USGS
science for a changing world

Rec'd 12/18/98

In cooperation with the
Ohio Department of Agriculture

Analysis of the Sensitivity of Soils to the Leaching of Agricultural Pesticides in Ohio

Water-Resources Investigations Report 98-4108

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
U.S. Geological Survey

Analysis of the Sensitivity of Soils to the Leaching of Agricultural Pesticides in Ohio

By Charles W. Schalk

Water-Resources Investigations Report 98-4108

In cooperation with the
Ohio Department of Agriculture

U.S. Department of the Interior
Bruce Babitt, Secretary

U.S. Geological Survey
Thomas J. Casadevall, Acting Director

For additional information write to:

District Chief
U.S. Geological Survey
975 West Third Avenue
Columbus, Ohio 43212-3192

Copies of this report can be purchased from:

U.S.Geological Survey
Branch of Information Services
Box 25286, Building 810
Denver, Colorado 80225-0286

CONTENTS

PLATES

FIGURES

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter
	Area	
acre	4,047	square meter
acre	0.4047	hectare
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second
	Application rate	
pounds per acre (lb/acre)	1.121	kilograms per hectare
	Permeability	
inches per hour (in/hr)	25.4	millimeters per hour

Analysis of the Sensitivity of Soils to the Leaching of Agricultural Pesticides in Ohio

By Charles W. Schalk

Abstract

Pesticides have not been found frequently in the ground waters of Ohio even though large amounts of agricultural pesticides are applied to fields in Ohio every year. State regulators, including representatives from Ohio Environmental Protection Agency and Departments of Agriculture, Health, and Natural Resources, are striving to limit the presence of pesticides in ground water at a minimum. A proposed pesticide management plan for the State aims at protecting Ohio's ground water by assessing pesticide-leaching potential using geographic information system (GIS) technology and invoking a monitoring plan that targets aquifers deemed most likely to be vulnerable to pesticide leaching.

The U.S. Geological Survey, in cooperation with Ohio Department of Agriculture, assessed the sensitivity of mapped soil units in Ohio to pesticide leaching. A soils data base (STATSGO) compiled by U.S. Department of Agriculture was used iteratively to estimate soil units as being of high to low sensitivity on the basis of soil permeability, clay content, and organic-matter content. Although this analysis did not target aquifers directly, the results can be used as a first estimate of areas most likely to be subject to pesticide contamination from normal agricultural practices.

High-sensitivity soil units were found in lakefront areas and former lakefront beach ridges, buried valleys in several river basins, and parts of central and south-central Ohio. Medium-high-sensitivity soil units were found in other river basins, along Lake Erie in north-central Ohio, and in many of the upland areas of the Muskingum River Basin. Low-sensitivity map units dominated the northwestern quadrant of Ohio.

Introduction

Agriculture is the largest industry in Ohio. In 1994, about 75,000 Ohio farms encompassed 15.2 million acres of land, drove a $57 billion industry, and produced $1.7 billion in net cash income (Ohio Department of Agriculture, 1995). Money spent on agricultural chemicals continues to grow to accommodate this industry. In 1992, Ohio farmers spent $190 million on agricultural chemicals, not including fertilizers; of all acres on which these chemicals were applied, 80 percent were treated with herbicides and 18 percent were treated with insecticides (U.S. Department of Commerce, 1994).

Pesticides have been found seasonally in Ohio's surface water for years; less frequent or widespread, however, has been the detection of pesticides in ground water. More than 5 million Ohioans (about 46 percent) rely on ground water for drinking supply (R. J. Veley, U.S. Geological Survey, 1997, written commun.). Of these, about 64 percent are served by public water systems, whereas 36 percent are supplied by domestic wells. Protection of ground-water sources is an important issue facing Ohio and its agricultural community.

The proposed State Management Plan (SMP) for Pesticides for the State of Ohio (State Coordinating Committee on Ground Water, 1996) addresses concerns of pesticides in ground water from a regulatory and managerial perspective. Few detections of pesticides in ground water can be documented, and most of them were in samples from areas known to be especially vulnerable, such as the karstic limestone sinkhole region in Hardin, Wyandot, and Seneca Counties (plate 1) (State Coordinating Committee on Ground Water, 1996). The ground-water data base is limited—not necessarily to the inclusion of pesticides as constituents of interest, but to the detections of pesticides in samples. The highest concentrations of pesticides in ground-water samples are associated with improper storage or handling of pesticides (State Coordinating Committee on Ground Water, 1996).

Because of the absence of pesticide detections in ground-water samples, the generic SMP for pesticides in Ohio is preventative rather than remedial in nature. Continued monitoring for pesticides is an important part of the plan. Component 5 of the SMP addresses methods whereby a monitoring network can be established; the overlay of geographic information system (GIS) data layers is an integral part of the proposed methodology for establishing the network.

The U.S. Geological Survey (USGS), in cooperation with the Ohio Department of Agriculture (ODA), used a GIS data base to identify mapped soil units from which ground-water samples are likely to contain detectable concentrations of pesticides; that is, those soil units that are sensitive to pesticide contamination in Ohio. In accordance with SMP recommendations, GIS technology is the basis of the analysis. ODA and other agencies will use this information to establish a network of monitoring wells that can be used to support the goals of the generic SMP.

Three terms must be defined in order to place this report in its proper context of the generic SMP. The definitions that follow are derived from definitions used by U.S. Environmental Protection Agency (USEPA) (U.S. Environmental Protection Agency, 1993, p. 9). Aquifer sensitivity refers to the relative ease with which a pesticide can migrate to an aquifer of interest, and is a function of the intrinsic properties of the aquifer and overlying geologic materials. Aquifer sensitivity is not dependent on land-use practices or pesticide properties. Aquifer vulnerability refers to the relative ease with which an underlying aquifer can be affected by contamination resulting from the combined effects of the physical characteristics of the soil and pesticide, the hydrogeologic processes occurring in the area of ground-water recharge, and the management of the land. Analogous to aquifer sensitivity is soil sensitivity, which is the likelihood of a soil to have properties affecting the leaching of surface-applied pesticides to ground water. Again, soil sensitivity is not dependent on agronomic practices or pesticide properties.

In most cases, vulnerable aquifers are overlain by sensitive soils. In other cases, vulnerable aquifers may be recharged from areas that are distant from the overlying soils, which may be relatively unlikely to leach pesticides. A sensitive soil may not indicate the presence of a vulnerable aquifer if, for example, land management is such that pesticides are never applied or are applied sparingly. For a further discussion on the definitions of these terms, the reader can examine the review provided by USEPA (1993).

Purpose and scope

The purpose of this report is to present results of a study to characterize the sensitivity of mapped soil units of Ohio with respect to pesticide-leaching potential. The results are presented in the form of a statewide map (plate 1) and supplementing text. This report is intended for use by state planners who, in their need to institute the generic SMP and establish a representative well-monitoring network, require a reasonable estimate of areas likely to contain soil units with high pesticide-leaching potential.

The results of this study are a small part of fulfilling the requirements of Ohio's generic SMP for pesticides. A discussion is presented in the section "Suggestions for Further Study" on the means whereby the results of this study can be applied to estimates of aquifer sensitivity and vulnerability. GIS data layers that could be used in a vulnerability assessment, including land use and pesticide-application distribution, are described. Both are related to land management. None of the data layers used in this analysis are related directly to hydrogeologic processes, which must be addressed in a comprehensive assessment of aquifer vulnerability.

The results of this analysis are preliminary. No statewide pesticide-detection data were available to use as a "calibration target" for this analysis. The methods used for this analysis probably will be refined in the future as more and (or) better ground-water-quality data and appropriate GIS data layers are obtained. It is understood that, just as the SMP itself is dynamic and somewhat iterative, so also are the methods used to estimate sensitive soils.

These statewide estimates of sensitive soil units, compiled from statewide soils data, should be interpreted at the proper scale. The results cannot be applied to areas at scales any smaller than 1:250,000 without introducing distortion to the results. The reader should have a clear understanding of the composition of the STATSGO data base (discussed later) in order to interpret and use the results of this study correctly.

Description of study area

Ohio lies within the Great Lakes and Ohio River watersheds. Major streams and their tributaries that flow north to Lake Erie include Maumee, Sandusky, Cuyahoga, and Grand Rivers (plate 1). Major streams and their tributaries that flow south to Ohio River include Muskingum, Hocking, Scioto, Little Miami, and Great Miami Rivers (plate 1). More than 40 percent of Ohio's 10.8 million people (U.S. Bureau of the Census 1990 decennial census files) live in the five major metropolitan areas that are on or near these streams.

Ohio's climate is temperate, characterized by hot and humid summers and fairly cold winters. About 39 in. of precipitation falls on the State annually. Most of Ohio lies in two physiographic provinces: the Central Lowland, which covers most of the western half of the State, and the Appalachian Plateaus, which cover the eastern half of the State (fig. 1). A small part of southern Ohio is in the Interior Low Plateaus. Topography of the Central Lowland is flat, with some relief in glaciated moraine areas, whereas topography of the mostly unglaciated Appalachian and Interior Low Plateaus is hilly.

A generalized map of principal aquifers in Ohio is shown in figure 1. The most productive aquifers are coarse-grained, unconsolidated deposits of glacial outwash and alluvium; these aquifers typically yield 100-500 gal/min, but can yield more than 2,000 gal/min. Other primary aquifers and their typical yields are carbonate-bedrock aquifers in western Ohio, 5-300 gal/min; fine-grained unconsolidated aquifers, 25-50 gal/min; and sandstone-bedrock aquifers in northeastern Ohio, 5-25 gal/min (U.S. Geological Survey, 1985).

Acknowledgments

The author recognizes the efforts and assistance of those who served on the ground-water and pesticides subcommittee, especially Chris Kenah, Mark Bamberger, and Mark Wilson of Ohio Environmental Protection Agency, Larry Berger and Keith James of Ohio Department of Agriculture, and Rebecca Petty and Mike Hallfrisch of Ohio Department of Natural Resources, Division of Water. Thanks also are given to Rich Gehring, U.S. Department of Agriculture, Natural Resources Conservation Service.

Literature review

The following review of the literature addresses three concepts concerning the scope of this report. The first is processes relating to the leaching of pesticides through soil; these are important as they pertain to the selection of variables used in the analysis of soil sensitivity described in this report. Also discussed are two techniques reported in the literature for assessing aquifer vulnerability to pesticide contamination. The last part of this review is a brief examination of regulations concerning the management of pesticides in Ohio.

Movement of pesticides in soil

Pesticides move through the soil profile under the effect of hydraulic and chemical gradients and numerous inhibiting factors. Two main processes affecting pesticide movement, transport and adsorption, are discussed here; a third, decay, is not discussed.

Transport processes. Ground-water flow in a soil matrix can be distinguished as being either Darcian or preferential. Darcian flow is readily predictable and uniform, being proportional to the hydraulic gradient and the hydraulic conductivity. Advection is the transport of pesticides with the flow of ground water. Diffusion, which is the movement of chemicals in solution due to concentration gradients, and dispersion, which is the mechanical spread of chemicals due to variabilities in flow velocities at particle-sized scales, occur simultaneously with advection. Preferential flow through soil macropores, which are channels 0.9-5.0 mm or larger, is irregular, highly localized, and often unpredictable but of extreme importance in agricultural systems. Primarily, the effect of macroporosity is to accelerate the transport of water and dissolved chemicals beyond the root zone and deep within the soil profile (Kelley and others, 1986). Soils with

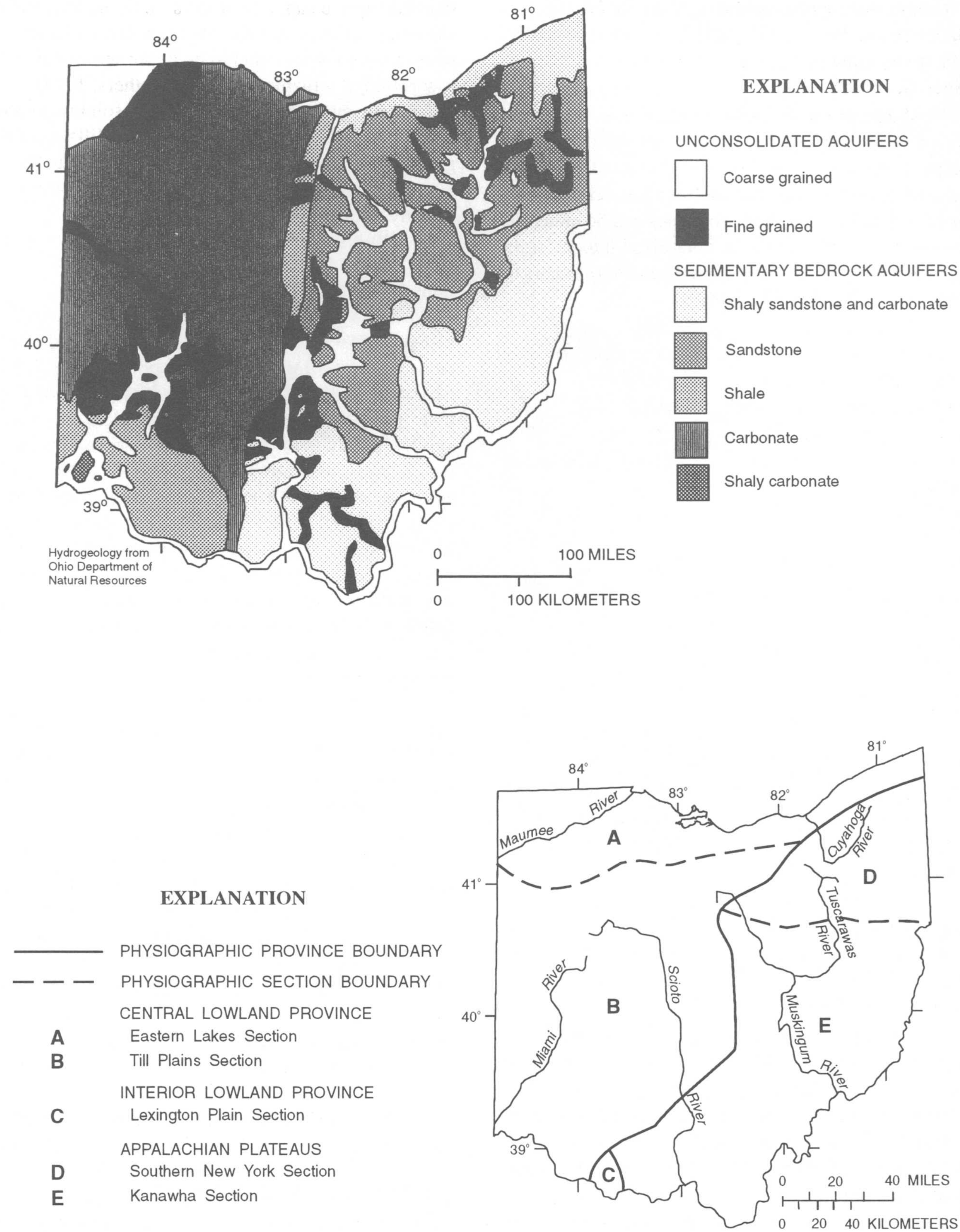

Figure 1. Principal aquifers and physiographic diagram and divisions in Ohio.

extensive macroporosity and high shrink-swell potential often are important in the determination of high-sensitivity aquifers (U.S. Environmental Protection Agency, 1993, p. 12).

Adsorption processes. Adsorption is the bonding of a chemical constituent to some part of the solid phase of the soil matrix. Adsorbed molecules are considered immobile and unavailable for either transport or plant uptake. Desorbed molecules can be either dissolved in the soil solution or volatilized into the soil air (under unsaturated conditions) and are available for chemical reaction or transport.

Much research has focused on determining the most important soil and chemical properties that affect adsorption. Some chemicals, especially pesticides, will adsorb strongly to soil particles where the organic content is significant (Baker and Johnson, 1977; Leonard and others, 1986). Pesticide mobility is indirectly proportional to organic content and directly proportional to soil moisture in the soil (Lichtenstein, 1958). Organic matter plays the most significant role in the adsorption of chemicals on most soils (Cherry and others, 1984; Saltzman and Yaron, 1986). Two major reasons are the availability of functional bonding groups (carboxyls, phenolics, peptides, and others) and the large number of polyvalent exchange sites (Fe^{2+}, Ca^{2+}, Al^{2+}) for complexation of the chemical (Sposito, 1989). When in aqueous solution, organic compounds bond preferentially to organic matter rather than to mineral surfaces (Saltzman and others, 1972; Huang and others, 1984).

Soil moisture affects adsorption because water molecules compete with chemical ions for exchange sites on the soil and (or) organic matter particles (Sposito, 1989). In general, adsorption potential of most pesticides is greater at low moisture content than at high moisture content (Barlow and Hardaway, 1956; Best and others, 1972). Leaching potential increases with soil-moisture content.

The effect of pH in soil-chemical reactions is varied. In some circumstances, adsorption is not at all affected by pH (Hance, 1965; Lemley and others, 1988), whereas in other circumstances, pH is highly important (Wood and others, 1987; Murray and Hall, 1989; Best and others, 1972). In general, chemicals that dissociate in solution are likely to be strongly affected by pH, whereas the rest will appear not to be affected by pH (Jury, 1986).

Clay particles, like organic matter, usually contain complexation sites and therefore contribute to the total adsorptive capacity of the soil. Some iron and aluminum oxides common in clay minerals (called sesquioxides) were found to be important in the adsorption of atrazine (Huang and others, 1984).

Adsorption usually increases as soil temperature decreases (Saltzman and Yaron, 1986; Mills and Biggar, 1969). This inverse relation may be due to the effects of temperature on solubility, which increases directly with temperature.

Sensitivity and vulnerability assessments

The USEPA published a review of methods used to assess aquifer sensitivity and vulnerability to pesticides (U.S. Environmental Protection Agency, 1993). Methods that address aquifer sensitivity included hydrogeologic setting-classification (HSC) methods and scoring methods. HSC methods are used to delineate subareas that have similar sensitivities based on key hydrogeologic factors. Factors used in the HSC methods include depth to water, hydraulic conductivity, land slope, soil characteristics (including texture, permeability, pH, and composition), and characteristics of parent material. For the most part, groupings of subareal units are used with these methods rather than numerical rankings or weightings of the effects of each hydrogeologic factor.

The HSC method has been used in several applications, including assessments of aquifer sensitivity in the Denver area, soil leachability in Kansas, shallow-aquifer contamination in Illinois, aquifer-contamination vulnerability in South Dakota, and soil-attenuation potential in Wisconsin (U.S. Environmental Protection Agency, 1993). A New Jersey study (Vowinkel and others, 1994; Vowinkel and others, 1996) found that the factors that affected aquifer sensitivity the most were distance of the wells from the aquifer outcrop area, organic-matter content of the soils at the wells (which in this case were public-supply wells), and depth to the top of the open interval of the wells. Additionally, land-use and distance factors were found to affect on the presence of pesticides in water from the wells.

In most HSC case studies, the data of a particular kind (such as depth to aquifer or soil texture) are mapped in separate layers and the analysis includes a geographically referenced data overlay. Generally the mapping is at large scales, and the analysis is appropriate as a screening tool for broad areas, such as counties. The HSC methods are empirical by nature and, therefore, require users to have high levels of hydrogeologic expertise (U.S. Environmental Protection Agency, 1993).

Hydrogeologic factors also are used in scoring or ranking methods, but because the weighting "rules" are more universally applied than those in HSC methods, the results are understandable by nontechnical people and are readily reviewed. In these methods, the ranges of factors are subdivided into increments, and each increment is assigned a sensitivity value on a scale of 1 to 10, with 10 being the most sensitive. After each factor is scored, the scores are combined to produce an overall score for the map unit. The scoring factors and weights remain consistent for all map units.

Applications of the scoring method include DRASTIC (Aller and others, 1985), SEEPAGE (Moore, 1988), and state-specific studies in Idaho, Michigan, Minnesota, South Dakota, and Wisconsin. Several of these applications might incorporate additional factors, such as the SEEPAGE method, which accounts for whether a contamination source is concentrated or dispersed.

The DRASTIC method uses ratings from 1-10, based on data ranges, and weightings from 1 to 5 of 7 factors (**D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the unsaturated zone, and hydraulic **C**onductivity of the aquifer) to calculate a pollution potential index for an area of interest (Aller and others, 1985). This method can be applied to large-scale areas, such as states, or small-scale areas, such as counties, depending on the availability of scale-pertinent data. The Ohio Department of Natural Resources (DNR), Division of Water, is in the process of mapping the counties of Ohio according to DRASTIC methods (R. Petty, Ohio Department of Natural Resources, oral commun., 1997).

Ohio's SMP for pesticides (State Coordinating Committee for Ground Water, 1996) promotes an HSC method to assess aquifer vulnerability on the basis of land use, geologic factors (drawn from DRASTIC analysis), and soil factors. High, medium, and low categories in DRASTIC and the soils maps will provide indications of which aquifers of Ohio are most vulnerable to pesticide leaching.

A second major review of ground-water vulnerability assessments was done as part of the USGS National Water-Quality Assessment (NAWQA) program (Barbash and Resek, 1996). Of the 19 studies of ground-water vulnerability reviewed, only a few studies had their results reported with statistical comparisons; results from the other studies were described qualitatively. Of those studies that reported statistical comparisons, most (including an Ohio study described in Baker and others (1989)) obtained relatively small coefficients of determination. In the words of the authors, "These low coefficients of determination demonstrate the limited ability of most vulnerability assessment schemes to predict subsurface contamination . . . Such limitations are a concern, given the widespread use of vulnerability assessments by state and federal agencies for setting ground-water protection priorities and designing sampling programs" (Barbash and Resek, 1996, p. 389).

Regulations

A detailed set of Ohio's regulations concerning the management of pesticides and other potential contaminants is given in the appendix to the proposed SMP for pesticides (State Coordinating Committee for Ground Water, 1996). Previous sections of that document address the legal authority for various Ohio agencies, including ODA, Ohio DNR, Ohio EPA, and the Department of Health, to be involved in the management of pesticides, the prevention of misuse or mishandling of pesticides, and various aspects of response to their detections in water supplies.

Methods

A digital, statewide, soil data base was selected to perform a predictive estimate of the areas in Ohio containing soils most sensitive to the transport of agricultural pesticides. The data used in this analysis are the state soil geographic data base (STATSGO), which is a 1:250,000-scale digital map "designed to be used primarily for regional, multistate, river basin, state, and multicounty resource planning, management, and monitoring" (U.S. Department of Agriculture, 1991).

The STATSGO data base is spatial and tabular. Only the 166 map units are distinguished spatially. Each map unit is based on sample statistics of soils that are geographically associated. One cannot tell how soils with a particular physical characteristic are distributed within a map unit, only that a certain percentage of the soils in that map unit have such a characteristic (R. Pierce, U.S. Geological Survey, written commun., 1998). Tabular detail of the map units includes information on sequence and layer. Each map unit contains 21 or fewer sequences, resulting in 2,224 combinations of map units and sequences (an average of about 13 sequences per map unit). Each sequence contains descriptions of one to six soil layers. Generally, the map units are fairly distinctive groups of soils, but soil properties can vary by sequence. Data contained in STATSGO generally describe the upper 5 to 6 ft of soil. A schematic of the arrangement of data in STATSGO is shown in figure 2.

Variables used in the analysis of soil sensitivity

The literature and a local expert (Rich Gehring, Natural Resources Conservation Service, Columbus, Ohio, oral commun., 1997) indicate that three fields in the STATSGO data base represent properties that are most likely to be influential on pesticide leaching: clay content, organic matter content, and permeability. All three properties are quantified as upper and lower limits within each soil layer for each sequence. Since the values of the properties were used as variables in the analysis described in this report, they will be referred to henceforth as variables.

Clay content (CLAY) is clay fraction present in the soil layer. The U.S. Department of Agriculture defines clays as being soil particles of diameter less than 0.002 mm (Hillel, 1982). A soil is classified as a clay texturally if it contains more than 55 percent clay and no more than 15 percent sand.

Organic matter (OM) is the percentage of organic material in a soil layer. The range of organic content in productive mineral soils is about 2 to 5 percent by weight, with perhaps 4 percent being regarded as optimal (Gustafson, 1941).

Permeability (PERM) is the vertical hydraulic permeability of the soil in a given layer. Generally this is quantified under saturated conditions, and because of the nonlinear relations among permeability, volumetric moisture content, and soil-water potential, hydraulic permeability decreases with decreases in moisture content (Hillel, 1982). Sandy soils generally are most permeable, whereas silty clays are least permeable (James, 1988).

A Pearson's correlation matrix was computed on the 2,224 combinations of map unit and sequence to determine whether any of the variables provided redundant information. The results of this analysis are shown in table 1. The highest correlation was between PERM and CLAY (0.54); OM was not highly correlated to either of the other two variables.

Table 1. Cross-correlation matrix of Ohio STATSGO variables used in soil-sensitivity

[OM, organic-matter content; PERM, permeability; CLAY, clay content]

	CLAY	OM	PERM
CLAY	1.00	0.01	-0.54
OM	0.01	1.00	0.00
PERM	-0.54	0.00	1.00

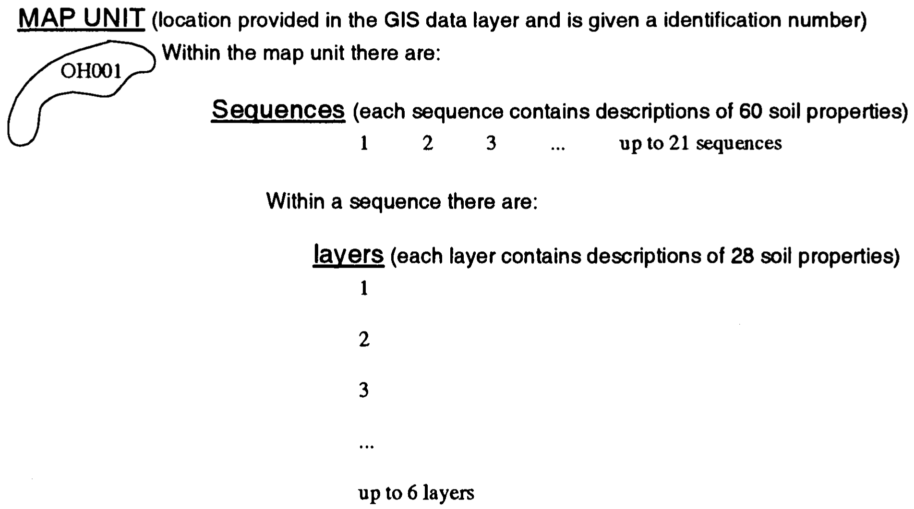

Figure 2. Relation among map units, sequences, and layers in STATSGO (adapted from U.S. Department of Agriculture, 1991).

Assumptions

The following assumptions for the STATSGO analysis were made on the basis of the chemical and hydrologic literature:

- High clay content inhibits pesticide movement; in a soil profile, the layer having the most clay content (and correspondingly smallest pores and largest number of mineral-reaction sites) controls the vertical movement of water.
- High organic content inhibits pesticide migration because of the high number of reaction sites provided by organic matter.
- High permeabilities promote high advective pesticide movement.

Because all three variables (clay content, organic matter, and permeability) are quantified by soil layer in STATSGO, the value associated with the soil layer that would limit pesticide leaching the most was used in this analysis (that is, the highest values of clay content and organic matter and the lowest value of permeability were used from each soil profile for each sequence in the map units). The most limiting values were used because they provide a controlling threshold for pesticide migration. For example, if the permeability of five of the six soil layers is 6 in/hr, but the permeability of the sixth layer is 0.2 in/hr, the lowest permeability would control the vertical flux of infiltrating water and would subsequently be of most interest to this analysis.

Distribution of sensitivity indices

Sensitivity indices on a scale of 1 (low likelihood of pesticide leaching to an underlying aquifer) to 10 (high likelihood of leaching) were assigned to each variable. The indices were based on ranges of values (table 2), and each index contained approximately the same number of observations, where possible. In some cases, the index spanned a group of values (such as index 1 for all organic-matter contents greater than 15 percent) because of the distribution of data in STATSGO, but most of the indices were associated with a single value in the data base (such as index 3 for organic-matter content equal to 6 percent). The modal values for each variable (0 percent for organic matter, 0.6 in/hr for permeability, and 35 percent for clay content) occurred many times more than the other values of those variables; consequently, those modal values represent more than 10 percent of the data for each variable.

Table 2. Sensitivity indices for three variables used in the Ohio STATSGO analysis

[--, no associated value; >, greater than]

Assigned sensitivity index	Clay content		Organic content		Permeability	
	Value (percent)	Percentage of total	Value (percent)	Percentage of total	Value (inch per hour)	Percentage of total
1	>54	8.9	> 15	0.2	0.0-0.01	8.5
2	45-53	6.7	7-15	1	0.06	15.6
3	36-42	6.8	6	1.5	--	--
4	35	20.9	5	1.5	.2	20.2
5	31-34	5.8	4	6.7	--	--
6	28-30	10.1	3	13.5	.6	43.4
7	27	16.0	2	4.1	2	7.1
8	22-26	8.7	1	4.5	--	--
9	18-20	8.6	0.1-0.5	10	6	4.5
10	1-17	7.5	0	57	20	.7

Classification of soil sensitivity

The end product of this analysis was the grouping of soil-map units into five classes of relative sensitivity to pesticide leaching. The classes were described as low, medium-low, medium, medium-high, and high sensitivities. The basis for grouping soils with respect to their sensitivity to pesticide leaching depends partly on statistical methods and partly on scientific expertise. The method described hereafter was based on statistical methods to produce a result that was afterward evaluated by the pesticide subcommittee. Generally, an exercise such as sensitivity assessment should contain a component of verification; that is, unbiased ground-water-quality data that have been obtained previously and can be used as calibration targets for a model such as the one described in this report. Such data were not available for this analysis.

Probably the most difficult problem in this analysis was how to weight the three variables (CLAY, OM, and PERM) for use in the high-to-low grouping of soil-map units. Unlike DRASTIC, where seven input variables are weighted based on consensus of experts, statistical methods were used in this study in order to determine which variables should be weighted most heavily for any given STATSGO map unit. To this end, an iterative analysis was prepared for the STATSGO data set. The purpose of this analysis was to determine the sensitivity of the resulting classification (high, medium, low, and others) to uncertainty in the weighting of the factors (described below). In this analysis, each of the three variables was weighted independently from 1 to 3, resulting in 27 (3^3) separate predictions of sensitivity to pesticide leaching by the methods described in the rest of this section.

Sums were calculated for each map unit-sequence combination according to the equation

$$SUM = a(OM) + b(PERM) + c(CLAY)$$

where the coefficients a-c are the iterative weighting factors (each of which could take integer values from 1 to 3) and OM, PERM, and CLAY are the assigned sensitivity indexed values of the soil variables listed in table 2. The sums were grouped by percentiles to assess the classes of soil sensitivity into which they fell. For example, map unit-sequence combinations whose sums were in the lowest 20 percent of all sums were assigned a low sensitivity rank (value = 1), and map unit-sequence combinations whose sums were between the 20th and 40th percentiles of all sums were assigned a medium-low sensitivity rank (value = 2). Combinations whose sums were in the highest 20 percent of all sums were assigned a high sensitivity rank (value = 5), and so forth.

The final step in the statistical analysis was to aggregate the results of the iterative procedure to determine which variable had the greatest positive effect on the high-to-low ranking for each map unit. This was done by a cross-correlation of the weighted value of each factor (1-3) and the resultant sensitivity rank (1-5) determined during the iterative procedure. The most positively correlated variable for each map unit was weighted heaviest in the final calculation (using the SUM equation), and the resultant sums were grouped into high-to-low sensitivity categories according to the percentile procedure described above.

Soil sensitivity to pesticide-leaching potential

The results of the statistical analysis of soils in the STATSGO data base are shown on plate 1. Soil-map units of high sensitivity are found primarily in glaciofluvial areas, along Lake Erie, and in parts of south-central Ohio. The glaciofluvial areas correspond generally with soils that are underlain by permeable sands and gravels in recent river valleys and (or) glacial buried valleys, such as are prevalent in southwestern Ohio and the Muskingum River Basin. The soil-map units along Lake Erie that are classified as high sensitivity contain high percentages of beachfront sands. High-sensitivity soil-map units in south-central Ohio are described as generally well drained.

Some of the high-sensitivity soil-map units are found in alluvial settings along 11 rivers and streams. Included are St. Joseph River in Williams County, Auglaize River in Paulding County, St. Marys River and Beaver Creek in Mercer County, Scioto River in Hardin County, Ohio River in Meigs County, and Muskingum River and its tributaries (including Tuscarawas River, Mohican River, Sandy Creek, and Salt Creek) in Muskingum, Coshocton, Stark, Tuscarawas, Carroll, Guernsey, Ashland, and Richland Counties (plate 1).

In some areas, high- sensitivity soil-map units are adjacent to low-sensitivity soil-map units. The Auglaize and St. Joseph River valleys in northwestern Ohio are high-sensitivity soil-map units in alluvium surrounded by low-sensitivity soil-map units in glacial till. High-sensitivity map units dominated by beach-ridge sands and coarse-grained recent alluvium in Van Wert and Mercer Counties are adjacent to low-sensitivity soil-map units of the Pewamo-Blount association, which were formed in glacial till (Brock and Tornes, 1972). Adjacent high- and low-sensitivity soil-map units in Crawford, Marion, Delaware, and Jackson Counties are described similarly in their respective county soil surveys; however, the high-sensitivity map units contain soils that are described as being well drained or moderately well drained, whereas the low-sensitivity map units contain soils that are described as poorly drained. In the cases of these soil-map units, permeability was the deciding variable in the analysis.

In most areas, medium-high-sensitivity soil-map units are adjacent to medium-sensitivity map units. The buried valleys in eastern Ohio (Muskingum River Basin) are represented by high-sensitivity soil-map units, whereas the buried valleys in southwestern Ohio (Great Miami, Mad, and Little Miami River Basins) are represented by mostly medium-high-sensitivity soil-map units. Other areas containing medium-high-sensitivity map units are the southern Scioto River Basin, the central shoreline of Lake Erie, and most of the uplands in the Muskingum River Basin (plate 1).

Low-sensitivity soil-map units are found mostly in the agricultural north and west parts of Ohio. These map units can contain occasional areas of highly transmissive soils, but are predominantly deep silt loams or silty clays of glacial origin having organic-matter content in the range of 2-4 percent and low permeabilities.

Suggestions for additional study

This study was designed to provide preliminary estimates of soil sensitivity to pesticide leaching without using or providing calibration or verification data. Generally, a study of this nature can be enhanced with an improved methodology that includes calibration data based on multivariate statistics and long-term verification analysis. The ODA will use the results of this study to focus initial pesticide-sampling efforts in areas designated as high or medium-high sensitivity, and the data acquired during sampling can be used as calibration data for an improved method of estimating aquifer sensitivity.

Data contained in STATSGO are statistical representations of properties of soils that are spatially associated; they are averages of soils that are grouped primarily on the basis of their location (R. Pierce, U.S. Geological Survey, written commun., 1998). As such, the data are limited in their usefulness to quantitative analysis. A much better estimate of sensitivities of the kind addressed in this report can be obtained using small-scale, highly detailed digital county soil maps. These maps are being developed for Ohio counties and, when completed, should provide the basis for a similar analysis having results that are less averaged than those obtained during this study.

This study did not address hydrogeologic effects on pesticide leaching and transport. Additional study could include the effects of recharge rates, proximity to recharge areas, ground-water-flow directions, and pumping on potential leaching pathways. These factors could be included in a multivariate statistical analysis, along with soil, aquifer, and chemical characteristics, to determine the most important factors concerning the detection of pesticides in ground water.

Data layers such as pesticide use, land use, or land cover can be used to estimate aquifer vulnerability. USGS land-use and land-cover data (known as GIRAS files) are 1:250,000-scale digital files that contain information on hydrogeologic, political, and land-use units. The data are in ARC/INFO format and are available on the World Wide Web (http:www.epa.gov/docs/ngispr/metalulc.html). GIRAS regions in Ohio are categorized as urban, agricultural, rangeland, forest, water, wetlands, or barren. Twelve quadrangles are needed to cover Ohio.

Pesticide-sales data can be used as an estimate of where pesticides are being applied, though this estimate requires the assumption that the pesticides are being applied near the areas where they are purchased. Sales data are in ARC/INFO format and are reported as county-wide averages in pounds per acre (Battaglin and Goolsby, 1994).

The benefits of a comprehensive study that includes soil, aquifer, chemical, and hydrogeologic aspects on pesticide leaching were demonstrated recently in New Jersey (Vowinkel and others, 1996). The New Jersey study identified low-vulnerability aquifers that could be sampled much less frequently than other, higher vulnerability aquifers. By using multivariate statistics to estimate the presence of pesticides in ground water (and these factors could vary from state to state or aquifer to aquifer), local and state agencies could spend funds for sampling most appropriately in high-vulnerability areas and monitor for pesticides in low-vulnerability areas only as needed.

Summary

A statistical analysis of selected characteristics of Ohio soils was used to predict the sensitivity of mapped soil units to pesticide leaching. The 1:250,000-scale STATSGO data base (U.S. Department of Agriculture, 1991) was used as the basis for this analysis. Variables included in the analysis were clay content, organic-matter content, and permeability.

Soil-map units from STATSGO were ranked on a five-tiered scale of high to low sensitivity as a result of the statistical analysis. Soil-map units of highest sensitivity were found in parts of the Auglaize, St. Joseph, and Muskingum River Valleys; in parts of central and south-central Ohio; and in beach-ridge areas along Lake Erie and in Van Wert and Mercer Counties. Many of the other river valleys in Ohio contain medium-high-sensitivity soil-map units, including the valleys in southwestern Ohio, the rest of the Muskingum River valley, and parts of the Scioto and Ohio River valleys. Soil-map units of lowest sensitivity were primarily in northern and western Ohio.

References cited

Aller, L., Bennett, T., Lehr, J.H., and Petty, R.J., 1985, DRASTIC—A standardized system for evaluating ground water pollution potential using hydrogeologic settings: U.S. Environmental Protection Agency EPA/600/2-85/018, Ada, Okla., 163 p.

Baker, D.B., Wallrabenstein, L.K., Richards, R.P., and Creamer, N.L., 1989, Nitrate and pesticides in private wells of Ohio—A state atlas: Heidelberg College, Water Quality Laboratory, Tiffin, Ohio, 304 p.

Baker, J.L., and Johnson, H.P., 1977, Impact of subsurface drainage on water quality: Third National Drainage Symposium, Chicago, Illinois. American Society of Agricultural Engineers, St. Joseph, Mich.

Barbash, J.E., and Resek, E.A., 1996, Pesticides in ground water—Distribution, trends, and governing factors: Chelsea, Mich., Ann Arbor Press, 588 p.

Barlow, F., and Hardaway, A.B., 1956, Effect of changes in humidity on the toxicity and distribution of insecticides sorbed by some dried soils: Nature, v. 178, p. 1299-1300.

Battaglin, W.A., and Goolsby, D.A., 1994, Spatial data in geographic information system format on agricultural chemical use, land use, and cropping practices in the United States: U.S. Geological Survey Water-Resources Investigations Report 94-4176, 87 p.

Best, J.A., Weber, J.B., and Weed, S.B., 1972, Competitive adsorption of diquat^{2+}, paraquat^{2+}, and Ca^{2+} on organic matter and exchange resins: Soil Science, v. 114, p. 444-450.

Brock, A.R., and Tornes, L.A., 1972, Soil survey of Van Wert County, Ohio: Washington, D.C., U.S. Department of Agriculture Soil Conservation Service, 73 p.

Cherry, J.A., Gillham, R.W., and Barker, J.F., 1984, Contaminants in ground water *in* Studies in geophysics—Groundwater contamination: Washington, D.C., National Academy Press, p. 46-64.

Gustafson, A.F., 1941, Soils and soil management: New York, McGraw-Hill, 424 p.

Hance, R.J., 1965, The adsorption of urea and some of its derivatives by a variety of soils: Weed Research, v. 5, p. 98-107.

Hillel, Daniel, 1982, Introduction to soil physics: San Diego, Calif., Academic Press, 364 p.

Huang, P.M., Grover, R., and McKercher, R.B., 1984, Components and particle size fractions involved in atrazine adsorption by soils: Soil Science, v. 138, p. 20-24.

James, L.G., 1988, Principles of farm irrigation system design: New York, John Wiley and Sons, 543 p.

Jury, W.A., 1986, Chemical movement through soil *in* S.C. Hern and S.M. Melancon, eds., Vadose zone modeling of organic pollutants: Chelsea, Mich., Lewis Publishers.

Kelley, R., Hallberg, G.R., Johnson, L.G., Libra, R.D., Thompson, C.A., Splinter, R.C., and DeTroy, M.G., 1986, Pesticides in ground water in Iowa *in* Proceedings of Agricultural Impacts on Ground Water, Omaha, Nebraska: Dublin, Ohio, National Water Well Association.

Lemley, A.T., Wagenet, R.J., and Zhong, W.Z., 1988, Sorption and degradation of aldicarb and its oxidation products in a soil-water flow system as a function of pH and temperature: Journal of Environmental Quality, v. 17, p. 408-414.

Leonard, R.A., Shirmohammadi, A., Johnson, A.W., and Marti, L.R., 1986, Pesticide transport in shallow ground water: St. Joseph, Mich., American Society of Agricultural Engineers, American Society of Agricultural Engineers Paper 86-2508.

Lichtenstein, E.P., 1958, Movement of insecticides in soils under leaching and non-leaching conditions: Journal of Economic Entomology, v. 51, p. 380-383.

Mills, A.C., and Biggar, J.W., 1969, Solubility-temperature effect on the adsorption of gamma- and beta-BHC from aqueous and hexane solutions by soil materials: Soil Science Society of America Proceedings, v. 33, p. 210-216.

Moore, J.S., 1988, SEEPAGE—A system for early evaluation of the pollution potential of agricultural ground water environments: Chester, Pa., U.S. Department of Agriculture, Soil Conservation Service, 1 p.

Murray, M.R., and Hall, J.K., 1989, Sorption-desorption of dicamba and 3,6-dichlorosalicyclic acid in soils: Journal of Environmental Quality, v. 18, p. 51-57.

Ohio Department of Agriculture, 1995, Annual report and statistics, 1994: Reynoldsburg, Ohio, 139 p.

Saltzman, S., Kliger, L., and Yaron, B., 1972, Adsorption-desorption of parathion as affected by soil organic matter: Journal of Agriculture and Food Chemistry, v. 20, p. 1224-1226.

Saltzman, S., and Yaron, B., 1986, Pesticides in soil: New York, Van Nostrand Reinhold.

Sposito, G., 1989, The chemistry of soils: New York, Oxford University Press, 277 p.

State Coordinating Committee on Ground Water, 1996, Proposal for pesticide management plan for the state of Ohio, part 1—The generic SMP: Reynoldsburg, Ohio, Ohio Department of Agriculture, 79 p. with appendix.

U.S. Department of Agriculture, 1991, State soil geographic data base (STATSGO) data users guide: Washington, D.C., Soil Conservation Service Miscellaneous Publication 1492, 88 p.

U.S. Department of Commerce, 1994, Census of agriculture, 1992, volume 1—geographic area series, part 35—Ohio state and county data: Washington, D.C., 520 p. with appendixes.

U.S. Environmental Protection Agency, 1993, A review of methods for assessing aquifer sensitivity and ground water vulnerability to pesticide contamination: U.S. Environmental Protection Agency 813-R-93-002, 147 p. with appendixes.

U.S. Geological Survey, 1985, National water summary 1984—Hydrologic events, selected ground-water trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p.

Vowinkel, E.F., Clawges, R.M., and Uchrin, C.G., 1994, Evaluation of the vulnerability of water from public-supply wells to contamination by pesticides, p. 495-510, *in* Weigman, D.L., ed., 1994, New directions in pesticide research, development, management, and policy: Proceedings of the Fourth National Conference on Pesticides, November 1-3, 1994, Blackburg, Va., Virginia Water Resources Center, 852 p.

Vowinkel, E.F., Clawges, R.M., Buxton, D.E., Stedfast, D.A., and Louis, J.B., 1996, Vulnerability of public drinking water supplies in New Jersey to pesticides: U.S. Geological Survey Fact Sheet FS-165-96, 4 p.

Wood, L.S., Scott, H.D., Marx, D.B., and Lavy, T.L., 1987, Variability in sorption coefficients of metolachlor on a Captiva silt loam: Journal of Environmental Quality, v. 16, no. 3, p. 251-256.

APPENDIX

APPENDIX 1. STATISTICAL SUPPLEMENT: ANALYSIS OF RANKINGS

In order to understand the results of the STATSGO analysis, some statistics were determined for the results of the sensitivity rankings. Two data sets were used for this part of the analysis: (1) a listing of map unit, ranking result, number of times a combination of map unit and sequence resulted in that ranking, and percentage of times that the combinations of map unit and sequence resulted in that ranking (766 rows of data); and (2) a listing of map unit and maximum percentage of times any ranking was produced (166 rows of data, one row per map unit). Examples of the two data sets are shown in table 1. Data set 2 was a subset of data set 1.

The data supplied for map unit OH001 can be used as an example to explain the statistical approach. As the iterative procedure was run with the STATSGO data base, map unit OH001 and its 10 sequences produced combinations that fell into the upper quantile (high sensitivity) 27 times, or 10 percent of the times; the middle quantile (medium sensitivity) 59 times, or about 22 percent of the times; and the lowest quantile (low sensitivity) 62 times, or 23 percent of the times. Soils in map unit OH001 were ranked most frequently as medium-low sensitivity (76 times, or about 28 percent), and the value corresponding to this maximum frequency was stored in data set 2.

Distributions of the fourth column of data set 1, the frequency of a ranking expressed as a percentage for each map unit, and the equivalent second column of data set 2 were nearly lognormally distributed and skewed to the right. Histograms of the square roots of the data were approximately normally distributed. Summary statistics for these data are presented in table 2.

Maximum frequencies for 4 map units were greater than 80 percent. For another 22 map units, maximum frequencies were between 60 and 80 percent. Rankings were distributed somewhat evenly for 77 map units (such as OH001; table 3) whose maximum frequency of a ranking was between 20 and 40 percent. Maximum frequencies for most of the map units were between 40 and 60 percent. These results indicate that most of the combinations of map unit and sequence did not fall overwhelmingly into one ranking, although rankings for most map units fell at least 40 percent of the time into one category.

Table 1. Partial listing of two data sets used to determine statistics on the rankings analysis in STATSGO

Data set 1				Data set 2	
Map unit	Ranking result	Frequency (N)	N as a percentage of records for the map unit	Map unit	Maximum N as a percentage of records for the map unit
OH001	1	62	23.0	OH001	28.1
OH001	2	76	28.1	OH002	25.5
OH001	3	59	21.9	OH003	54.8
OH001	4	46	17.0	OH004	70.8
OH001	5	27	10.0	OH005	38.2
OH002	1	112	21.8	OH006	58.8
OH002	2	131	25.5	OH007	28.0
OH002	3	36	7.0	OH008	30.9
OH002	4	125	24.4	OH009	65.4
OH002	5	109	21.2	OH010	74.7
OH003	1	74	54.8	OH011	42.2
OH003	2	34	25.2	OH012	35.2
OH003	4	27	20.0	OH013	63.0
OH004	1	29	13.4	OH014	41.0
OH004	2	153	70.8	OH015	53.7

Table 2. Statistics on the ranking analysis

	Parameter value (in percent)	
	Data set 1, column 4	**Data set 2, column 2**
Maximum	89.3	89.3
Minimum	0.2	25.5
Mean	21.7	45.8
Median	18.0	42.2
Standard deviation	16.4	14.0

Schalk—Analysis of the Sensitivity of Soils to the Leaching of Agricultural Pesticides in Ohio—WRIR 98-4108