high leaching potential.

In addition to the benefits provided by non-legume cover crops, legumes add nitrogen to the soil through nitrogen fixation. However, the seeding costs of legumes are higher than those of rye or wheat, and legumes must be seeded earlier in the fall to establish the crop and maximize nitrogen fixation. While some legumes are not winter hardy, they are generally more difficult to kill with herbicides or plowing. Some hard-seeded legumes may not germinate until the spring after seeding, which might reduce yields of spring-seeded crops, especially small grains. Deep-rooted legumes also may deplete soil moisture more than non-legume cover crops and limit early season growth of the next crop. To receive the maximum benefit of nitrogen-fixing by legumes, planting of the next crop may have to be delayed, and this delay could drastically reduce yields (Worsham, 1989).

Climatic differences between northern and southern Illinois affect the use of cover crops. In northern Illinois, the corn harvest is usually completed in mid-October (Reynolds 1987), yet the rye cover crop should be planted by mid-September (Soil Conservation Service 1977); thus a rye cover crop following corn would have to be aerially seeded. Soybeans are normally harvested by mid-September in northern Illinois, making conventional seeding of rye feasible. In the southern part of the state, farmers have more flexibility in the use of cover crops. Hairy vetch is a legume that may be suitable as a cover crop in southern Illinois

(Smith et al. 1987). Winter oats have been used as a cover crop in the southern third or quarter of the state (Anderson et al. 1987); however, oats are not winter hardy and are killed in most winters (Pike 1989).

Cover crops remove soluble nutrients such as nitrates from the soil and reduce the amount available for leaching in the winter and spring. When the cover crop is killed, these nutrients are mineralized and become available to the next crop. When a legume cover crop is incorporated, more nitrogen may be initially available than when the cover crop is killed by a herbicide and left on the soil surface. In the next year, approximately the same amount of nitrogen would be available to the crop (Sarrantonio and Scott 1988, Varco et al. 1989).

The net effect of cover crops on leaching of agricultural chemicals is not known. While application rates of nitrogen fertilizer and herbicides may be reduced, increased infiltration capacity and reduced runoff may increase cumulative infiltration and recharge. In addition, evaporation from the soil surface may be reduced if the cover crop is not incorporated (Sarrantonio and Scott 1988). However, cover crops may lower the water content of the soil in spring (Gercu et al. 1988). The net effect on water movement, however, will be dependent upon timing and intensity of precipitation, water-use characteristics of the plant, and the water-holding characteristics of the soil. Increases in organic matter may increase adsorption of pesticides and consequently decrease leaching.

Recommendations Although the net effect of cover crops on leaching of agricultural chemicals has not been extensively studied, cover cropping could be an effective management practice to reduce leaching. Development of specific recommendations for using cover crops in various areas of the state and for evaluating effects on leaching should be a priority for future research.

- Use cover crops to improve soil physical properties and to reduce the potential for nitrogen leaching in winter and early spring.

- Reduce nitrogen fertilizer application rates according to the nitrogen credit from the cover crop.

- Reduce herbicide application rates if the cover crop has an allelopathic effect on weeds.

Tile Drainage

Approximately one-third of all farm land in Illinois has subsurface drainage to lower the water table. Of this land, approximately 50 percent is drained with systematic tile layouts (Konyha 1989), including the herringbone, parallel, and double main patterns designed to lower a water table over an entire field (fig. 14) (Anderson et al. 1987). The other 50 percent of drained land is underlain with random tile layouts that lower the water table in limited areas, such as under a natural waterway or an isolated depression (Konyha 1989, Anderson et al. 1987).

Lowering the water table provides several benefits (Bagley 1976, Anderson et al. 1987):
- more land available for production,
- improved seed germination and plant growth due to more rapid increases in soil aeration and temperature in the spring,
- more timely application of pesticides,
- higher yields due to more rapid drying of the soil and the longer growing season,
- improved soil tilth,
- reduced runoff and soil erosion due to increased infiltration.

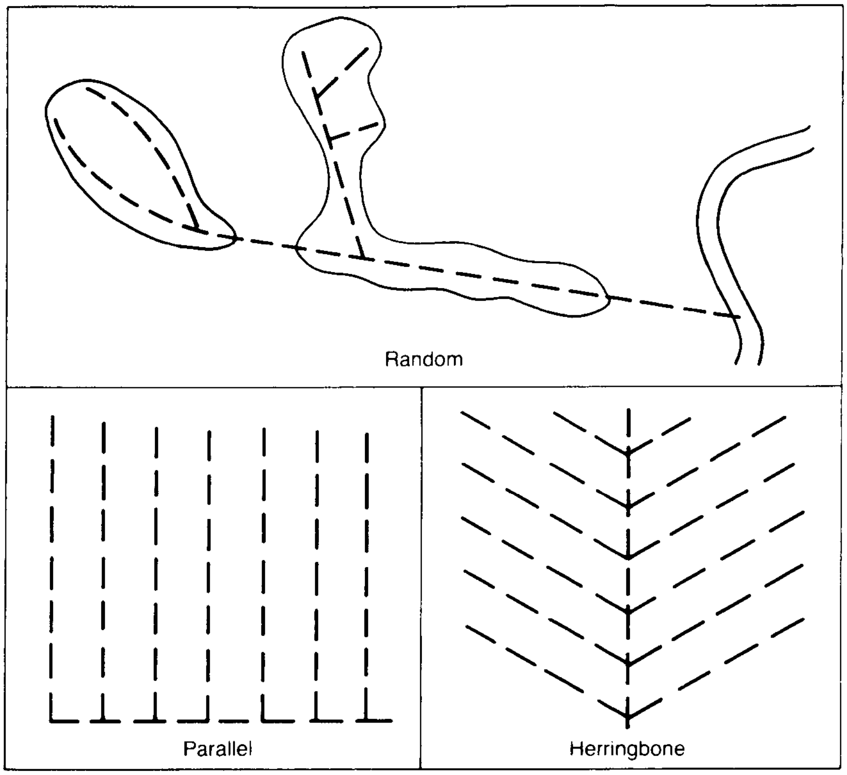

Figure 14 Typical random and systematic tile-drainage system layouts.

Soil properties and processes Rapid lowering of the water table has been reported to increase soil aggregate stability by allowing normal wetting and drying of the soil and the subsequent shrinking and swelling of clays (Anderson et al. 1987, Bagley 1976). Other research indicates, however, that increases in soil aggregate stability due to drainage may not be statistically significant (Black et al. 1976). Increases in crop rooting depth due to a lowered water table will increase the density and depth of macropore distribution in the soil. Increases in aerobic microbial activity can be expected with an increase in soil aeration accompanying a rapid decrease in soil moisture (Anderson et al. 1987). The increase in aeration will favor nitrification in soils.

Drainage changes the soil environment in other ways that affect the fate of water and agricultural chemicals. An increase in infiltration capacity will reduce runoff and erosion and contribute to greater cumulative infiltration. Rapid decreases in soil moisture reduce losses to evaporation; however, a thicker unsaturated zone provides favorable conditions for volatilization of pesticides (Letey and Farmer 1974). Increased volatilization will reduce pesticide concentrations in the soil, thus reducing the amount available for leaching. Pesticide degradation is also favored by drier, warmer soil conditions and increased microbial activity.

Transpiration demands are likely to increase in drained soils due to more favorable conditions for plant growth. Increased root development and transpiration rates will create larger soil-water tension gradients toward the plant roots in drained soils than in undrained soils (Letey and Farmer 1974, Hillel 1980). These gradients cause the movement of soil water and associated dissolved constituents toward the plant roots. The increased infiltration capacity of the soil may increase recharge in the spring and fall when evapotranspiration is low (Baker et al. 1975).

Leachlng of pesticides and nitrates Several studies in Minnesota, Iowa, and Illinois have identified nitrates and pesticides in drainage tile effluent (Baker et al. 1975, Baker and Johnson 1976, Randall et al. 1986, Hallberg et al. 1986, Gold and Louden 1982, Krawchuk and Webster 1987, Patni et al. 1987, McKenna et al. 1989b). Baker and Johnson (1976) evaluated the impact of soil drainage practices on soil properties and processes; the other studies were designed simply to monitor for specific compounds in drainage tile effluent.

In undrained soils, the water table seasonally rises and remains near ground surface for extended periods of time. In drained soils, the water table rises but quickly drops due to the drains and does not remain near ground surface long enough to affect plant rooting. During wet spring and fall seasons, tile drainage can cause significant increases in downward water flow to the drains. In undrained soils, when the water table is higher and the soil moisture content is correspondingly higher, smaller amounts of precipitation are generally required to recharge the water table. Accordingly, dissolved chemicals are more likely to leach to the shallow water table of undrained soils. However, because the downward flux of water away from the water table is much smaller in undrained soils, drainage is more likely to increase the total downward movement of dissolved chemicals to the tile drains.

This conclusion is supported by Baker and Johnson (1976) who suggested that drainage increases the potential for leaching of nitrates through soils. In drained soils, conditions are generally more favorable for nitrification because they are better aerated than undrained soils in the spring and fall. Accordingly, the quantity of nitrates produced by nitrification in drained soils may be larger than in undrained soils. The larger availability of nitrates suggests that drainage significantly increases the potential for leaching of nitrates to the drains.

Most pesticides have a tendency to adsorb and desorb to soil organic matter and clay particles. The sorption process is commonly considered to be a rapid, equilibrium reaction, where the concentration of pesticides adsorbed/desorbed is a function of the adsorption coefficient and the dissolved pesticide concentration. If water is moving rapidly through preferential pathways in the soil, incomplete mixing between the soil constituents and soil solution may prevent the chemical equilibrium conditions from being reached. This could result in less adsorption and higher dissolved pesticide concentrations in soil water and groundwater. Because drained soils have a significantly increased downward water flux, and under matrix flow conditions pesticide dissolution will occur as a function of concentration, drainage is expected to increase the net leaching of pesticides to the drains.

Effects on water quality Although drainage practices may increase the potential for leaching of pesticides and nitrates to the water table, tile drainage probably reduces agricultural chemicals contamination of aquifers since they remove much of the shallow groundwater from the saturated zone when the water table is above the drain depth (fig. 15). Tile effluent discharges into surface water bodies. Consequently, tile drainage may increase loadings of pesticides and nitrates in areas where previously agricultural chemical loadings into streams due to surface water runoff had been low. However, by decreasing runoff, tile drainage may decrease pesticide/nitrate loading into surface water in areas where previously runoff had contributed to high loadings.

Systematic drainage layouts can be expected to remove much more shallow groundwater than random drainage systems, however, actual flow characteristics depend upon the specific conditions at each field. Differences in the properties of shallow geologic materials below drainage systems will produce highly variable patterns in shallow groundwater flow when the water table is above the drains. The presence of a relatively impermeable material at depth below the drains will tend to direct more shallow groundwater flow to the drains. A continuous deposit of more highly permeable material at depth below the drains will tend to

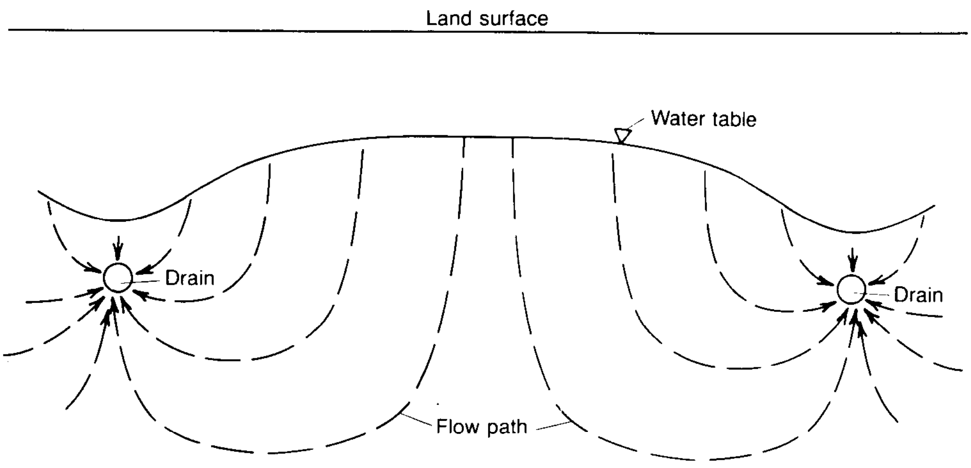

Figure 15 Shallow groundwater flow toward tile drains.

direct more shallow groundwater downward, past the influence of the drains. The tendency for downward flow of shallow groundwater will occur around the midpoint between drains in a systematic layout, or with increasing distance from the drains in a random layout.

When the water table is below the drains, water and associated dissolved compounds in downward moving wetting fronts will generally not flow into the drains, and the drains will not impose any control on this water movement.

Land-Shaping Practices

Terraces, diversions, and waterways are constructed to control erosion; land may be leveled to improve surface drainage. Alterations in the topography of the land affect the direction, distribution, and velocity of water flowing across land surface.

Earth-moving practices may remove part or all of the topsoil, which has the highest organic carbon content, and thus reduce the capacity of soils to adsorb pesticides. Topsoil removal also reduces soil productivity by altering tilth, moisture availability, and cation exchange capacity. Consequently crop yields and plant uptake of nitrogen are likely to decrease. If applications are not adjusted for the lower productivity in areas where the topsoil has been removed, more nitrates may be available for leaching. In addition, if earth moving exposes more permeable materials, the rate and amount of water moving through the soil may increase. Whether topsoil removal will increase leaching depends upon site characteristics, particularly on the degree of soil development and the properties of both the removed soil and the exposed materials (Edwardson et al. 1988, Sewell 1970, Quackenbush 1967).

Land leveling Surface-water drainage can be improved by creating a slight, uniform grade across a field. Primarily used in southern Illinois, land leveling is either used alone or with field ditches to provide land drainage to fields with low-permeability subsoils. As the soils in these areas generally have thin surface horizons containing little organic matter, land leveling that removes the existing surface layer also reduces the capacity of the soil to adsorb pesticides. However, this effect may be offset by the removal of ponded water that would normally infiltrate the soil.

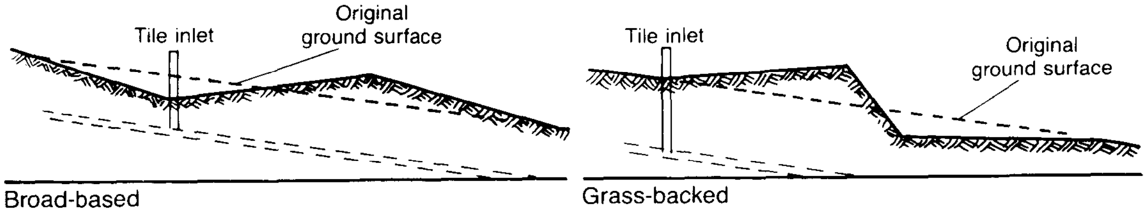

Figure 16 Construction of broad-based and grass-backed terraces.

Terraces Consisting of a channel and an earthen embankment roughly parallel to the contour of the land, a terrace reduces erosion by reducing slope length and controlling the path of surface runoff. Level terraces retain surface water, allowing it to infiltrate the soil. Other types of terraces direct runoff water along the terrace channel to a discharge point. This point may be a grass waterway, or more commonly in Illinois, a tile inlet located in a low area of the terrace channel. Whether the runoff discharges to a grass waterway or tile line, the final discharge point is a stream or other surface-water body.

Research on level terraces in Iowa indicate that infiltrating water carries nitrates and other nutrients to groundwater (Saxton et al. 1971, Burwell et al. 1976). The tile-outlet terraces commonly used in Illinois remove a portion of runoff water, however, a significant volume of water may infiltrate the soil near the tile inlet and recharge groundwater. Infiltration of runoff water ponded around the tile inlet can reduce water yields at the tile outlet by at least 30 percent (Hanway and Laflen 1985). The increased volume of infiltrating water in the terrace channel increases the potential for leaching of agricultural chemicals. However, a modeling study using computer simulations (Steenhuis 1979) predicted only slight increases in leaching of pesticides over an entire field where corn was planted on the contour with terraces compared to corn planted in straight rows without terraces.

Also, adsorption of pesticides may decrease if topsoil has been excavated from the terrace channel during construction. Whether or not topsoil is removed from the terrace channel depends partly on the type of terrace. In building some terraces, particularly broad-based terraces, soil is excavated from the channel and moved downhill to form the ridge (American Society of Agricultural Engineers 1980). With narrow-based or grass-backed terraces, soil is moved uphill to build the terrace ridge (fig. 16). Construction of narrow-based and grass-backed terraces leaves the original soil intact in the channel, except where corrections are made for channel grade.

Runoff may transport pesticides and nitrogen compounds, either in solution or adsorbed to eroded sediments (Wischmeier and Smith 1978). Where runoff encounters ponded water in the terrace channel near tile inlets, sediments accumulate (Laflen et al. 1978; Laflen et al. 1972; Foster et al. 1985). Despite the increased loading of agricultural chemicals to the soil, the accumulated sediments may provide some resistance to leaching by reducing infiltration and adsorbing pesticides. The effect of accumulated sediments would be temporary, however, because sediments excavated from the terrace channel are commonly spread onto the slope to preserve the capacity of the terrace to store runoff.

Diversions A channel and ridge constructed across a slope routes or diverts runoff water from one area to another. Channels may be vegetated. Diversions provide a direct conduit for runoff water to a discharge point—a pond, grass waterway, ditch, or stream. Thus they prevent water from flowing directly to low ground or from entering a highly erodible area. Water quality may be affected by diversions, which can be used to prevent

- runoff from flowing through a field or feedlot where it would pick up and transport agricultural chemicals and other contaminants to surface- or groundwater (SCS 1987);
- additional inflow of runoff water to a field or feedlot so that leaching of agricultural chemicals and other contaminants would not increase in that area;
- surface runoff from a cultivated field from transporting chemicals, either in solution or absorbed to sediments, into another area where they could leach into groundwater.

Vegetated diversions could affect the quality of water moving through them, just as grass waterways do (see below). Commonly, diversions redirect runoff water to a location where it will have the least impact on soil and on surface- and groundwater quality.

Sediment basins These short earthen embankments built across the face of slopes, particularly across minor water courses, are usually drained by a surface inlet to a tile line. Sediment basins are similar to terraces but not usually as linearly extensive. They are usually installed on terrain too irregular or dissected to terrace (Mielke 1985). The effect of sediment control basins on leaching of agricultural chemicals would be similar to the effect of terraces (Schepers et al. 1985).

Grass waterways Vegetation in a graded channel or watercourse allows water to move through the channel without eroding it. Grass waterways have been shown to remove 2,4-D from runoff from field plots (Asmussen 1977). The reduction in pesticide concentrations was attributed primarily to attachment-adsorption on vegetation and organic matter; more readily sorbed pesticides would be removed more efficiently.

Recommendations In most cases, erosion control practices such as terraces will reduce movement of agricultural chemicals to surface water. However, the potential for increased leaching should be considered in areas where aquifers are particularly vulnerable.

- Maintain the original topsoil in the terrace or diversion channel during construction by moving soil up the slope to form the ridge.

- Where cutting (removal of soil in the channel) is necessary to maintain an adequate grade toward the tile inlet, stockpile and replace the topsoil in the channel.

- Use erosion-control practices, such as crop rotations that include a meadow or small grain, in areas where aquifers are close to the surface.

Vegetation Practices

Filter strips Although they do not prevent erosion, filter strips are designed to protect surface-water quality by removing sediments, debris, and chemicals from surface runoff. Filter strips are most effective if they are placed to intercept runoff occurring as sheet flow (Dillaha et al. 1988, Dillaha 1989). Where they intercept runoff as channelized flow, they are less efficient but not totally ineffective for removing sediments, adsorbed pesticides, and pesticides in solution.

Filter strips have also been used for treatment of livestock waste (Nye and Jones 1980). Nitrates and other nutrients in effluent passing through filter strips are removed by the same mechanisms that affect pesticides in runoff. Contaminants are retained in filter strips by the deposition of sediments, infiltration of runoff, and filtration of large solids as well as by soil adsorption and plant uptake of chemicals. The effectiveness of these mechanisms varies according to site characteristics and chemical properties of a pesticide. Where tile drainage underlies filter strips, the reduction of nitrates in surface runoff entering filter strips has been associated with an increase in nitrates in the drainage water (Fausey et al. 1988, Edwards et al. 1986). Without tile drainage, a portion of the soluble constituents in runoff water entering filter strips may be leached to groundwater. Thus a vegetation filter strip functions as a sink for surface-water contaminants but a potential source of groundwater contaminants.

If properly sited and maintained, filter strips contribute to improving surface-water quality (Dillaha 1989). Any negative impact on groundwater is limited by location: filter strips are usually located near surface water, and in Illinois near-surface groundwater flow paths tend to discharge into surface water bodies. Thus contaminants entering groundwater below filterstrips may eventually discharge into surface water.

Critical area plantings Highly erodible areas may be removed from production and converted to grass or sod, requiring little or no pesticide treatment. Indirectly, this practice contributes to maintaining groundwater quality.

Field borders The edge of a field may be planted with perennial vegetation or converted from trees to herbaceous vegetation or shrubs. Taking land out of production for field borders, which require little or no pesticide treatment, contributes to maintaining groundwater quality. Grass and legumes are more effective than shrubs, however, when functioning as filterstrips (Dillaha 1989).

Conservation Reserve Program (CRP) and set-aside programs These federal programs encourage farmers to remove cropland from production. The CRP is limited to highly erodible cropland. Planting cover crops reduces use of nitrogen fertilizer and pesticides. According to a survey of Illinois farmers (Pike 1989), less than one tenth of 1 percent of set-aside acreage in Illinois received herbicide treatment; 85 percent of the farmers mowed to control weeds at an average of two mowings per field.

Other Erosion-Control Practices

Contouring This practice is a cost-effective alternative to terracing on fields with moderate slopes. For contouring, a 1- to 2-percent slope should be no more than 400 feet long; a 3- to 5-percent slope should be no more than 300 feet long; and a 6- to 8-percent slope should be no more than 200 feet long (SCS 1985). Maximum slope length can be doubled when contouring is used with strip cropping (Wischmeier and Smith 1978). Where slopes exceed these limits, farmers can use terraces or diversions to shorten the slope length.

Contouring increases infiltration of water into the soil. Richardson (1973) found that surface runoff from a contoured, graded-furrow watershed was significantly less than runoff from a tile-outlet terraced watershed; soil losses were comparable. Less runoff from the contoured watershed than from the terraced watershed was attributed to a more uniform distribution of excess water. Reductions in runoff imply greater infiltration of water and increased potential for leaching of agricultural chemicals. Although contouring produces more infiltration than terraces, contouring does not concentrate chemicals and infiltration in the terrace channel.

Strlp cropping In Illinois, strip cropping is usually used with contouring to reduce erosion. A common strip-cropping system is alternate strips-90 to 150 feet wide—of corn and a hay crop such as alfalfa. Consequently, strip cropping is only practical where cattle or sheep are raised or where a market for hay is available. In such a system, most erosion would occur on the corn strip. The rate of water flowing through the hay strip would decrease, resulting in deposition of agricultural chemicals in solution and adsorbed to sediment.

Ponds

Ponds are created either by excavating earth material and allowing the hole to fill with surface- or groundwater, or by blocking a water course so that surface runoff collects behind an earthen embankment or other barrier. Constructing an embankment pond may include removing earth upgradient, both to provide construction material and to increase the volume or depth of the pond. Because they are located in a water course, embankment ponds are usually a sink for pesticides and nitrogen compounds carried in surface runoff.

Embankment ponds also may be areas of increased groundwater recharge. If the water level in the pond is above the local water table, the pond will recharge groundwater. The accumulation of agricultural chemicals and increased recharge in embankment ponds may have negative effects on groundwater quality (Exner 1989).

In the aquatic environment, the potential for some pesticides to degrade increases at the same time as the potential for other pesticides to bio-accumulate increases. Some sediments accumulating on the bottom adsorb other pesticides entering the pond. Degradation, bio-accumulation, and adsorption to sediments reduce the impact on groundwater from pesticides in the aquatic system.

Irrigation Practices

Irrigation is used in localized areas throughout Illinois, primarily in areas with sandy soils (fig. 17). Soils in these areas generally have a low moisture-holding capacity, so irrigation water is used to provide an adequate, timely water supply to the crop. Major centers of irrigation include the Havana Lowlands in Mason and Tazewell Counties, Kankakee County, and the Green River Lowlands in Lee and Whiteside Counties (fig. 18). More than 90 percent of all irrigation water is obtained from groundwater sources, predominantly from shallow sand and gravel aquifers (Bowman and Collins 1987).

At present, irrigation scheduling practices in Illinois are quite variable (Bowman 1989). A few irrigators schedule water applications based on soil moisture data collected with tensiometers; some base the irrigation schedule simply on soil texture; others apply water continuously during key stages of plant growth to avoid crop stress.

Irrigated agriculture is potentially a major source of nitrates in groundwater (Keeney 1982, 1983). Compared to nonirrigated lands, irrigated lands have a greater potential to introduce nitrates into groundwater because (1) irrigation is concentrated in areas where the soils generally have high hydraulic conductivities; (2) irrigated lands generally receive heavy applications of nitrogen fertilizers, as high yields are necessary to recover the costs of irrigation; and (3) irrigation causes greater amounts of nitrates to leach from the soil (Mossbarger and Yost 1989).

The results of a field study conducted in Minnesota reveal that nitrate leaching losses from fertilized, irrigated corn were 17 to 62 percent greater than the losses from fertilized, nonirrigated corn (Timmons and Dylla 1981). The results of numerical modeling indicate that leaching of nitrates depends upon both the quantity of nitrogen fertilizer and the amount of irrigation water applied (Martin et al. 1982).

In addition, pesticides have been shown to leach into shallow groundwater as a result of irrigation. A numerical modeling study (Knisel and Leonard 1989) indicated that irrigation may increase the amount of pesticide leaching to groundwater, depending upon the pesticide characteristics. Leaching of pesticides with longer half-lives (30 days versus 3 days) was shown to be increased by irrigation. Pesticide leaching may be greater with irrigation because it can reduce volatilization of some pesticides (USEPA 1986). Irrigation application

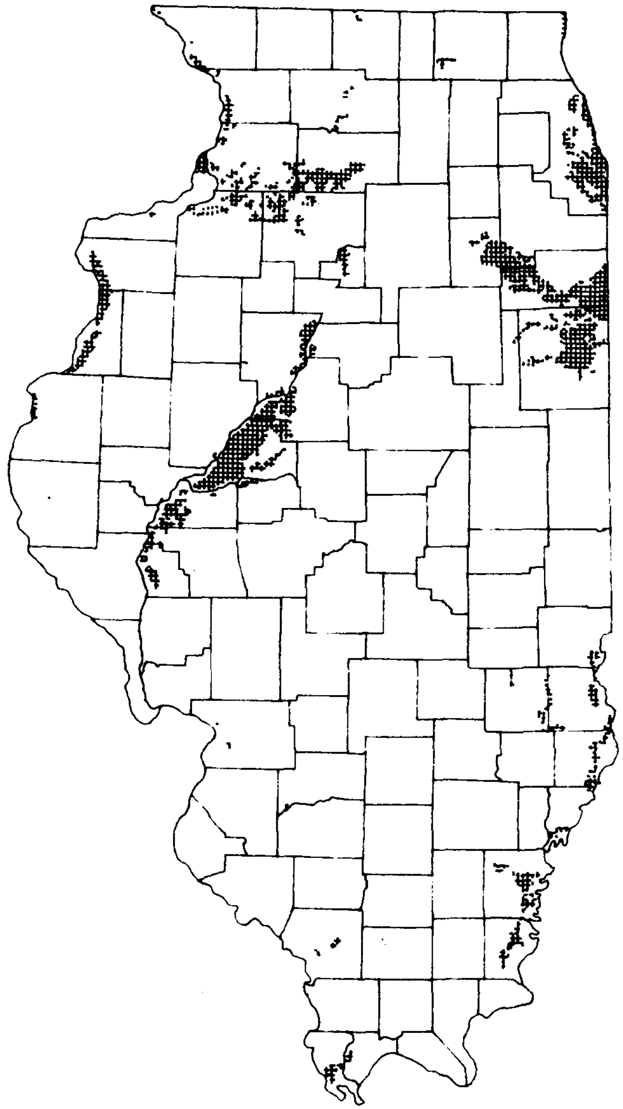

Figure 17 Areas with sandy soils (from Bowman and Collins 1987).

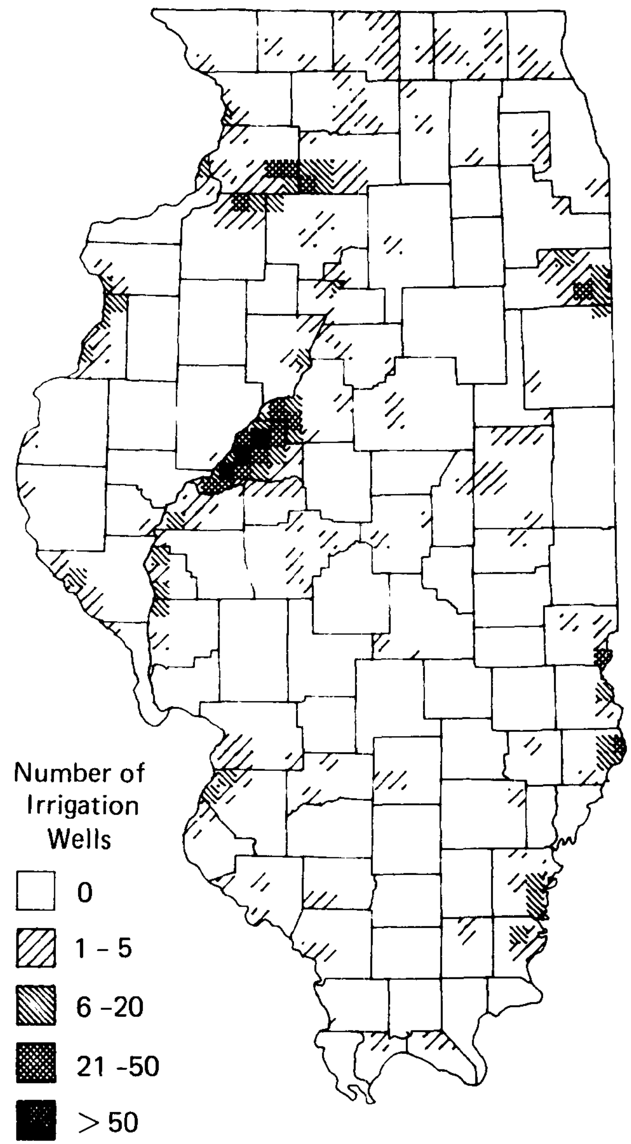

Figure 18 Major centers of irrigation in Illinois (from Bowman and Collins 1987).

rates, as reflected in pore water velocity, also affects leaching. Van Genuchten et al. (1974) found that movement of picloram was significantly reduced when the average rate of water flowing through pores was decreased from 57 inches to less than 6 inches per day.

Chemigation Chemigation is defined as the application of agricultural chemicals by injecting the chemical into the water flowing through an irrigation system (Threadgill 1985). Chemicals that can be applied by this technique include fertilizers, herbicides, insecticides, fungicides, and nematicides. The term fertigation is used to describe the application of fertilizers with irrigation water. In Illinois, as many as 80 percent of the farmers using center-pivot systems apply nitrogen fertilizer to corn through the irrigation system. Chemigation of herbicides and insecticides is reported to be less widespread, but not uncommon (Drablos et al. 1989).

Chemigation may impact groundwater quality in two ways: potential backsiphoning of agricultural chemicals through the well into the aquifer and increased leaching of applied chemicals. Protective measures may be used to prevent backsiphoning. Specific system components would include a functional check valve on the irrigation pipeline, an automatic quick-closing check valve on the pesticide injection pipeline, controls to shut off the pesticide-injection pump when water flow stops, and a pressure switch to stop the pump when pressure drops significantly (Drablos et al. 1989). In Illinois, chemigation systems are not regulated by the state. Although requirements for applying pesticides through an irrigation system are specified on the pesticide label and thus subject to enforcement under the Illinois Pesticide Act administered by the IDOA, these requirements do not apply to systems that apply only fertilizers.

There has been little research to determine whether chemigation affects leaching of pesticides and nitrates. Pesticides applied to cropland by chemigation require significantly more water to apply the chemical uniformly than do conventional methods of application. The greater volume of water increases the potential for pesticide leaching at the time of application. Because chemigation allows chemicals to be applied at any stage of plant growth, the chemical may be used more effectively than as a single preplant application. For example, split applications of nitrogen fertilizer result in more efficient use of nitrogen fertilizer (see *Nitrogen Application* Timing). However, this benefit may be offset by the use of more soluble forms of nitrogen. Similarly, applications of herbicides or insecticides may be delayed until an infestation exceeds the economic threshold, but the benefits may be negated if pesticides with a high leaching potential are used.

Recommendations

- Use irrigation scheduling based on the physiological requirements of the crop to prevent over-application of water and the subsequent increase in water movement through the soil. Hergert (1986) reported that on a sandy soil, where the amount of applied water was limited to 85 percent of evapotranspiration losses, yields were similar to applying water in excess of evapotranspiration losses, while reducing in-season leaching of nitrates.
- Limit preplant applications of nitrate-containing fertilizers to avoid early season leaching.
- Select pesticides that are less persistent in soils.
- Apply less soluble forms of nitrogen fertilizer.
- Where aquifers lie at shallow depths, limit planting of crops that require frequent or high rates of pesticide applications.
- Install check valves on all irrigation systems used to apply agricultural chemicals.

- Periodically inspect the well, the injection system, and protective devices.

- If backsiphoning occurs, immediately pump water through the irrigation system. Results of a numerical modeling study indicate that pumping the well is an effective cleanup for nitrates, which do not adsorb to the aquifer materials. For pesticides, which do adsorb, the length of time required to pump the contaminant from the aquifer is increased significantly (Nielsen and Warner 1986).

Other Soil Amendments

Sewage sludge Treatment of municipal and industrial wastes produces sludge, solid sewage, and effluent, liquid sewage. Sludge is an nonhomogeneous, highly variable mixture of organic and inorganic compounds. The composition of sewage sludge varies widely as a function of geographic area as well as time of the year. However, the content of major plant nutrients in sludge is constant enough to be used as a source of nitrogen (N), phosphorous (P), potassium (K), organic matter, and micronutrients. Other, less desirable, constituents of sludge include potentially dangerous heavy metals, bacteria, parasites, viruses, and synthetic organic contaminants. The total amount of nitrogen in sludge ranges from 3.4 to 9.5 percent (0.8 to 4.1 percent ammonium, NH_4) when moist and considerably less when dried. If used as a fertilizer, the amount of NH_4 that the soil can retain depends upon the method of application; that is, sludge applied on the surface loses much more nitrogen than sludge incorporated into the soil (Sommers et al. 1986). If sewage sludge is applied on the soil surface and not incorporated into the soil, volatilization can be responsible for the loss of 20 to 50 percent of the total NH_4 present in sludge (Tisdale et al. 1985).

As a fertilizer, sewage sludge can provide necessary nitrogen, phosphorous, and other nutrients to cropland. However, sewage sludge from large industrial centers also contains heavy metals. One of the greatest concerns is cadmium (Cd), which is a limiting factor in the amount of sludge that can be applied to a field. Cd can become toxic to plants and may accumulate in plant tissues that will later be consumed by humans (Keeney et al. 1975). For most of Illinois, heavy metals are not a problem, particularly with sludge from rural areas where industrial waste is not a significant contribution to the waste stream. Other constituents that deserve consideration include pathogens, organic chemicals, and soluble salts; for example, soluble salts can interfere with the germination of seedlings.

Nitrogen is often a limiting factor in determining the amount and frequency of application of sewage sludge. Commonly, the recommended application rate of sludge is limited by the nitrogen necessary for the desired crop; this rate may be determined through soil testing or from crop yields. Such an estimation will reduce the risk of nitrogen loss due to leaching. Incorporation of sludge during application will also reduce nitrogen loss due to volatilization. In addition, the type of soil is also a factor in the loss of nitrogen; sandy soil may lose up to 50-percent ammonium (NH_4), whereas a clay-rich loam may lose as much as 75-percent NH_4 (assuming sludge is applied on the surface). However, sludge incorporated into a clay-rich loam will lose much less NH_4 than sludge incorporated into sandy soils (State of Illinois 1984a). Fertilizer requirements for specific Illinois crops and guidelines for sludge application rates are provided by the State of Illinois(1984a).

Manure Like sludge, manure can be used as a source of NH_4 as well as P (which is essential to plant growth) and other nutrients. However, the composition and NH_4 content can vary depending on the source animals and the method of collection and storage (State of Illinois, 1984b). Unlike sewage sludge, manure does not have the problems associated with an industrial component (e.g., heavy metals and synthetic organic compounds), although the high salt content of manure can be a problem. While nitrogen is often the limiting factor in its application, P and K levels can become excessive in soils to which large amounts of manure are applied. Solid waste storage and spreading systems are more desirable than liquid waste systems if the nitrogen loss is to be minimized. For example, an anaerobic, solid-waste collection system will minimize loss of nitrogen due to volatilization. Incorporation of manure into the field will also keep nitrogen loss to a minimum and may improve the growing capabilities of the soil. In addition, nitrogen loss in the course of application to the soil can be minimized by incorporating the manure directly into the soil. Manure is considered a relatively complete fertilizer source and is often the mainstay of livestock farms. The application of manure to a field is beneficial in several ways: manure application may increase moisture retention, improve soil structure, increase infiltration rates, decrease soil bulk density, buffer pH of the soil, complex potentially toxic elements (Tisdale et al. 1985), and increase adsorption of pesticides (Bicki et al. 1990).

As with nitrogen fertilizer and sludge, NH_3 in manure is quickly converted to NO_3 through nitrification, and in that form, is subject to leaching and denitrification. Tables containing the approximate amount of nitrogen present in fresh manure are available (State of Illinois 1984b), as are nitrogen needs for various crops (State of Illinois 1984a). Because of variability in soil conditions and compositions of manure, these values are only approximate.

Recommendations The following recommendations for the application of sewage sludge and manure onto cropland reflect those included in the two State of Illinois documents (1984a and b).

- Analyze sewage sludge because of the variability of composition as a function of source and time. The amount of sludge and frequency of use should be based on the amount of nitrogen required for a particular crop.

- Monitor the long-term loading of metals to the soil.

- Limit the amount of sludge or manure applied in the fall in order to avoid the leaching of contaminants during winter and early spring. During application, incorporate these materials into the soil to avoid loss of NH_3 due to volatilization and runoff.

- Do not apply sludge or manure to sandy soils or relatively thin soils overlying fractured bedrock or sand and gravel.

- Use manure effectively by (1) measuring nutrient composition through chemical analysis or estimating it from published data (State of Illinois 1984b), and (2) calibrating application equipment. More accurate estimates of nitrogen application rates should reduce the risk of groundwater contamination.

- Use manure storage facilities in order to allow flexibility for application of manure at the proper time, and to minimize the loss of NH, during this waiting period. A manure storage facility should be constructed to minimize seepage into groundwater.

Point Sources

Point sources of groundwater contamination in rural areas include pesticide and fertilizer handling, storage, and transfer facilities; septic systems; animal feedlots; abandoned wells; pesticide and fertilizer mixing near farm wells; and spills from vehicular accidents. High pesticide loadings to soil due to spills or leaks in small volumes of concentrated solution or large volumes of diluted solutions can reduce soil microbial populations and significantly reduce biodegradation (Felsot and Dzantor 1990, Davidson et al. 1980).

Agricultural chemical distribution facilities There have been several instances of point source contamination of aquifers by agricultural chemicals at chemical mixing and loading facilities (Long 1988, Clark and Sinnott 1988, Taylor 1989). The Illinois Department of Agriculture (IDOA) estimates that there are approximately 1,200 to 1,500 facilities for distribution of agricultural chemicals in Illinois (Sinnot 1989). The Illinois Department of Public Health reported the detection of pesticides in groundwater samples collected from 43 of 56 wells located at agrichemical facilities (Long 1988, Taylor 1989). The drinking water standard for nitrate (10 mg/L NO_3-N) was exceeded in samples from 35 of the wells. Wide ranges of concentrations for specific pesticides were observed. For example, alachlor was detected in samples from 34 of the wells at concentrations ranging from 0.01 to 1300 ppb with a median concentration of 118 ppb.

The Illinois Environmental Protection Agency is currently investigating 16 agrichemical facilities in 14 counties where groundwater contamination has been discovered in nearby private, potable and nonpotable water wells (Taylor 1989). The containment rules for commercial and noncommercial facilities adopted by IDOA (Illinois Administrative Code) became effective on January 1, 1990. However, these facilities can be expected to require another 5 years to fully comply with the new rules.

Farmsteads Accidental spills of pesticides or fertilizers and discharge of pesticide rinse water can also occur near water-supply wells at individual farms. If the mixing area is too close to the well and the casing is not properly grouted near the surface, spills may also cause contamination of private wells.

Little is known about setback distances, activities, and wellhead protection practices adjacent to rural private wells in Illinois. Limited information on wellhead activities and conditions is available in a wellhead protection survey conducted on 240 farmsteads in 24 Illinois counties (Bicki 1989). Survey results indicate that storage, handling, and mixing of pesticides, fuel storage, livestock confinement, and other potential sources of aquifer contamination occur in close proximity to wellheads. Nearly 83 percent of respondents surveyed have pesticide storage facilities within 100 feet or less of their well. Only 8 percent of survey respondents who formulate and mix pesticides, conducted such activities more than 100 feet from their well. Above-ground fuel storage tanks were located less than 100 feet from wells in 47 percent of farmsteads surveyed. Seventeen percent of respondents with livestock confinement facilities had wells less than 100 feet from confinement facilities.

Septic systems that are improperly located, designed, constructed, and maintained can also cause groundwater contamination. In rural areas with low housing densities, septic systems should not significantly affect regional groundwater quality since dilution within the aquifer will reduce nitrate concentrations (Wehrmann 1983). The rate of groundwater recharge and aquifer transmissivity are the two most important factors in the dilution process.

The estimated 50,000 to 80,000 abandoned wells in Illinois (Koltun 1989), if improperly sealed, may serve as conduits for contaminants. Rusted casings or the absence of grout may allow contaminant transport along the casing from the surface to the aquifer (Canter et al. 1987). Abandoned wells with multiple screens may lead to interaquifer contamination.

Recommendations The following recommendations focus on wellhead protection at the farmstead since IDOA regulations address operation of agricultural chemical distribution facilities.

- Avoid mixing pesticides near the well; use a nurse tank.

- Prevent backsiphoning by keeping the end of fill hoses above the water level in the tank.
- Use equipment with anti-backflow devices and check valves.
- Never rinse sprayer equipment near wells or other water sources.
- Triple rinse pesticide containers and pour the rinse water into the spray tank.
- After spraying, flush sprayers in the field with 50 to 100 gallons of clean water to avoid dumping rinse water near the well site (Jackson et al. 1987).
- Periodically inspect and pump septic systems; repair or replace corroded and broken tanks and pipes promptly.
- Test well water annually for nitrates and coliform bacteria.
- Seal abandoned wells properly.
- Follow setback rules established by Illinois Department of Public Health when locating wells, septic systems, and animal feedlots. Wells should be at least 50 feet from feedlots, 75 feet from septic fields, and 25 feet from lakes, ponds, or streams. Septic fields should be located downslope from the well.

II. INITIAL EVALUATION OF AGRICULTURAL CHEMICALS IN ILLINOIS GROUNDWATER

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II. INITIAL EVALUATION OF AGRICULTURAL CHEMICALS IN ILLINOIS GROUNDWATER

Knowledge of the extent of agricultural chemical contamination of groundwater in Illinois is limited. To date, Illinois has had no coordinated sampling program to determine the presence of agricultural chemicals in groundwater. In previous sampling programs, the Illinois Environmental Protection Agency (IEPA), the Illinois Department of Public Health (IDPH), and the Illinois State Geological Survey (ISGS) have analyzed for relatively few compounds and/or only sampled public water supply wells or wells thought to be highly vulnerable to contamination. A national pesticide survey (NPS), currently being conducted by the U.S. Environmental Protection Agency (USEPA), has also sampled wells in Illinois; but no data appropriate for describing conditions at the state level will be generated. Several county-level groups have also sampled private wells for pesticides. The design of these county sampling programs, however, does not allow for estimates of pesticide occurrences to be made for other than the wells sampled on the day they were sampled.

To provide statistically valid estimates on the occurrence of agricultural chemicals in rural private wells in Illinois, the Illinois State Geological Survey and the Illinois State Water Survey (ISWS) proposed a design for stratified random sampling of wells in the state (McKenna et al. 1989a). A primary goal of that survey is to determine whether the potential for groundwater contamination varies across the state. Currently, the ISGS and ISWS and the Illinois Department of Agriculture (IDOA) are conducting a pilot study to test various aspects of the experimental design of the proposed stratified random survey. Recently, the IDOA, the Cooperative Extension Service of the University of Illinois, the ISGS, and the ISWS initiated planning for a simple random survey of private wells in the state. That survey is intended to provide initial estimates of agricultural chemical contamination of rural wells across the state, but will not provide a sound scientific basis upon which to determine whether some areas of the state are more vulnerable than others.

Information regarding previous studies was obtained from published reports and responses to inquiries by the ISWS and ISGS. Details of monitoring studies obtained from published sources are summarized first. In addition, the ISWS and ISGS conducted a mail survey of county, state, and federal agencies in Illinois concerned with drinking water supplies and/or agriculture. The agencies were surveyed to obtain information on any groundwater sampling programs for pesticides. The survey and its results follow the summary of published sampling programs. Ongoing or proposed sampling programs of state agencies are described at the end of this part of the report.

PREVIOUS GROUNDWATER SAMPLING PROGRAMS

The first attempt to investigate groundwater contamination by pesticides was conducted jointly by the Illinois Department of Agriculture (IDOA), the Illinois Department of Public Health (IDPH), and the Illinois Natural History Survey (INHS). In this study (Felsot and Mack 1984), 25 private wells were sampled in five "susceptible" regions across the state. Samples were collected in June 1983 and analyzed for a wide variety of pesticides. Reported characteristics of susceptible areas were well-drained or sandy soils with low organic matter content and shallow aquifers. None of the samples contained pesticides above the 1.0 µg/L detection limit.

Illinois Environmental Protectlon Agency

The IEPA conducts compliance monitoring of public water supply wells for compounds and elements specified under state and federal drinking-water regulations. Until 1986, monitoring was conducted to measure inorganic chemicals to comply with the Safe Drinking Water Act. in the IEPA program, most public water supply systems are sampled every 3 to 5 years. If the water supplies are not in compliance with the regulations, local officials are notified and further testing is conducted. Corrective actions are initiated if repeated sampling indicates a problem.

In 1984, the IEPA initiated a pilot program to monitor community water supply wells for pesticides. During 1985, samples were collected from 92 public wells, including 68 wells withdrawing water from sand and gravel aquifers, 15 wells finished in dolomite aquifers, and 9 wells in sandstone aquifers. No pesticides were detected in this sampling program (Clark and Sinnott 1988).

During fall 1985 and spring 1986, the IEPA collected samples from an additional 195 public water supply wells finished in sand and gravel aquifers. Most of these wells were a selected subset of a groundwater monitoring network proposed by O'Hearn and Schock (1985) to assess regional ambient (background) groundwater quality in the state’s principal aquifers. A principal aquifer is identified by O’Hearn and Schock (1985) as one with a potential yield of at least 100,000 gallons per day per square mile and an area of at least 50 square miles. In addition, 78 wells located outside the "principal aquifer boundaries" were sampled. Analyses for 34 pesticides (chlorinated hydrocarbon and organophosphate insecticides and six currently used herbicides) found none above detection limits (Clark and Sinnott 1988).

With these results, the IEPA shifted its monitoring to a site-specific approach and selected wells for sampling on the basis of hydrogeologic factors and the proximity of potential point sources, such as agricultural chemical distributors. Through 1988, this approach has identified three public water supply wells with trace levels of currently used herbicides (Clark and Sinnott 1988). These detections have been attributed by the IEPA to point sources located within 50 to 700 feet of the wellhead.

During 1989, 50 additional public water supply wells near chemical facilities were tested for pesticides. Preliminary results show no detections to date. Final results of those analyses will be available in the summer or fall of 1990.

Illinois Department of Public Health

The IDPH has sampled wells to determine the extent of contamination of wells serving agrichemical mixing and loading facilities (Long 1988). Wells were randomly selected for sampling from a list of more than 1500 facilities licensed by the IDOA; approximately 77 percent of the 56 well samples analyzed have had detectable levels of at least one pesticide. The most frequently detected compounds were the commonly used corn and soybean herbicides. Although most compounds were detected at low parts per billion (ppb) levels, concentrations greater than 1000 ppb were found in some wells. More than 60 percent of the wells tested exceeded the drinking water standard of 10 parts per million (ppm) nitrate-nitrogen (NO_3-N). Nitrate concentrations ranged from 1.2 to 1288 ppm. The median concentration was 25.0 ppm.

Long (1988) also reported on two joint IDPH/IEPA investigations of water quality in private or noncommunity wells close to agrichemical facilities. Neighboring wells generally had pesticide concentrations ranging from less than 0.1 to 5 ppb; however, pesticides were detected at concentrations greater than 50 ppb in several samples.

Illinois State Geological Survey

The ISGS has completed a study to determine spatial and temporal variability in the occurrence of agricultural chemicals in groundwater in Mason County (McKenna et al. 1988). Preliminary results indicate that the upper part of the aquifer has been significantly contaminated by nitrogen fertilizers. Nitrate-nitrogen levels in the groundwater samples exceeded the drinking water standard (10 mg/L) in 58 percent of the samples from monitoring wells 10 to 30 feet deep and 49 percent of the samples from private wells 25 to 40 feet deep.

Trace levels of pesticides were detected in shallow groundwater; however, pesticide concentrations exceeding the drinking water standards were found in only a few samples. Analyses of 15 samples from irrigation wells (75 to 120 feet deep) indicated that the lower part of the aquifer is relatively unaffected by pesticides and nitrates. Although the overall frequency of detection of agricultural chemicals in the shallow monitoring and private wells was high, the occurrence of agricultural chemicals in any particular well was extremely variable over time.

National Pesticide Survey

The US. Environmental Protection Agency (USEPA), through its Office of Pesticide Programs and Drinking Water, has initiated a multiyear, nationwide survey of pesticide contamination in domestic and community water wells (Mason et al. 1987). The National Pesticide Survey (NPS) has two goals: (1) characterize pesticide contamination of drinking water wells, and (2) determine how pesticide concentrations in drinking water wells correlate with patterns of pesticide usage and groundwater vulnerability. The NPS consists of a planning phase to characterize the United States in terms of pesticide usage and groundwater vulnerability and to select sampling points; a pilot study to test concepts of the plan; sample collection; and analysis of the information resulting from the survey.

During the planning phase, all 3,137 counties in the United States were stratified by a scheme that placed each county into one cell of a 3 by 4 matrix: three categories of groundwater vulnerability and four categories of pesticide use (fig. 19). Public wells to be sampled were selected based on the groundwater vulnerability/pesticide usage stratification scheme. The private wells to be sampled are located in a 90-county subset selected using a stratified, random design. Counties evaluated as having vulnerable groundwater and high pesticide usage were overselected in comparison to medium- and low-usage counties. (Overselected means that a higher proportion of wells from one stratum are sampled than wells in other strata.) Areas within each of the counties were evaluated in terms of cropping and vulnerability. Finally, wells in subcounty areas were selected, oversampling those in areas evaluated as cropped and vulnerable.

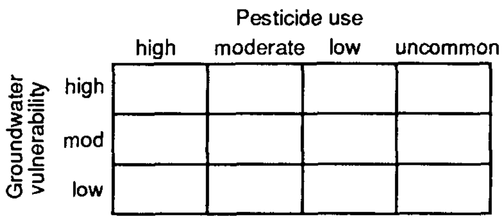

Figure 19 Classification matrix.

Four of the 90 counties randomly selected for private well sampling in the NPS are in Illinois: Kane (8 wells), McHenry (12 wells), Peoria (12 wells), and Warren (12 wells) Counties. Sampling began in October 1988 in Kane County and will finish in January 1990 in Peoria County. In the stratification scheme used in the NPS, the wells in Kane and McHenry Counties are classified as high pesticide usage and medium groundwater vulnerability. The wells in Peoria and Warren Counties are classified as high pesticide usage and low groundwater vulnerability. Also, 12 public water supply wells in Illinois have been sampled as part of the NPS. Wells in Knox, Lake, McHenry, and White Counties were sampled in the second half of 1988, while wells in Edgar, Effingham, Hancock, Henry, McHenry, and Woodford counties were sampled in the first half of 1989.

Preliminary results released by the USEPA in September 1989 indicated no detections of pesticides in samples from six public water supply systems in Illinois. No pesticides were detected in the eight private wells sampled in Kane County; however, in Warren County, one private well sample had a detection of a pesticide, and one well sample contained 10 ppm nitrate as nitrogen. Six other wells in Warren County had no detections.

The NPS was designed to characterize pesticide contamination of water wells on a national level. Interpretation of NPS results at a state- or county-wide scale would be incorrect and misleading.

SURVEY OF AGENCY ACTIVITIES: SAMPLING GROUNDWATER FOR PESTICIDES

A questionnaire was developed to gather information from agencies collecting groundwater samples for pesticide analyses (see Appendix A); it was sent to 405 agencies and university departments. These included county health departments, Farm Bureau offices, soil and water conservation districts, and offices of the Cooperative Extension Service. Also included were the Illinois Environmental Protection Agency, Illinois Departments of Agriculture and Public Health, the three Illinois State Scientific Surveys, the U.S. Geological Survey, and the U.S. Department of Agriculture. The questionnaire was also sent to universities with departments of agriculture, agricultural engineering, and agronomy, and to one company—the Monsanto Corporation in St. Louis, Missouri.

Response to the Questionnaire

There were positive, negative, and nonresponses to the questionnaire. Twenty-one agencies had conducted a sample collection program; 96 agencies returned the survey, but had no sampling programs; 288 agencies did not respond. Follow up phone calls to nonrespondents disclosed that most had no sampling programs (table 7). That 21 agencies had programs indicates a significant interest in potential groundwater contamination.

Table 7 Total returns (including followup responses)

Category	*Returns*	*%*
Positive returns	21	5
Negative returns	206	51
Total returns	227	56
No responses	178	44
Questionnaires sent	405	100

The programs to sample for pesticides in Illinois groundwater were undertaken for various reasons. Some county programs responded to complaints; the majority reported that the collections were made to determine the status of water quality in wells in the county.

County agencies collected 410 samples from private water supply wells. Few public water supply wells were included in these programs. Most sampling programs were carried out during a single day. A few were conducted over a few weeks. Most reported sampling took place between 1987 and 1989. In 1987, one program occurred in the summer, two in the fall, and one in the winter. Two programs were conducted during the summer in 1988. In 1989, six programs took place in the spring, three in the summer, and one in the fall; one was not specified. The IEPA program began in 1985 and continued through 1989. To date, the IEPA has collected 548 samples from 446 public water supply wells.

The season of the year and duration of the sampling period varied so greatly that the information generated from these programs cannot be considered a consistent body of data from which to draw conclusions. For example, collecting a few samples on one day or sampling during the winter may not provide an adequate assessment of water quality with respect to pesticides.

Table 8 shows the reasons for sampling as reported by the agencies that conducted programs. The greatest number of county studies was motivated by the interest of both the individual well owners and the county agencies in beginning to determine some facts about private drinking water supplies.

Table 8 Rationale for conducting sampling programs

Reasons	*Number of programs*
Public awareness/status of groundwater quality in county	11
Suspicion of contamination/request from individuals	6
General screening	1
Legislated state mandate	1
Response to federal mandate and follow-up study	1
No reason given	1

County Programs

The IDOA Laboratory of Animal Disease Control in Centralia, Illinois, has been the analytical laboratory for a series of collection programs in cooperation with Cooperative Extension Service offices and other agencies in Washington, Crawford, Clark, Jackson, DeKalb, Grundy, and Will Counties.

The IDOA Centralia laboratory uses a modified USEPA gas chromatograph (GC) method for analyses of up to 90 organic compounds. Detection limits of the method are determined by using several spiked standards. Performance levels for each compound are based on percent extraction. Standards are used after every few samples are run during each analytical procedure. The IDPH laboratory in Springfield also uses a modified GC/mass spectrometer (MS) method for analysis of up to 80 organic compounds.

• *The Calhoun, Green, and Jersey County Health Departments* collected six samples from private water supply wells in these three counties (table 9). The collection occurred over a 5-year, period in response to accidents or suspected misuse of chemicals. Samples were collected in brown glass containers with no preservatives and transported without refrigeration to the IDPH laboratory in Springfield for analysis. When a positive result was found, the well was usually flushed and resampled. No analytical results were returned with the questionnaire.

• *The Champaign County Farm Bureau* collected 26 samples in April 1989. Samples were taken at taps away from the private water supply wells, which varied in type from 25-foot-deep dug wells to greater than 100-foot-deep drilled wells. Samples were collected in glass containers by homeowners and driven to the IDOA Centralia laboratory. A broad-spectrum screen for more than 70 pesticides yielded a report of no detections in any of the 26 samples analyzed.

• *The Clark County Cooperative Extension Service* collected eight samples in June 1988. Samples were taken at taps away from the wells, seven of which were considered to be in high risk areas because of soil type. Wells included two public water supply wells, one irrigation well, and five private water supply wells. The private wells were driven, sand point wells, 25 to 30 feet deep. The irrigation well was 50 feet deep. The depths of public wells were not given. Samples were collected in brown glass containers by a staff member of the Cooperative Extension Service and transported by car to the IDOA laboratory in Centralia. A broad-spectrum analysis for more than 70 pesticides yielded one detection of simazine and three detections of atrazine.

Table 9 Summary of county programs

county	*Agency**	*Sampling dates*	*Number of wells*	*Laboratory***
Calhoun, Green, Jersey	D	84-89	6	2
Champaign	A	4/3/89	26	1
Clark	B	6/88	8	1
Crawford	B,C	12/I11/87	10	2
De Kalb	A,B	2/28/89	24	1
		8/2/89	20	1
De Witt	A	3/27/89	26	1
Fayette	D	6/87	1	2
Henry	A	2/21 /88	24	1
		3/20/89	21	1
Henry	D	7/21/89	12	2
Jackson	B	11/2/88	43	1
Shelby	B	3/13/89	24	1
Washington	D	8-9/87	20	3
		8/88	25	3
Will	A	89	104	1

* A = Farm Bureau; B = Cooperative Extension Service; C = Soil and Water Conservation District; D = Health Department
**1 = IDOA Centralia Laboratory; 2 =IDPH Springfield; 3 = unspecified

• *The Crawford County Soil and Water Conservation District and Cooperative Extension Service* collected 10 samples in December 1987. One sample was collected from a dug, private water well in each of ten townships. Wells ranged in depth from 18 to 40 feet; samples were taken at the wells, at taps away from the wells, or from inside taps. IDPH staff collected the samples in brown glass bottles and transported them by car to the IDPH laboratory in Springfield, Illinois, for volatile organic analyses. The IDOA Centralia laboratory performed the broad-spectrum scan for more than 70 pesticides. Samples from two dug wells showed trace levels of atrazine.

• *The De Kalb County Farm Bureau and Cooperative Extension Service* collected 20 samples in February 1989; 24 more samples were collected in August 1989. Samples from private water supply wells were collected in glass containers by homeowners, picked up by staff of Northern Illinois University, and transported by county staff to the IDOA laboratory in Centralia. A questionnaire about the wells, samples, pesticides use, and activities near the well was given to each owner. A broad-spectrum screen for lead and 90 pesticides yielded no detections.

• *The De Witt County Farm Bureau* collected 26 samples in March 1989. Samples were collected from private homes by homeowners, who brought samples in glass bottles to the agency for transport to the laboratory. The IDOA Centralia laboratory performed a broad-spectrum screen for more than 70 pesticides. No detections were reported.

• *The Fayette County Health Department* reported the collection of one sample in June 1987 at the request of the owner of a business-owned well. The sample was taken at a tap in a brown glass container and transported to the IDPH laboratory in Springfield. Three pesticides were detected (chlordane, cyanazine, and metribuzin).

• *The Henry County Farm Bureau* collected 24 samples on February 21, 1989, and 21 samples on March 20, 1989. Samples were collected from each of 45 homes with private water supply wells. Twenty-five of the wells were more than 50 feet deep; 11 were less than 50 feet deep; nine were of unknown depth. Samples were collected in glass containers by individual homeowners and submitted to the agency for transport to the IDOA Centralia laboratory. A broad-spectrum screen for more than 70 pesticides yielded one detection of atrazine.

The Henry County Health Department reported that 12 samples were collected for herbicide analysis near a chemical spill site on July 21, 1989. Details about the spill were not given. The samples were collected from private water supply wells withdrawing water from a shallow aquifer. All wells were driven, sand-point wells that ranged from 15 to 20 feet deep. Samples were collected at taps away from the well in brown glass containers. Agency staff collected the samples and transported them, refrigerated, to the IDPH laboratory in Springfield. There were four detections of cyanazine, four of atrazine, and one of alachlor.

• *The Jackson County Cooperative Extension Service* collected 43 samples in November 1988. Samples were taken at wells, at taps away from wells, and in homes from private water supply systems. Samples were collected in brown glass containers by home owners and transported by car by Cooperative Extension Service staff to the IDOA Centralia laboratory. Analyses by broad-spectrum screen for 80 herbicides, insecticides, and fungicides yielded two detections of atrazine. No levels were above USEPA lifetime advisory levels.

• *Shelby County homeowners* volunteered to sample 24 private water wells at kitchen taps in January 1989. Sampled wells included 12 drilled wells from 21 to 92 feet deep and 12 dug wells from 5 to 35 feet deep. Cooperative Extension Service staff transported the brown glass containers to the IDOA laboratory at Centralia by car. No results were available from this program.

• *The Washington County Health Department,* participated in a program with the Addieville Groundwater Committee, during August-September 1987 and August 1988. Twenty-four samples were analyzed for 90 pesticides. Four deep wells had traces of pesticides; five shallow wells and four surface-water supplies tested positive. Compounds detected were atrazine (7) DDE (8) chlordan (1) dieldrin (1) prometone (2), heptachlor epoxide (1) metribuzin (1), and DDD (1). In August 1988, 25 samples were collected and analyzed. Detections of pesticides in samples from one deep well and three shallow wells included atrazine (2), alachlor (1), and chlordane (1). A third round of samples will be collected in 1990.

• *The will County Farm Bureau* collected 104 samples over 8 weeks in 1989. Samples from private water supplies were taken at the well, collected in brown glass bottles, and mailed to the IDOA laboratory in Centralia. A broad-spectrum scan for pesticides was performed. Four detections of pesticides were reported; concentrations were not above regulatory limits.

Other Programs

• *The Monsanto Company Environmental Science Department* (St. Louis, Missouri) conducted two sampling programs in Illinois. In 1985, in response to the alachlor registration standard required by the USEPA, sampling took place in Adams and Iroquois Counties. Sample sites were selected randomly from 15 counties in the United States with the highest sales, that is, usage of alachlor. The collection program was carried out by Geraghty and Miller Inc. Consultants.

In 1987, samples were collected in McHenry and Bureau counties in Illinois as part of the National Alachlor Water Well Survey. In 1987 the sample sites were selected in a manner similar to that used by the National Pesticide Survey of the USEPA, using sales of alachlor rather than use of pesticides as a stratification variable. The sampling program was carried out by the Hydrogeology Department of the Center for Environmental Measurements of the Research Triangle Institute in North Carolina. No results of chemical analyses were returned with the questionnaires sent to these sampling programs.

- *The Illinois Department of Agriculture laboratories* (Springfield) reported a very limited program of groundwater sampling for pesticides. The laboratory has been involved in the sampling of 41 wells and ponds over the past 5 years. The collections were motivated by complaints involving the misuse of pesticides or possible violations of regulations related to pesticides. The IDOA laboratory in Springfield uses a GC/MS method for the analysis of pesticides. The analyses have been primarily for triazines and organophosphates. Results of the analyses were returned to the complainants only.

Design of Sampling Programs

Key components in the design of a sampling program include selecting the sampling points and determining the number of samples needed to make statistically valid inferences about the population being tested. The process used for selecting sampling points varied in the programs. Many programs were based on volunteers, who were solicited through local newspapers. Participants contacted the agency for instructions and/or containers. Most of the county programs claimed that the well sites were randomly selected. However, no list of all wells qualified for sampling was compiled and used for random selection of sites. Four collection programs reported that their sampling points were selected on a statistical basis; in two of the cases, students who were working toward masters theses developed the sample selection procedures. Programs conducted by the IEPA and Monsanto used a statistically based selection process. County programs were generally limited, and none had a truly random sampling program. In addition, none of the county programs collected enough samples to provide statistically valid estimates of pesticide ocurrence private water wells in the county.

The 1980 census information (NWWA 1986) indicates that the lowest number of private wells in any county in Illinois is approximately 900. Table 10 shows the number of samples that would be needed to make statistically valid inferences about the status of that population of wells at different confidence limits and estimates of probability of occurrence. The numbers are only valid when all the variables are the same; otherwise a greater number of samples would be necessary.

Table 10 Required sample sizes for population of 900 to 1,000

Probability of occurrence	*Number of samples* 95% confidence	90% confidence
0.50	278	213
0.10	122	89

The variability of the sampling point can contribute to the differences in results. Every time the sampling point is changed, new factors affect the water quality. Water at the tap may be affected by an aerator. It may have passed through a softener or some other treatment apparatus. If the water was taken early in the day without running the water to flush the system, metals and scale from the house pipe system and faucet could be higher in concentration than flushed samples (Schock 1988, Schock 1989). The type of pipes through which water passes can affect the quality. Taps near the well vary greatly. Some are on a hydrant directly above the well. Others are on pipe systems which take them several feet to a house. Still others are tens of feet from the source. Yet all of these situations can be considered taps at the well or taps away from the well. A tabulation of the reported types of sampling points demonstrates that there were a variety of sampling points represented in the programs in Illinois (table 11).

In addition to the type of sampling point, a variety of information was collected about the well settings and well construction. The source of the sample must be known in order that the results can be evaluated with respect to any naturally occurring chemical conditions of that source. The source will also determine the population for which the results have meaning. Table 12 shows a categorical listing of the types of information collected by the sampling programs in Illinois.

Table 11 Sample point type

Sampling point type	*Number of programs*
Private water well samples	
• collected at house tap	9
• collected at well	4
• collected at outside tap	5
• unspecified	4
Mixed surface and well water samples	
• unspecified	2
Non-private water well samples	
• collected at house tap	3
• collected at well	1

Table 12 Supplemental well information

Information collected	*Number of programs*
Well depth	
• ranges	8
• specific	2
Location	
• general	6
• specific	2
Well setting details	4
Well construction details	4
No information	5

Sampling Protocols

Half of the sampling programs used volunteers to collect samples in their homes. Most county agencies must rely on volunteer programs because of the money and manpower required to conduct a sampling program.

One apparent problem with this type of sampling program is the highly variable sampling protocols, which can dramatically affect analytical results, especially when testing for compounds that occur in the parts per billion range. The containers can affect the samples; for example, clear containers transmit more light and photosensitive analytes may degrade more than if stored in amber or brown glass bottles. If containers are carried in warm vehicles without refrigeration, and in boxes open to sunlight, the chemical composition of the samples can be altered. If the containers are not prepared in the same manner, the sample may be contaminated (USEPA 1981). If a preservative is used in the container with the sample, the probability that trace amounts of an analyte will still be available for measurement is higher. (Preservatives are used to inhibit degradation during transport and storage.) In sampling programs that use volunteer or untrained sample collectors, preservatives cannot be used because they are extremely toxic; handling them requires special training. In some instances, U.S Department of Transportation regulations prohibit shipping of preserved samples.

Sampling protocols in the reported programs varied. The county programs used instructions from either the IDOA or from the IDPH. The IDOA protocol specifies the use of a glass container, washed and rinsed several times. It states that the sample can be taken before or after the softener, but to collect cold water. A warm water sample could change in volume as it cools, or a cold sample which warms up during storage, can change the amount of head space in the sample container, which can affect the volatile components of the sample.

In conversations with laboratory staff, it was found that in the spirit of cooperation, the laboratory could not specify that the program must use the IDOA-supplied containers. This was reasonable under the circumstances of the program. However, it makes the results of these volunteer programs less comparable. The fact that samples could have been collected before or after softening, and no record indicates which occurred for each sample, makes the interpretation of the results more difficult. The IDPH protocol did not specify to collect the samples before or after treatment, nor did it specify rinsing the containers. There was no indication that any well or well-environment information was collected.

On the other hand, the sampling programs carried out by IEPA and Monsanto had detailed protocols for sample collection and samples were collected by trained staff or consultants who had been trained by the company.

Analytical Methods

Analytical methods have different detection limits and sensitivities. For any method, there are variances from analytical run to analytical run. Detection limits are the lowest concentrations of an analyte that can be reliably identified by a method (IUPAC 1978, Porter 1988). Changes in instrumentation, sample preparation, or other analytical conditions can change the detection limits of a method (USEPA 1981). Method sensitivity is the ratio of change in instrument response to the change in analyte concentration (FDA 1979, Graham 1988). In groundwaters where trace amounts of a compound are expected to be found, this sensitivity may be the capacity of a method to determine a compound. The large number of organic compounds that exist in our environment can complicate the sensitivity issue. Analytical traces of many of these compounds can be confusing in the chromatographs (results) unless a rigorous program of method preparation is performed so that the output for any instrument is understood by the analyst. Method preparation requires complicated, consistent, and tedious work by the analyst. The variability from laboratory to laboratory and from analysts to analyst is a serious concern to the analytical world (Massart 1978). Trying to compare analytical results from one program to another will be affected by all of these factors.

Laboratories use the same method to analyze the same compounds over long periods of time. In recognition of the variability of the results of these methods, several procedures are used to ensure that the method is giving consistent, comparable results from analytical run to analytical run and from day to day. In addition to detecting problems with procedures, quality assurance measures are intended to help correct procedural problems (ACS Committee 1980). Knowledge of the quality assurance/quality control (QA/QC) programs at the laboratories involved in these programs is important for interpretating results.

The county-level programs have used the laboratory facilities of either the IDOA or the IDPH. Both of these laboratories use an USEPA approved GC/MS method (EPA 60014-22-039) for broad-spectrum screening of a large number of organic compounds. These broad-spectrum methods, as implied by their name, are not intended to detect trace levels of a large number of compounds. Rather they are intended to scan a sample for compounds of interest. The broad-spectrum analytical methods cannot achieve the same level of detection limits for all compounds on any run. The detection limits will be lower for a small number of the 70 to 90 compounds scanned than for the rest of the compounds.

The Monsanto sampling program in 1985 used a GC method for initial analysis and an MS confirmation method in its first round of samples. They perfected their MS methods and used MS with simultaneous confirmation in the second round of analyses. In their 1987 program, they used a GC/MS isotope dilution dual selected ion quantification method. Only IEPA and Monsanto employed field QA and carried trip blanks on sample collection trips. Each method has its own detection limits for each compound. IEPA and Monsanto laboratories use similar, but not exactly the same laboratory QA/QC procedures.

Reporting

In the county programs, when there were detections of pesticides, laboratory reports were returned to the county agency. Each agency determined how it communicated results to the owners/users of the wells. In programs responding to complaints, the laboratory reports were returned to the well owners/users.

Several laboratory reports were returned with the words "no levels detected." A further statement explained that all compounds measured at levels below USEPA allowable limits are not violations of a regulation; therefore, they were reported as undetected. (Levels of between 0.5 ppb and 10.0 ppb are typical standards for pesticides.) This type of statement is misleading. To those unfamiliar with chemical analyses, it will probably be interpreted to mean that the sample contained no chemicals. This is not the case, although nothing untrue has been reported. For the broad-spectrum analytical methods used for many of the county programs, it is very unlikely that detection limits would be the same as the levels of all standards for so many compounds.

Some reports released to the press or returned to the well owners/users were accompanied by quotes from officials at the state and county level and are paraphrased as follows.

- It was not surprising that there were no violations (detections) due to Illinois' clay and highly organic soil types and the conscientious farming practices of Midwest farmers protect groundwater from chemicals leached through the soils.

- The results are partly due to the soil types, and that chemicals attach to surface layers where they are degraded by sunlight.

- Groundwater is not contaminated because the wells are properly constructed. (In many studies, poor well construction is frequently cited as the reason for contamination.)

- Farmers are doing a good job protecting our water supply.

The generalizations in these statements are misleading at best. The problems with reporting results in this overgeneralized manner could be- serious. For example, if the county agency has said that there is no problem, and a problem does show up, then the county agency loses credibility. The laboratory officials who have made generalizations also lose credibility. It is likely that none of these statements were intended to mislead anyone. Perhaps the most serious problem created by these reports is that large segments of the population decide there is no problem in their area. These people will be less interested in future programs. This, coupled with the idea espoused by many groups that all pesticide contamination is from point sources, make it more difficult to convince people that it is in their best interest to help answer the questions about the status of groundwater with respect to pesticides.

Point Versus Nonpoint Sources of Contamination

When a water sample from a well is determined to be contaminated by agricultural chemicals, questions about the source of contamination quickly arise. A pile of discarded agricultural chemical containers, a spill of agricultural chemicals, or some other point source is frequently identified as the source. Locating a source in the proximity of the well is not proof, it is only circumstantial evidence. One must identify all potential sources of contamination (both point and nonpoint), then determine the transport mechanisms.

Transport mechanisms include flow down a poorly constructed well or a well in disrepair, infiltration and transport through the soil to groundwater. Determination of potential transport mechanisms requires a thorough hydrogeologic investigation, including an analysis of the regional and local surface water and groundwater flow regimes and the spatial relationship of the suspected source(s) of contamination and the well intake. Generally, this type of information is obtained by measuring water levels in numerous wells and by collecting water samples for chemical analysis. Water levels in wells, taken around the contaminated well and at various depths, provide information on the groundwater flow regime and possible interaction with any surface water bodies. Chemical analyses of well water allows one to determine how the contaminant is distributed in the groundwater. With these data, the source(s) of contamination generally can be determined.

The following example illustrates the need to understand the site hydrogeology. The cross section (fig. 20) reveals that the well extracts water from a confined aquifer at depth. A source of agricultural chemicals (a pile of discarded agricultural chemical containers) is

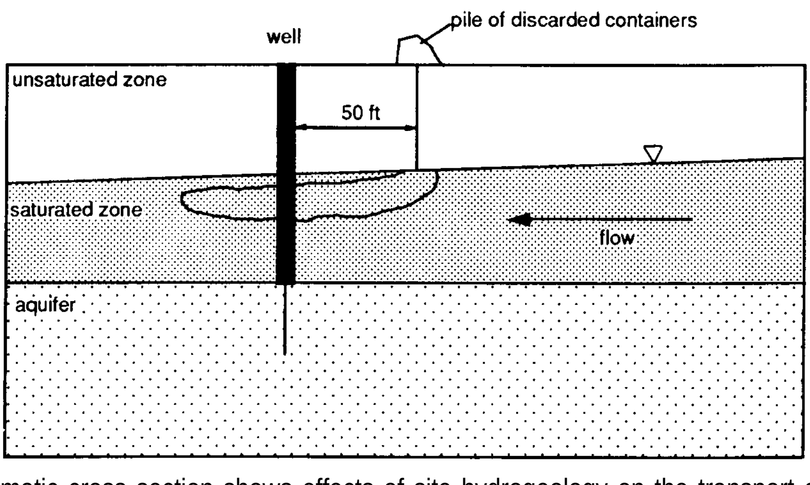

Figure 20 Schematic cross section shows effects of site hydrogeology on the transport of point source contamination.

located approximately 50 feet upgradient of the well. The well is properly cased and grouted, so the well is not a pathway for contaminant transport. The water table is shown on figure 20 and is sloping from right to left, Some of the agricultural chemical will infiltrate with precipitation and flow downward through the unsaturated zone until it reaches the water table. In the saturated zone, the contaminant will spread out, forming a plume of contamination. The plume will generally move in the same direction as the groundwater (from right to left in fig. 20). For the scenario shown, because of the flow regime and the hydrogeology in this area, the agricultural chemicals from the source near the well are probably not the source of contamination for the well shown.

Determination of the source of well contamination requires identification of the contaminant and its pathway(s) to the well. One cannot assume that because one source has been found that it is the only source of the well contamination. Are there nonpoint sources of contamination? Could the source be buried—a remnant of long forgotten practices? The site hydrogeology should be investigated thoroughly.

Summary and Conclusions

The growing number of volunteer-based sample collection programs reflects the concerns of individuals and county agencies and a desire to act in some positive way toward assessing and solving potential problems of groundwater contamination.

In designing a sampling program, care must be taken to examine exactly what is to be evaluated. For example, many counties were looking to assess the status of water in rural wells. By using volunteer sites, the statistical definition of randomness was not fulfilled. Therefore, the results will not be statistically representative of the wells in these counties, although they may be a typical sampling from the taps of private homes. The sampling program must be carefully designed in terms of the number of samples and where the samples will be collected.

Also, water quality of a sample is affected by the source of the water and the sampling protocol (the procedure used to collect and transport the sample to the analytical laboratory). For example, the environment in which the well is set has many factors that can influence the quality of the water from that well. In typical studies, the unknown variables, such as the plumbing, and treatments possibly affecting these samples have not been determined. In most county sampling programs, the depths of the wells sampled were not recorded and the history of the wells was undetermined. Therefore, subsets of the population of wells cannot be reanalyzed with these variables.

When a specific sampling population has been defined and samples from that population have been collected and analyzed, results of those analyses cannot be interpreted for a larger or different population. As the figure demonstrates, each level of the population sampled defines the segment of the population about which the conclusions can be drawn. Figure 21 describes the population represented by various sample groups.

The questions in the survey questionnaire were designed to determine whether the sampling programs had requested information about the environment of the wells sampled. The questions were intended to determine the conditions of all aspects of the sampling and analyses. The information was needed in order to determine if the results of various programs could be considered comparable. The results of this survey have clearly shown that the sampling programs in Illinois, to date, are varied enough that the results cannot be considered comparable to one another.

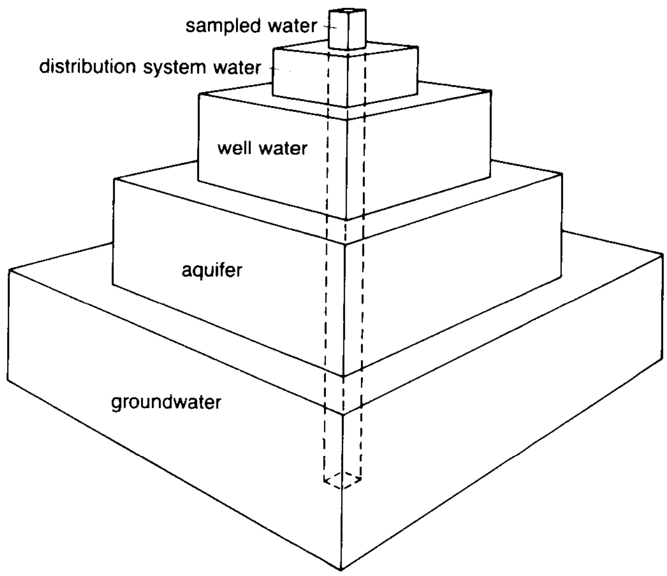

Figure 21 Relationship between various groundwater subpopulations available for sampling.

The information gathered from the mail survey further indicates that the results of the chemical analyses themselves cannot definitively answer the questions that motivated the sample collection programs. This is based on the facts that the programs themselves vary, the analytical processes are affected by many variables, and the number of samples is too small to draw defensible conclusions. Furthermore, the information cannot be used as one body of data for a statewide assessment of agricultural chemicals in groundwater.

PROPOSED STATEWIDE GROUNDWATER SAMPLING PROGRAMS

Proposed Stratified Random Survey of Rural Private Wells

The Illinois State Geological Survey and the Illinois State Water Survey have developed recommendations for the design of a statewide survey to assess the level of occurrence of agricultural chemicals (pesticides and nitrates) in rural private wells (McKenna et al. 1989a).

Key elements of the experimental design are

- sample population defined as drilled, rural, private water-supply wells;
- recommended analytes based on use in Illinois and potential to contaminate groundwater;
- stratified random sampling with the potential for contamination of shallow aquifers as the stratification variable;
- sampling plan to randomly select wells to sample within each of the strata;
- characterization of well sites and identification of potential contamination sources;
- well-sampling schedule that addresses the potential for temporal variability in the occurrence of agricultural chemicals;
- protocols for sample collection, transport, and storage to ensure that samples are representative of the sampled wells;
- use of the USEPA NPS analytical methods;
- quality assurance/quality control procedures to ensure collection of data of known quality;
- recommendations for project organization and management;
- recommendations for data management, statistical analysis, and interpretation of survey results.

The definition of the sample population excludes large-diameter dug or bored wells, which are highly susceptible to surface or near-surface sources of contamination because of their design and generally shallow depth. Inclusion of these wells might bias the assessment of the validity of using depth-to-aquifer as a predictor of contamination potential.

The groundwater samples should be analyzed for agricultural chemicals that have been extensively used in Illinois and that have a high potential to contaminate groundwater (tables 13 and 14). The USEPA-NPS analytical methods permit analysis of a wide variety of chemical compounds and are recommended for use in the statewide survey. Nitrate-nitrogen should also be a priority analyte.

Table 13 Recommended analytes for which USEPA NPS analytical methods are available

Chemical Name	*Type* [1]	*Chemical name*	*Type* [1]
2,4-D	H	disuifoton	I
2,4-DB	H	disulfoton sulfone	D
acifluorfen	H	disulfoton sulfoxide	D
alachlor	H	endrin	I
aldrin	I	endrin aldehyde	D
atrazine	H	EPTC	H
atrazine, dealkylated	D	ethoprop	I
bentazon	H	heptachlor	I
butylate	H	heptachlor epoxide	D
carbaryl	I	linuron	H
carbofuran	I	metolachlor	H
carbofuran phenol	D	metribuzin	H
carboxin	F	metribuzin DA	D
chloramben	H	metribuzin DADK	D
chlordane	I	metribuzin DK	D
chlorpropham	H	nitrate-nitrogen	PN
cyanazine	H	picloram	H
DDT	I	propachlor	H
diazinon	I	simazine	H
dicamba	H	terbufos	I
dieldrin	I	trifluralin	H
dinoseb	H	vernolate	H

[1] H = herbicide, I = insecticide, F = fungicide, D = degradation product, PN = plant nutrient

Table 14 Additional analytes dependent upon availability of analytical methods

Chemical Compound	*Type* [1]	*Chemical compound*	*Type* [1]
bromoxynil	H	metalaxyl	F
CDAA	H	methyl parathion	I
chlorpyrifos	I	pendimethalin	H
ethalfluralin	H	phtorate	I
fluazifop-butyl	H	phorate sulfone	D
clomozone	H	phorate sulfoxide	D
fonofos	I	sethoxydim	H
glyphosate	H	terbufos degradation products	D
imazaquin	H	trimethacarb	I

[1] H = herbicide, I = insecticide, F = fungicide, D = degradation product

The use of statistical sampling has been recommended by McKenna et al. (1989a) as the most cost-effective approach to estimate the statewide occurrence of agricultural chemicals in rural, private wells. The most appropriate statistical sampling technique for this survey is stratified random sampling, which involves the division of the population into nonoverlapping subpopulations called strata. The use of stratified random sampling is recommended because the potential for contamination of aquifers or water wells by agricultural chemicals varies across the state. The rural areas of the state were classified into one of four contamination-potential strata on the basis of depth to the uppermost aquifer (table 15).

The mapping of the contamination potential sequences was based primarily on depth from ground surface to highly permeable aquifer materials (fig. 7). For this study, the distinction between aquifer materials and aquifers is that aquifer materials have the hydrogeologic characteristics to be classified as aquifers, but the materials may not be saturated. In Illinois, the water table generally occurs 5 to 15 feet below ground surface. Below this depth, aquifer materials are generally saturated and capable of yielding water to a well. In areas mapped as having aquifer materials within 5 feet of the surface, the upper few feet of these materials may not be saturated. (These areas occupy 14.7 percent of the land area in rural Illinois.) Since these highly permeable materials would not significantly restrict movement of agricultural chemicals, these areas were interpreted to have a potential for contamination equivalent to areas having aquifers within 5 feet of ground surface.

Depth to the uppermost aquifer currently is considered to be the most appropriate, mappable criterion for statewide assessment of the potential for agricultural chemical contamination of rural, private wells. This approach is further justified by the fact that private water wells are usually completed within the uppermost aquifer. The mapped contamination potential of the area surrounding a well is assumed to be representative of the geology at the well site and consequently will not be field checked.

This sampling design will allow statistically valid inferences to be made regarding the frequency of occurrence of agricultural chemicals in groundwater samples from rural, private water wells in Illinois and in each of the four strata (table 15). It will also determine the significance of the differences between the occurrence of agricultural chemicals in the different strata. A minimum of 384 samples will be collected from each stratum. This sample size will allow valid inferences on the occurrence of agricultural chemicals in rural private wells to be made with a high level of confidence (95 percent) and at an acceptable level of precision (±5 percent). Consequently, the results of the statewide survey could be used to target educational and monitoring programs to areas where contamination is likely to occur.

Table 15 Drilled wells in rural Illinois by contamination potential strata (calculations based on NWWA data)

Strata class	Wells *total no.*	*Rural wells %*	*Rural land area %*
<5 ft	54,354	20.0	14.7
>5 to <20 ft	37,708	13.8	13.1
>20 to <50 ft	34,614	13.8	10.7
>50 ft	142,694	52.3	61.5

After all wells have been sampled, the wells will be restratified based on other variables, such as well depth, depth of screened intervals, and source aquifer. Restratification will allow for estimates, at a lower level of confidence, of the significance of these factors in the occurrence of agricultural chemicals in the sampled wells. Seasonal differences in the frequency of occurrence of agricultural chemicals in wells within the various strata also may be statistically verifiable.

The sampling schedule addresses the potential for temporal variability in the occurrence of agricultural chemicals; samples should be collected weekly for 1 year from a constant, equal number of locations in each stratum. To expedite sampling, two or three sampling teams would be formed, and wells sampled during the 1-year period would be grouped by geographic region.

The estimated total cost to complete the statewide survey is $2.3 million for a 2-year period (McKenna et al. 1989a). This estimate is based on the experimental design proposed in this study and assumes new staff and equipment would be required by each of the agencies to implement the statewide survey. The estimate also assumes that space for laboratories and offices is available and that no funds for space or basic support services are needed.

Pilot Study

The Illinois State Geological Survey (ISGS) and the Illinois State Water Survey (ISWS), in cooperation with the Illinois Department of Agriculture (IDOA), currently are conducting a pilot study to evaluate various components of the experimental design of the statewide survey. Funding to the Surveys is from the Environmental Protection Trust Fund through the IEPA and IDENR. IDOA activities are being funded through internal sources. The primary goal of the pilot study is to assure that the results of the statewide survey will be valid. There are two critical questions: (1) Are the sampled wells representative of all rural, private wells in the State? (2) Are the results of the chemical analyses accurate? The answer to both questions is important to state agencies. The second is of utmost importance to the users of each well sampled: Was the compound present in the sample at the reported concentration and were any other analyzed compounds present?

The pilot study will not provide statistically valid estimates of the occurrence of agricultural chemicals in rural, private wells in Illinois. However, the results of the pilot study should allow for more accurate estimates of the probability of occurrence of agricultural chemicals in rural, private wells in the four contamination potential strata (table 15), which are based on depth to the uppermost aquifer. Consequently, it may be possible to reduce the number of samples to be collected and analyzed in the statewide survey, while maintaining the same levels of confidence and precision. For example, if the results of the pilot study indicate that the highest estimated frequency of contaminant occurrence in any stratum is 30 percent, compared with the conservative estimate used in designing the statewide survey, the required number of samples for each stratum could be reduced to 322 from 384. Thus the required number of samples for all four subpopulations (strata) could be reduced by nearly 250 samples. If the highest frequency of occurrence is 20 percent, 552 fewer samples would be required. Any substantial reduction in sample numbers would result in significant cost savings in the statewide survey.

The principal goals of the pilot study are to

- implement six USEPA National Pesticide Survey (NPS) analytical methods;
- field test procedures (1) to inventory well sites and interview well-users, and (2) to collect, store, and transport water samples, and document sample custody;
- establish information management, including database development for sample custody and tracking, laboratory management, compilation of analytical results, and report generation;
- collect water samples from rural, private wells in five, hydrogeologically distinct, township-size areas for use in evaluating the validity of using depth to aquifer as a predictor of agricultural chemical contamination of rural private wells.

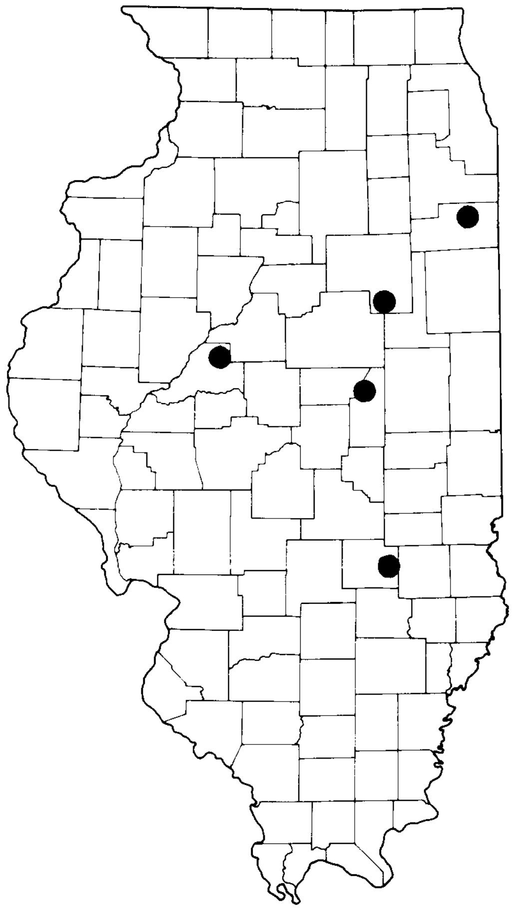

Figure 22 Location of pilot study areas.

In 1989, the ISGS and the ISWS implemented the NPS analytical methods; selected five township-size areas for sample collection in Mason, Kankakee, Livingston, Piatt, and Effingham Counties (fig 22); inventoried all private wells in each study area; and randomly selected well sites for sampling. Each of the five study areas will be characterized on the basis of land use, agricultural practices, agricultural chemical usage, soils, hydrogeology, and hydrology. Sample collection and analysis will begin in March 1990 and continue through February 1991. A final report will be released in December 1991.

Simple Random Survey of Rural Private Wells in Illinois

Recently the IDOA, the Cooperative Extension Service at the University of Illinois (CES), and the ISGS and ISWS initiated planning for a simple random survey of rural private wells in the state. The IDOA and the CES are currently planning to conduct this simple random survey with available resources.

This proposed study generally follows the experimental design for the stratified random sampling proposed by the ISGS and the ISWS (McKenna et al. 1989a). However, its design would have two key variations. First, the sample population would include large-diameter dug or bored wells. McKenna et al. had recommended that these wells be sampled in a special survey to assure the validity of the assessed depth to aquifer as a predictor of the potential for contamination of rural private wells. Second, wells for sampling would be randomly selected across all areas of the state without stratification on the basis of aquifer vulnerability. Consequently, statistical inferences could be made about the occurrence of agricultural chemicals in all rural wells in Illinois, although the simple random survey will not determine if any areas of the state are more vulnerable than others.

Table 16 Tentative initial schedule for pilot study and statewide survey

	1989	1990	1991	1992	1993
Pilot Study					
Method development	X				
Well selection	X				
Sample collection		X	X		
Sample analysis		X	X		
Training		X			
Report			X		
Simple Random Survey					
Well selection/characterization		X			
Sample collection		X	X		
Sample analysis		X	X		
Report			X		
Stratified Random Survey					
Well selection/characterization			X		
Sample collection				X	
Sample analysis				X	
Report					X

The schedule for the pilot study and tentative initial schedules for both the simple and stratified random surveys are shown in table 16. Actual scheduling and timing of the statewide surveys depends upon an evaluation of the procedures and results of the pilot study.

Structured Monitorlng of Public Water Supply Wells in Illinois

IEPA and the U.S. Geological Survey are planning a permanent monitoring network of up to 500 public water supply wells to be sampled on a 3- to 4-year cycle. The purpose of this network will be to establish a comprehensive background water quality for a broad spectrum of compounds including pesticides. The long-term monitoring will be structured similarly to the program proposed by O'Hearn and Schock (1985).

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Appendix A: Survey Questionnaire

SURVEY OF GROUNDWATER SAMPLING FOR PESTICIDES IN ILLINOIS
from
Illinois Department of Energy and Natural Resources

Agency ______________________________

Study or Program Name ______________________________

Contact Person ______________________________

Title ______________________________

Address ______________________________

____

Telephone ______________________________

Has your agency group conducted agricultural chemicals sampling programs?

Yes ________

No ________

Unknown ________

Has a report or summary been published?

Yes ________

No ________

Unknown ________

Are interim or partial results available?

Yes ________

No ________

Unknown ________

If such a report, summary, or Interim result is available, please forward a copy to us.

What was the reason for the collection of your data?

WELL INFORMATION

How many wells were sampled for water? ______________

How were those wells selected for sampling?

On what date were the well selections made?

What type of wells was selected?

Public Water Supply ________

Industrial/Commercial ________

Private Water Supply ________

Where were these wells located? (Please include a list of well locations — at very least the county and township.)

What were the depths of the wells selected?

Do you have information as to the aquifers tapped by each well?

Yes ______
No ______

Which aquifer(s) do the wells tap?

SAMPLE INFORMATION

What kind of samples were collected? How many samples were collected?

Groundwater ______ Number ______
Soil ______ Number ______

How were samples collected? Was there a written protocol to be followed by the sample collectors? If so, please include a copy of that protocol.

What was the sampling point?

At the well? ______
A tap at the well? ______
A tap away from the well? ______ Where? ______

What kind of sample containers were used?

How were the samples transported to the laboratory?

Where they refrigerated?
Yes ______ How? ______
No ______

What kind of preservation method was used?

ANALYSIS INFORMATION

What compounds were analyzed? (Please include a list of the compounds)

What analytical methods were used in your study?

What quality assurance/quality control practices were used in your study? Please be specific. Include how many blanks, duplicates, and spikes were used, standards used, etc.

Were positive determinations in those analyses confirmed?

Yes ______ By what technique? ______

No ______

If positive detections were determined, is the source of that compound known?

single near-well contamination event ______

what event? ______

long-term near-well contamination ______

what type? ______

other source of contamination suspected ______

what source? ______

What laboratory did the analyses?

Contact at laboratory: Lab Name ______

Yes ______ Name ______ Phone ______

No ______

Please include a list of the compounds, detection limits, and concentrations determined with your returned form.

ADDITIONAL SOURCES OF INFORMATION

Do your know of any other agency or group from whom we should request similar information?

Yes ______

No ______

Please list names and addressed of those groups or agencies.