NATURAL RESOURCES
CORNELL COOPERATIVE EXTENSION

Pesticides and Groundwater: A Guide for the Pesticide User

by Nancy M. Trautmann and Keith S. Porter
Center for Environmental Research
and Robert J. Wagenet
Department of Agronomy
Cornell University

Pesticide Contamination of Groundwater

Agricultural pesticide users traditionally have been concerned with protecting crop yields by controlling pest infestations. Environmental concerns have focused on protecting nontarget species, such as the birds whose eggs became unviable because of DDT; this compound was removed from agricultural use in 1973. Within the past decade a new concern has emerged. In the late 1970s, aldicarb was discovered in 96 wells on Long Island and DBCP (dibromochloropropane) was found in more than 2,000 wells in California, focusing attention on the question of how to control pests without contaminating groundwater. Subsequent surveys have discovered more pesticide residues in groundwater. In a recent study conducted by the U.S. Environmental Protection Agency, forty-six pesticides were found in groundwater in twenty-six states as a result of normal agricultural applications (table 1).

Once groundwater is contaminated, analyzing the problem and providing alternative water supplies can be quite expensive. Since the discovery in 1979 of aldicarb in Long Island groundwater, for example, more than $3 million has been spent measuring aldicarb concentrations in Long Island wells. Carbon filtration units have been installed in more than 2,500 affected households, and plans are being made to replace individual wells with expensive community water supply systems. These huge expenses have helped to define and treat the problem, yet have not corrected the underlying groundwater contamination.

Another possible consequence of pesticide contamination of groundwater is losing the use of a particular pesticide. Aldicarb, for example, may no longer be used on Long Island or in parts of California, Florida, Massachusetts, New Jersey, and Wisconsin. Other compounds such as DBCP and EDB (ethylene dibromide) were banned completely from agricultural use after their discovery in groundwater. Of the forty-six pesticides recently found in groundwater, twelve are no longer available for agricultural use.

Cleanup of groundwater contaminated by pesticides often is impossible, and the contamination may last for many years. The cold temperatures and low microbial activity in groundwater cause pesticide degradation to occur more slowly than at the soil surface. The slow movement of groundwater means that it may take decades for the contaminated water to flow beyond the affected wells. Even determining which wells will be affected and for how long is a difficult problem, necessitating expensive long-range monitoring to ensure the safety of drinking water supplies.

Table 1. Pesticides in current use that have been found in groundwater due to normal agricultural operations

Chemical Name	*Health Advisory Level*[a]	*States with Detections*	*Maximum Concentration (ppb)*	*Median Concentration (ppb)*[b]
1,3-D	0.20[c]	1	270.00	123.00
2,4-D	70	2	49.50	1.40
Alachlor	1.5[c]	12	113.00	0.90
Aldicarb	10	7	315.00	9.00
Aldrin		2	0.10	0.10
Atraton		1	0.10	0.10
Atrazine	3.0	13	40.00	0.50
Bromacil	80	2	22.00	9.00
Carbofuran	36	3	176.00	5.30
Chlorothalonil	1.5[c]	2	12.60	0.02
Cyanazine	9.0	6	7.00	0.40
Dacthal	3500	1	1039.00	109.00
Diazinon	0.63	1	478.00	162.00
Dicamba	9.0	2	1.10	0.60
Diuron	14	1		
Endosulfan		1	0.40	0.30
Ethoprop		1	12.60	
Fonofos	14	2	0.90	0.10
Hexazinone	210	1	9.00	8.00
Linuron		1	2.70	1.90
Malathion		1	53.00	41.50
Methamidophos		1	10.50	4.80
Methomyl	175	1	9.00	
Methyl parathion	2.0	1	256.00	88.40
Metolachlor	10	5	32.30	0.40
Metribuzin	175	4	6.80	0.60
Oxamyl	175	3	395.00	4.30
Parathion		1	0.04	0.03
Picloram	490	3	49.00	1.40
Prometon	100	1	29.60	16.60
Propazine	14	2	0.20	0.20
Simazine	35	7	9.10	0.30
Sulprofos		1	1.40	1.40
Trifluralin	2.0	4	2.20	0.40

[a] Proposed lifetime health advisory level
[b] Based on data from multiple studies, a single study, or a single well
[c] Lifetime exposure levels based on a 10^{-6} risk of causing cancer
Source: Williams (1988)

Clearly, the best solution is to keep pesticides out of groundwater through careful storage, use, and disposal practices.

Most farm families rely on their own wells. Such private wells are rarely tested or treated, and in many instances, they are located close to fields on which pesticides have been applied. Groundwater supplying the wells may contain pesticides that have been leached from the fields by rain, melted snow, and irrigation water. It should be noted, however, that most pesticides have not been found to leach, and certainly not all farm wells are contaminated. An understanding of what causes some pesticides but not others to leach is crucial in protecting groundwater quality.

Leaching of pesticides depends in part on the amount applied per acre per year; where, when, and how it is applied; the solubility of the compound; how strongly it is held by the soil; and how quickly it breaks down in the root zone. After a pesticide is applied to a field, it meets a variety of fates (fig. 1). Some may be lost to the atmosphere through volatilization, carried away to surface waters by runoff, or broken down in the sunlight by photolysis. Pesticides in soil may be taken up by plants, degraded into other chemical forms, or leached downward, possibly to groundwater. The remainder is retained in the soil and continues to be available for plant uptake, degradation, or leaching. How much pesticide meets each of these fates depends on many factors, including

- the properties of the pesticide,
- the properties of the soil,
- the site conditions, including climate, and
- management practices.

Many pesticides bind strongly to soil and are therefore immobile. For those that are mobile in soil, their leaching to groundwater can be thought of as a race in time between their degradation into nontoxic by-products and their transport to groundwater. If the pesticide is not readily degraded and moves freely with water percolating downward through the soil, the likelihood of it reaching groundwater is relatively high. If, however, the pesticide degrades quickly or is tightly bound to soil particles, then it is more likely to be retained in the upper soil layers until it is degraded to nontoxic by-products. Even if degradation is slow, this type of pesticide is unlikely to pose a threat to groundwater.

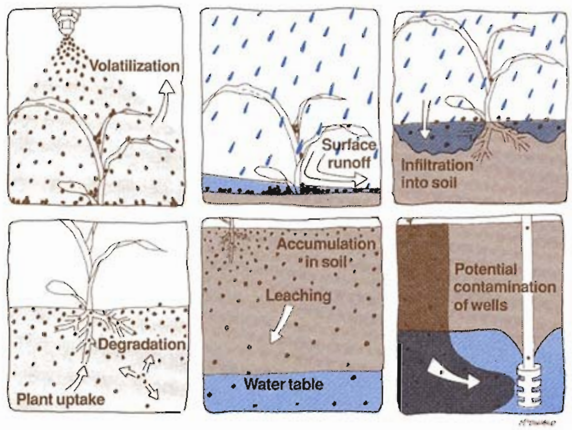

Fig. 1. ***Environmental fates of applied pesticides***

Pesticide Properties

Experience in the past ten years has shown that certain properties of pesticides are associated with leaching. As a result of many field and laboratory studies, the U.S. Environmental Protection Agency has compiled a list of key chemical and physical properties called threshold values (table 2). Compounds with properties that do not satisfy the threshold values warrant extra attention because of their relatively high potential for leaching to groundwater. The threshold values provide only a rough guide, however. The herbicide simazine, for example, is less soluble than the threshold value but nevertheless has been found in groundwater in seven states.

Table 2. Threshold values indicating potential for groundwater contamination by pesticides

Chemical or Physical Property	*Threshold Value*
Water solubility	greater than 30 ppm
Henry's Law Constant	less than 10^{-2} atm-m^{-3} mol
K_d	less than 5, usually less than 1 or 2
K_{oc}	less than 300 to 500
Hydrolysis half-life	more than 25 weeks
Photolysis half-life	more than 1 week
Field dissipation half-life	more than 3 weeks

Source: U.S. Environmental Protection Agency, 1986, *Pesticides in Groundwater: Background Document.*

Solubility

Chemicals that dissolve readily in water are said to be highly soluble. As water moves downward through soil, it carries with it water-soluble chemicals. All other properties being similar, the pesticide with a higher solubility has greater potential of being moved downward through the soil, possibly leaching to groundwater.

Volatilization

Vapor pressure is a measure of the tendency of a compound to become a gas. The higher the vapor pressure of a pesticide, the faster it is lost to the atmosphere and the less that remains available for leaching. This does not necessarily mean, however, that pesticides with high vapor pressures pose no threat to groundwater. Some pesticides, such as soil fumigants, are injected into the soil and therefore have limited exposure to the atmosphere. If these compounds are highly soluble in water, they can be carried with soil water to groundwater. EDB and DBCP, for example, are soil fumigants that have been detected in groundwater in several states.

The likelihood of a pesticide to volatilize is a function of both its vapor pressure and its solubility. This function is expressed by Henry's Law Constant (H), the second threshold value in table 2:

$$H = \frac{\text{vapor pressure}}{\text{solubility}}$$

The lower the value of the Henry's Law Constant, the greater the leaching potential of a pesticide. Examples of pesticides with high values for H and thus low leaching potentials include trifluralin, triallate, phorate, and dieldrin.

Adsorption

The tendency of a pesticide to leach also depends on how strongly it adsorbs to soil. Adsorption refers to the attraction between a chemical and soil particles. Compounds that are strongly adsorbed onto soil are not likely to leach, regardless of their solubility. They are retained in the root zone where they are taken up by plants or eventually degraded. Compounds that are weakly adsorbed, on the other hand, will leach in varying degrees depending on their solubility.

The strength of sorption is a function of the chemical properties of the pesticide, the soil type, and the amount of soil organic matter present. K_d and K_{oc}, the third and fourth threshold values listed in table 2, are measures of pesticide adsorption on soils.

K_d, the adsorption partition coefficient, can be calculated by mixing soil, pesticide, and water, then measuring the concentration of pesticide in solution after equilibrium is reached (fig. 2).

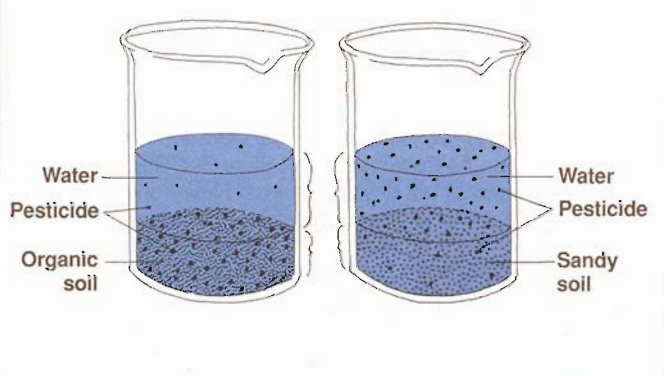

Fig. 2. K_d is calculated using measurements of pesticide distribution between soil and water. Organic soils retain more of a pesticide than do sandy ones.

The adsorption coefficient is the ratio of pesticide concentration in the adsorbed phase to that in solution:

$$K_d = \frac{\text{concentration of chemical adsorbed}}{\text{concentration of chemical dissolved}}$$

A wide range exists in pesticide partition coefficients. DDT, for example, has a K_d value roughly 20,000 times as high as that for aldicarb and 1,500 times as high as that for atrazine. This explains why aldicarb and atrazine have been found in groundwater in agricultural areas while DDT has not.

The major drawback of using K_d to predict leaching of pesticides is that it is highly dependent on soil characteristics. Organic matter is the most important soil constituent determining pesticide retention. It therefore is useful to adjust the K_d value by the percent organic carbon in the soil. This yields another adsorption coefficient, K_{oc}, which is relatively independent of soil type:

$$K_{oc} = \frac{K_d}{\text{\% organic carbon in soil*}}$$

(* percentage expressed as a decimal fraction)

Degradation

The final three threshold values listed in table 2 are measures of a pesticide's rate of degradation, or chemical breakdown. The longer the time before a compound is broken down, the longer it is available to treat the target pest, be it weed or insect. Unfortunately, however, the pesticide also is subject to leaching over this longer period of time.

One process through which pesticides degrade is photolysis, or breakdown caused by exposure to sunlight. Another is hydrolysis, the reaction of a chemical with water. Hydrolysis of pesticides occurs in the root zone and at slower rates in groundwater. The third major form of pesticide degradation is through oxidation and other reactions mediated by microorganisms in the soil.

The natural distribution of microbes in the soil has important implications for managing pesticides. The vast majority of microbes live in the uppermost parts of the soil. If a chemical leaches below the root zone, it encounters far fewer microbes and is less likely to degrade before leaching to groundwater.

The final value in table 2, the field dissipation half-life, is an overall empirical estimate of the length of time in which half of the original amount of the applied pesticide will disappear. This estimate takes into account physical, chemical, and biological degradation, plant uptake, and for highly volatile pesticides, volatilization. The longer the half-life, the greater the length of time the pesticide remains in the soil and, hence, the longer the opportunity to leach.

Half-life is difficult to predict because it varies widely for each compound and soil condition. Factors affecting half-life include

- soil type,
- soil temperature,
- soil moisture content,
- concentration of the chemical,
- method of application,
- chemical structure,
- amount of sunlight, and
- microbial populations.

Although half-life estimates provide a useful empirical measure of pesticide degradation in soil, their use requires caution. Because half-life estimates are highly dependent on the chemical, physical, and biological properties of the soil being tested, they cannot be accurately extrapolated to soils under different conditions. In general, degradation proceeds faster in moist soils than in dry ones, but the changes in half-life are not consistent from one soil to another.

Half-lives in subsoils are usually much longer than those for the root zone because of the great reduction in microbial populations and the changes in physical and chemical conditions. Once a pesticide gets into groundwater, therefore, its degradation is likely to proceed at a slower rate than that predicted by its half-life in the root zone.

Soil Properties

Many soil characteristics affect leaching; the principal ones are

- soil texture,
- soil permeability,
- soil organic matter content, and
- soil structure, including macropores.

Soil texture is determined by the relative proportions of sand, silt, and clay. Texture affects the movement of water through soil and, therefore, also the movement of dissolved chemicals such as pesticides. The coarser the soil, the faster the movement of percolating water and the lower the opportunity for adsorption of dissolved chemicals. Soils with more clay and organic matter tend to hold water and dissolved chemicals longer. These soils also have far more surface area on which pesticides can be adsorbed. The coarser the soil texture, therefore, the greater the chance of a pesticide reaching groundwater.

Soil permeability is a measure of how fast water can move downward through a particular soil. Water moves quickly through soils with high permeability, so frequent irrigation may be necessary. Because dissolved chemicals are transported by percolating water, in highly permeable soils the timing and methods of pesticide applications need to be carefully designed to minimize leaching losses.

Soil organic matter influences how much water is retained in the soil and how well pesticides are adsorbed. Increasing the soil's organic content, such as by applying manure or plowing under cover crops, therefore enhances the soil's ability to hold both water and dissolved pesticides in the root zone.

Soil structure, the way soil particles are aggregated, also affects water movement. Compared with compacted soil, loosely packed soil aggregates are more likely to allow easy downward movement of water. Sometimes large openings (macropores) resulting from physical processes such as animal borings or freezing and thawing permit rapid water movement through fine-textured soils in which water movement would otherwise be slow.

Site Conditions

Conditions of the site also affect the potential for leaching of pesticides. These include

- depth to groundwater,
- geologic conditions,
- topography, and
- climate and irrigation practices.

Depth to Groundwater

Depending on climate and local geology, groundwater may be only a few feet below the soil surface. With such shallow depths to groundwater, the filtering action provided by the soil and the opportunities for degradation or adsorption of pesticides are low. Extra precautions are needed to protect groundwater in such cases. If rainfall is high and soils are permeable, water carrying dissolved pesticides may take only a few days to percolate downward to groundwater.

The depth to groundwater does not remain constant over the course of the year. It varies according to the amount of precipitation and irrigation, whether the ground is frozen, and how much groundwater is being withdrawn by pumping. Groundwater levels tend to fall in summer, when evaporation and plant uptake are high, and in winter if recharge is hampered by frozen soils. Spring and fall generally are times of greatest recharge and, therefore, also of highest water table elevations. Such fluctuations in recharge quantities affect recharge quality as well. The high water table elevations in spring, for example, mean there is less possibility for soil filtration of pesticides leached from the root zone by heavy spring rains.

Geologic Conditions

In addition to the depth to groundwater, it is important to consider the permeability of the geologic layers between the soil and groundwater. Gravel and other highly permeable materials allow water and dissolved pesticides to percolate freely downward to groundwater. Layers of clay, on the other hand, are much less permeable and thus inhibit the movement of water. Groundwater quality is most vulnerable in areas where permeability of geologic layers is rapid.

Regions with limestone deposits are particularly susceptible to groundwater contamination because water with dissolved pesticides can move rapidly through cracks in the bedrock underlying the soil, receiving little filtration or chance for chemical degradation before reaching groundwater.

Topography

Whether water runs off the land surface or infiltrates into the soil depends on topography, plant cover, and soil type. Surface runoff is greatest on land with steep slopes, sparse vegetation, and relatively impermeable soils. Water that runs off hilltops and hillsides tends to collect in depressions, where it sits until it evaporates or infiltrates into the soil. In flat areas with permeable soils, water will infiltrate into the ground rather than run off. Susceptibility to leaching is highest in flat or depressed areas because of the greater chance for infiltration rather than runoff.

Climate and Irrigation Practices

Areas with high rates of rainfall or irrigation are most susceptible to leaching of pesticides, especially if the soils are highly permeable. If high rainfall or heavy irrigation occurs during or shortly after the application of agricultural chemicals, the chemicals can be quickly leached from the root zone. Once leached below the root zone, pesticides cease to be available for effective action on the target pest and become potential groundwater contaminants.

Management Practices

Another factor determining leaching potential is the way in which a pesticide is applied. The injection or incorporation of a pesticide into soil makes it readily available for leaching. The rate and timing of a pesticide's application also are critical in determining whether it will leach. The larger the amount used and the closer the time of application to a heavy rainfall or irrigation, the more likely that any pesticide prone to leaching will be lost to groundwater. When practicing chemigation, the risk of pesticide leaching can be minimized by using the lowest amount of water needed to activate the pesticide.

Protecting Groundwater

Many factors determine whether a pesticide will reach groundwater, including its chemical properties, the soil type, the depth to groundwater, and the pesticide management practices. By combining all these factors, the areas most vulnerable and the practices most conducive to pesticide contamination of groundwater can be determined (table 3).

Table 3. Factors indicating the greatest likelihood of groundwater contamination by pesticides

Pesticide properties	*Site conditions*
• high solubility	• shallow depth to groundwater
• low adsorption	• wet climate or extensive irrigation
• persistence	• depressions or flat areas where water collects
Soil characteristics	*Management practices*
• sand and gravel	• poor timing with respect to climate
• low organic matter content	• overapplication (rate too high or application too frequent)

Greatest care needs to be taken with pesticides that are highly soluble, do not adsorb strongly to soil particles, and persist for a long time in soil. The Environmental Protection Agency has established a list of such pesticides, called suspected leachers, for which extra precautions should be used to prevent contamination of groundwater. Some of these are listed in table 4.

Recommended Applicator Practices

Pesticide applicators can minimize leaching by following these guidelines:

- Use pesticides only when necessary and in the minimum dose consistent with effective pest management.
- Determine the soil type and its susceptibility to leaching before using pesticides.
- Apply pesticides specifically to the target site, avoiding wells and surface water such as ponds and streams.
- Choose pesticides with low susceptibility to leaching.
- Follow the storage, use, and disposal directions on the pesticide label. If regionally specific recommendations such as the *1990 Cornell Recommends for Field Crops* are available, use these instead.
- Measure carefully, and stay within the recommended application rates.
- Properly calibrate and maintain application equipment.
- Avoid pesticide spills, and prevent back-siphoning of pesticide-contaminated water into the water source.
- Properly dispose of any leftover pesticides, tank mixes, and rinse water according to label instructions or Cornell Cooperative Extension recommendations.
- Store pesticides safely, in the original labeled container and in a cool, well-ventilated location away from wells, pumps, or other water sources.
- Maintain records of pesticide use to avoid overuse and to help plan future applications.
- Delay irrigation at least one or two days after pesticide applications.
- Avoid irrigation runoff, especially in clay soils, to decrease erosion and pesticide contamination of water supplies.
- Periodically inspect wells to ensure that their location is distant from pesticide application sites and that the well seals are properly constructed and maintained to prevent the entry of surface contaminants.
- Spray-apply pesticides only under calm, no-wind conditions.
- Wherever possible, use Integrated Pest Management.

Integrated Pest Management

Integrated Pest Management (IPM) seeks to reduce pesticide use to the minimum level necessary to produce high-quality food and agricultural products while protecting human health and environmental quality. The New York State IPM program operates under five objectives:

- To minimize crop losses caused by insects, weeds, and plant diseases.
- To optimize the use of cultural management techniques, biological pest controls, and resistant varieties.
- To maximize the effectiveness of pesticide use.
- To reduce pest management costs.
- To minimize the development of pesticide resistance.

IPM encourages natural control with beneficial organisms such as predators, parasites, and pathogens. Monitoring, or "scouting," is used to detect pest infestations so that pesticide applications can be targeted to times of need. Such field monitoring can significantly reduce pesticide use while protecting crop yields. In New York State, for example, onion growers who followed IPM thresholds based on weekly monitoring reports from field scouts were able to reduce insecticide use by 54 percent and save $24 per acre in insecticide costs. Thrips

Table 4. Pesticides susceptible to leaching to groundwater

Chemical Name	***Common Trade Names***
Acifluorfen	Blazer, Tackle
Alachlor	Alanex, Alanox, Alatox, Bronco, Lasso, Nudor
Aldicarb	Temik
Aldrin	Aldrex, Aldrite, Altox
Ametryn	Ametrex, Evik, Gesapax, Trinatox
Atrazine	Aatrex, Atratol, Bicep, Conquest, Extrazine, Marksman
Bromacil	Hyvar, Krovar
Carbofuran	Furadan
Chloramben	Amiben
Chlorothalonil	Bravo, Daconil, Exotherm Termil
Cyanazine	Bladex, Conquest, Extrazine
Dalapon	Dalapon, DPA
DCPA (Dimethyltetra-chloroterephthalate)	Dacthal
Diazinon	Knox Out, Basudin, Dazzel, Spectracide, and others
Dicamba	Banvel, Marksman, Weedmaster
2,4-Dichloro-phenoxyacetic acid	Envert, Landmaster, Plantgard, Salvo, Tordon, Weedar, Weed-B-Gon, Weedone, and others
1,3-Dichloropropene	D-D 92, Telone II Soil Fumigant
Disulfoton	Di-Syston
Diuron	Karmex, Krovar
Endosulfan	Thiodan
Ethoprop	Mocap
Fenamiphos	Nemacur
Fluometuron	C-2059, Cotoran, Cottonex
Fonofos	Dyfonate
Hexazinone	Velpar
Linuron	Gemini, Lorox
Malathion	Cythion, Malamar, Vegfru, Zithiol, and others
Methamidophos	Monitor
Methomyl	Lannate, Lanox, Methomex, Nudrin
Methyl parathion	Penncap-M
Metolachlor	Bicep, Dual, Turbo
Metribuzin	Canopy, Lexone, Sencor, Turbo
Oxamyl	Vydate
Parathion	Alkron, Phoskil, Soprathion, Thiophos, and others
Picloram	Grazon, Tordon
Prometon	Pramitol
Pronamide	Kerb
Propazine	Gesamil, Milogard, Milo-Pro, Primatol, Prozinex
Simazine	Amizine, Princep, Simadex
Sulprofos	Bolstar
Tebuthiuron	Spike
Terbacil	Geonter, Sinbar
Trifluralin	Spike, Treflan

populations were 42 percent lower than those on farms that did not participate in the field scouting program, and the quality of the harvested onions was unaffected.

Most groundwater contamination problems are associated with pesticides applied to control soil-dwelling pests such as nematodes, weeds, pathogens, and insects. IPM programs of greatest importance in reducing groundwater contamination are those that minimize the use of soil pesticides. Such methods include crop rotation, fallowing, solarization, the use of resistant cultivars, and the use of less persistent pesticides.

Studies have shown that nematode damage of cotton yields in California can be fought just as effectively by rotating crops with resistant tomato cultivars as by fumigating the soil before planting. Nematode-resistant potato varieties likewise have reduced the need for pesticides on potato crops. To control the golden nematode, growers formerly had to both fumigate the soil prior to planting and apply other pesticides during the growing season. Using eleven newly developed resistant varieties, New York State potato growers have reduced pesticide use by 56,000 gallons over the past four years.

Various estimates suggest that the adoption of currently available IPM practices would permit a 40 to 50 percent reduction in the use of insecticides within a five-year period and a 70 to 80 percent reduction in the next ten years, without sacrificing crop yield or grower profit. Lower pesticide use would accordingly reduce the potential for groundwater contamination.

Conclusions

Although pesticide contamination of groundwater was unrecognized only twenty years ago, it has emerged in recent years as a major factor in the development, licensing, and use of pesticides in the United States. When pesticides do get into groundwater, cleanup of the contamination usually is impossible. The contamination can last many years and spread over a large area before dilution and chemical decay eventually reduce the pesticide concentrations to levels acceptable for drinking water. A major question facing modern agriculture, therefore, is how to control pests and protect crop yields without allowing pesticides to contaminate underlying groundwater.

Many factors determine whether a pesticide will leach to groundwater, including pesticide properties, soil characteristics, site conditions, and management practices. The pesticides most susceptible to leaching are those with high solubility in water, low adsorption to soil, and long-term persistence. When these pesticides are applied to sites with sandy soils, shallow depth to groundwater, and either a wet climate or extensive use of irrigation, the risk of groundwater contamination is high.

Pesticide applicators can take measures to help protect groundwater quality. These include assessing the susceptibility of the site before using pesticides, then tailoring pesticide applications to the particular site conditions. IPM programs can help protect groundwater by promoting the use of a variety of economically and ecologically sound pest control techniques rather than sole reliance on chemical pesticides.

For Further Reading

Cohen, S. Z., S. M. Creeger, R. F. Carsel, and C. G. Enfield. 1984. Potential pesticide contamination of groundwater from agricultural uses. In *Treatment and Disposal of Pesticide Wastes*, ed. R. F. Kruger and J. N. Sieber, 297-325. ACS Symposium Series no. 259. Washington, D.C.: American Chemical Society.

Cornell University and the New York State Department of Agriculture and Markets. 1987. *New York State Integrated Pest Management Program, 1987 Annual Report*. Geneva,N.Y.: New York State Agricultural Experiment Station.

Graham-Bryce, I. J. 1981. The behavior of pesticides in soil. In *The Chemistry of Soil Processes*, ed. D. J. Greenland and M.H.B. Hayes. Sussex, England: John Wiley and Sons Ltd.

Marer,P.J., M.L. Flint, and M.W. Stimmann. 1988. *The Safe and Effective Use of Pesticides*. University of California, Statewide Integrated Pest Management Project, Division of Agriculture and Natural Resources, Publication 3324.

New York State College of Agriculture and Life Sciences. 1990. *1990 Cornell Recommends for Field Crops*. Ithaca, N.Y.: Cornell Cooperative Extension. (Available from Cornell University Distribution Center, 7 Research Park, Ithaca, NY 14850)

Williams, W.M., P.W. Holden, D.W. Parsons, and M.W. Lorber. 1988. *Pesticides in Ground Water Data Base, 1988 Interim Report*. Washington: U.S. Environmental Protection Agency, Office of Pesticide Programs.

A Related Slide Set:

Porter, K. S., and M. W. Stimmann. 1988. Protecting Groundwater. A Guide for the Pesticide User. Slide Set, Storyboard, and Manual for Instructors. (Available from New York State Water Resources Institute, Cornell University, Ithaca, NY 14853.)

Other fact sheets in this series include

- *Modern Agriculture: Its Effects on the Environment* (400.01)
- *Nitrate: Health Effects in Drinking Water* (400.02)
- *Pesticides: Health Effects in Drinking Water* (400.03)
- *Groundwater: What It Is and How to Protect It* (400.04)
- *Water and the Soil* (400.05)
- *Nitrogen: The Essential Element* (400.06)

Acknowledgments: Illustrations were drawn by Michelle McDonald, and Mary Jane Porter served as production assistant. Funding was provided by the New York Farmers' Fund. Many individuals reviewed the initial drafts, including Cornell University faculty members, northeastern Cornell Cooperative Extension agents, and employees of the U.S. Environmental Protection Agency and the U.S. Geological Survey.

This publication is issued to further Cooperative Extension work mandated by acts of Congress of May 8 and June 30, 1914. It was produced with the cooperation of the U.S. Department of Agriculture and Cornell Cooperative Extension, College of Agriculture and Life Sciences, College of Human Ecology, and College of Veterinary Medicine, at Cornell University. Cornell Cooperative Extension provides equal program and employment opportunities.

46/100 11/89 4M GPP E90181G