EFFECTS OF LAND-USE BUFFER SIZE ON SPEARMAN'S PARTIAL CORRELATIONS OF LAND USE AND SHALLOW GROUND-WATER QUALITY

By Lauren E. Hay and William A. Battaglin

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply metric unit	By	To obtain inch-pound unit
millimeter (mm)	0.0394	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6215	mile (mi)
meter per Kilometer (m/km)	5.279	foot per mile (ft/mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
hectare	2.471	acre
meter per second (m/s)	3.281	foot per second (ft/s)

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ABSTRACT

Significant correlations were observed between land use and shallow ground-water quality in the Coastal Plain of New Jersey. The strength of correlations varies with the size of the land-use buffer used for the analysis. Sets of circular buffers with 1-, 250-, 400-, 600-, 800-, 1,000-, and 1,200-meter radii were generated around 41 wells for which water-quality data were available to determine the buffer size that maximizes these correlations. A geographic information system was used to estimate the percentage of urban, undeveloped, and agricultural land within each circular buffer.

Spearman's partial correlations were used to lessen closure effects and to minimize skewing of land-use and water-quality-data distributions. The largest number of significant partial correlations (probability level less than or equal to 0.05) occurred between constituents and percent of urban land, with the effect of agricultural land removed. For this case, 13 of 35 constituents had one or more significant partial correlations. Nine of the 13 relations having significant correlations reached their maximum correlation value when land use was quantified within buffers with 800- or 1,200-meter radii. Significantly correlated variables showed a general pattern: partial-correlation magnitude tended to decrease monotonically as buffer size increased or decreased away from the size at which the maximum correlation occurred.

INTRODUCTION

A goal of the U.S. Geological Survey's ground-water-quality programs is to develop methods for quantifying the relation between land use and shallow ground-water quality on a regional scale. A simple model or method that relates shallow ground-water quality to land-use patterns would be of value to water-use managers interested in assessing regional ground-water quality or in establishing a well-head-protection program. In 1984, the U.S. Geological Survey began studies to evaluate the effects of human activities at the land surface on regional ground-water quality, as part of the Toxic-Waste-Ground-Water Contamination Program (Helsel and Ragone, 1984). These studies were regional in scope and focused on shallow, unconfined aquifers.

Purpose and Scope

This report describes the results of an investigation to determine how the size of the buffer used to quantify land use around a well affects the value of the correlation statistics. A set of circular buffers with 1-, 250-, 400-, 600-, 800-, 1,000-, and 1,200-meter radii were generated around 41 wells in the Potomac-Raritan-Magothy aquifer system, in the northern Coastal Plain of New Jersey. The percentage of urban, agricultural, and undeveloped land was calculated within each buffer, for each well. Correlations between land-use and 35 water-quality constituents, in five major water-quality categories, were examined using a Spearman's partial correlation test. Tests were done on the set of buffers to determine if similarities in the behavior or occurrence of water-quality constituents in land-use or water-quality categories result in a pattern in the value of the correlation statistic with respect to buffer size. This report is methods development oriented, and does not attempt to establish causal relations between land use and shallow ground-water quality. The buffer areas are not meant to be a model for the zone of contribution to a well.

The methods and results presented in this report may provide insight for future studies which attempt to relate shallow ground-water quality to land use. This report builds upon the work of Barton and others (1987) who investigated the relation between land use and shallow ground-water quality in the outcrop area of the Potomac-Raritan-Magothy aquifer system in New Jersey.

Present Land Use

The northern outcrop area of the Potomac-Raritan-Magothy aquifer system (fig. 1) includes heavily industrialized areas near Trenton and Perth Amboy, as well as areas of agricultural and undeveloped land. The aggregated land-use categories used in this study are based on Anderson's classification system (Anderson and others, 1976), and are listed in table 1; their distribution within the study area are shown in figure 2. Since the 1950's, urban areas have been expanding into areas that were once agricultural or undeveloped. The rapid growth of industrialization within the Potomac-Raritan-Magothy outcrop area makes this aquifer system particularly susceptible to anthropogenic contamination.

Geohydrology

The Potomac-Raritan-Magothy aquifer system in the Potomac Group and overlying Raritan and Magothy Formations consists of Cretaceous sediments that are the oldest in the New Jersey Coastal Plain (fig. 1). The sediments crop out along a narrow strip 5 to 10 km wide that extends in the study area from Trenton, on the Delaware River, to Perth Amboy, on Raritan Bay (fig. 1). The Potomac-Raritan-Magothy aquifer system consists of fluvial-continental deposits that form a wedge-shaped mass of interbedded gravel, sand, silt, and clay. The system strikes northeast-southwest and dips to the southeast at 1.9 to 11.4 meters per kilometer (Zapecza, 1984).

The Potomac-Raritan-Magothy system in the northern Coastal Plain of New Jersey, contains two major aquifers generally referred to as the middle and upper aquifers of the Potomac-Raritan-Magothy aquifer system, or as the Farrington and Old Bridge aquifers (in the Farrington Sand Member of the Raritan Formation and Old Bridge Sand Member of the Magothy Formation), respectively. Both aquifers are generally less than 25 meters thick within their respective outcrops (Zapecza, 1984, pl. 8 and 11). Between the two aquifers is a confining unit that consists predominantly of the Woodbridge Clay Member of the Raritan Formation. The thickness of this confining unit within the Potomac-Raritan-Magothy outcrop area ranges between 0 and 45 meters (Zapecza, 1984, pl. 9).

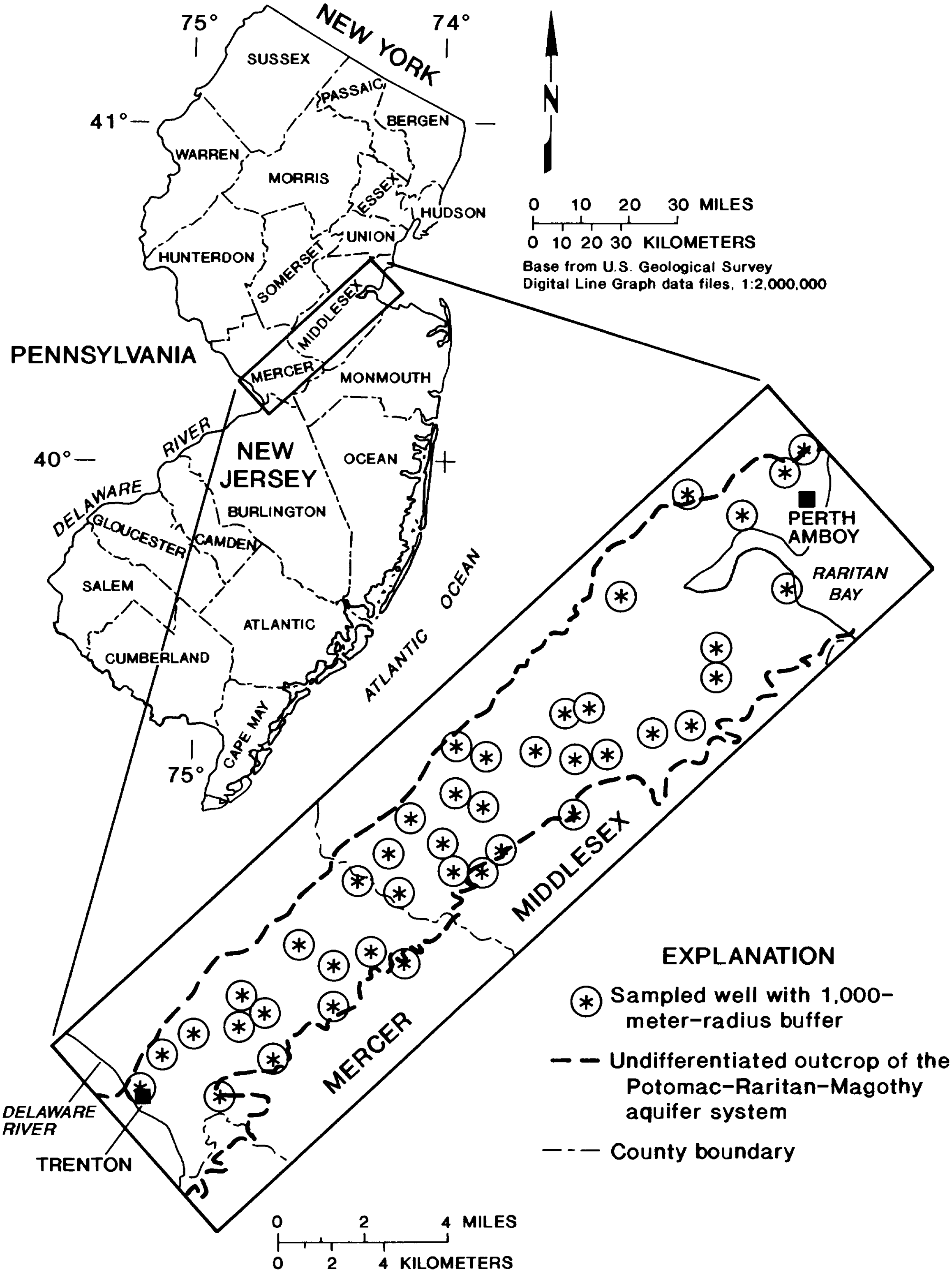

Figure 1.--Location of study area, sampled wells, and outcrop area of Potomac-Raritan-Magothy aquifer system.

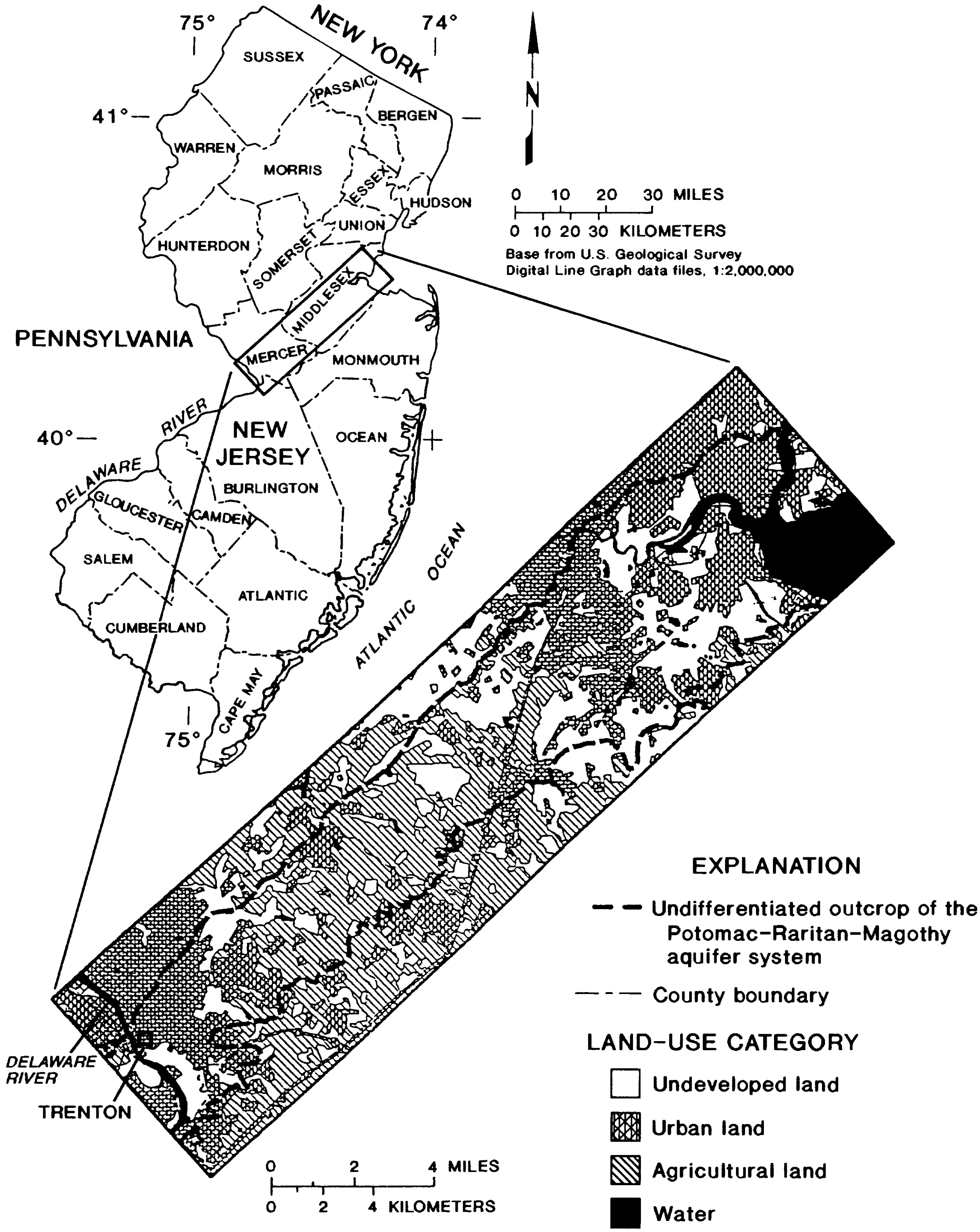

Figure 2.--Aggregated land-use categories within the study area.

Table 1.-- Aggregated land-use categories, and Anderson's[1] land-use, land-cover classification system

Aggregated land-use categories	Anderson's level I land-use categories	Anderson's level II land-use categories[2]
Urban land	Urban or developed land	11 Residential
		12 Commercial and services
		13 Industrial
		14 Transportation, communications and utilities
		15 Industrial and commercial complexes
		16 Mixed urban or built-up land
		17 Other urban or built-up land
Agricultural land	Agricultural land	21 Cropland and pasture
		22 Orchards, groves, vineyards, nurseries, and ornamental
Horticultural areas		
		23 Confined feeding operations
		24 Other agricultural land
Undeveloped land	Forest	41 Deciduous forest
		42 Evergreen forest
		43 Mixed forest
	Water	51 Streams and canals
		52 Lakes
		53 Reservoirs
		54 Bays and estuaries
	Wetland	61 Forested wetland
		62 Nonforested wetland
	Barren land	72 Beaches
		74 Bare exposed rocks
		75 Strip mines, quarries, and gravel pits
		76 Transitional areas

[1] Anderson and others, 1976
[2] Numbers correspond to class codes on land-use overlay maps

Well Data

Results presented in this study are based on data from wells sampled between 1985 and 1987. The samples were analyzed for 7 field characteristics, 7 major ions, 15 metals, 5 nutrients, and more than 50 organic compounds (Barton and others, 1987, table 5). A total of 80 wells were sampled within the Potomac-Raritan-Magothy outcrop area. From this original data base, 41 wells were selected for use in this study (locations are shown in fig. 1).

The 41-well subsample was used to eliminate errors associated with non-independence of the land-use data when all wells were considered. In short, when the data from 80 wells were used, land-use buffers overlapped significantly which resulted in double accounting of the land-use variable and spurious correlations. A more complete discussion of the reasons for subsampling and an explanation of the criteria used to generate the subsample can be found in Barringer and others (in press) or Vowinkel and Battaglin (1988).

The 41-well subsample consists of wells that range in depth from 5 to 46 meters. The median well depth is 23 meters. Wells can be grouped into two major classifications--withdrawal wells and observation (unused) wells. This data set contains 32 withdrawal wells and 9 observation wells, 21 of the wells are screened in the upper aquifer, and 20 in the middle aquifer. No distinction was made between observation and withdrawal wells, or between wells screened in the upper and middle aquifers in this study. Further stratification of the data set by pumpage rate or aquifer could lead to different results.

Methods of Study

The method used in this study is based on the assumption that the land use in the vicinity of a well either influences, or is indicative of the quality of, the water in that well. The simplest model of radial flow to a well shows that a circular cone of depression will form around a pumping well. At some radius from that well, water entering the system as recharge from the land surface will be drawn into this cone, and eventually to the well. The correlations between land use and the concentration of 35 water-quality constituents were calculated for seven buffer sizes to identify patterns in the correlation statistics.

This method makes two assumptions that are simplifications of the system being studied. The first assumption is that circular buffers can be used to describe the land use that affects water quality in the vicinity of a well. Because pumping wells in the study area exhibit their influence on an existing ground-water flow gradient, the zone of contribution to that well would be better described as an ellipse or shield, oriented in the direction of shallow ground-water flow (U.S. Environmental Protection Agency, 1987, fig. 2-2). The size, orientation, and upgradient extent of such an ellipse would be a function of several hydrogeologic variables including; the water-table gradient, discharge rate of the well, physical properties of the aquifer, and construction characteristics of the well. Ideally, an analytical solution could be developed for each well that would include some or all of the information mentioned above. This solution would provide a more precise estimate of the zone of contribution for each well.

The second assumption made by this method is that the land-use variable is spatially random (patternless). Urban land within the study area tends to be clustered in the northeastern and southwestern ends of the study area (fig. 2); clearly not a random pattern. To account for the spatial variability of land use, one would need to develop a spatial statistical model. Development of analytical solutions for the zone of contribution at each well, and spatial statistical models, were deemed to be beyond the scope of this study, and are suggested by the authors as topics for future research.

Previous Investigations

The Potomac-Raritan-Magothy aquifer system in the New Jersey Coastal Plain has been studied extensively. A summary of the hydrogeologic framework of the area is given by Zapecza (1984). Earlier studies of the region's hydrogeology include works by Barksdale and others (1943) and Farlekas (1979).

Water quality of the Potomac-Raritan-Magothy aquifer system in southern New Jersey has been investigated by Fusillo and Voronin (1981) and Fusillo and others (1984). Other studies concerned with water quality of the Potomac-Raritan-Magothy aquifer system deal largely with chloride concentrations (Appel, 1962; Schaefer, 1983).

Three studies of the effects of land use on ground-water quality in New Jersey have been completed. Fusillo and Hochreiter (1982) reported on organic-compound contamination in the Potomac-Raritan-Magothy aquifer system in southern New Jersey and its relation to land use. Greenberg and others (1982) reported on ground-water contamination throughout New Jersey and its relation to land use. Barton and others (1987) reported on the relation of hydrogeology and land use to water quality in the Potomac-Raritan-Magothy outcrop area.

Two studies of statistical procedures used in land-use and water-quality data are summarized by Vowinkel and Battaglin (1988) and Barringer and others (in press) which outline methods and pitfalls to be considered when analyzing relations between land-use and water quality.

Acknowledgments

The authors extend thanks to Dennis Dunn (Sachs Group, Philadelphia, Pa.) for providing technical assistance necessary for the completion of this study; to those in Mercer and Middlesex Counties who permitted access to their wells, and to the New Jersey Department of Environmental Protection for providing well-construction data.

LAND-USE DATA

Land-use and land-cover information used for this study were compiled from high-altitude aerial photographs taken in 1974. This information was classified according to the system developed by Anderson and others (1976), and compiled onto 1:250,000 base maps. These base maps were digitized by the U.S. Geological Survey National Mapping Division and are available through the National Cartographic Information Center (Fegeas and others, 1983). For this study, Anderson's land-use categories were aggregated into three groups: urban land, agricultural land, and undeveloped land (table 1).

Sources of Error in the Land-Use Data

The land-use data have several potential sources of error, including: (1) photointerpretive accuracy; (2) minimum mapping-unit size (planimetric errors); (3) base-map errors; (4) outdated information errors; and (5) data distribution errors (Barringer and others, in press).

Photointerpretive Errors

The photointerpretive accuracy of a map is an indication of the number of misclassified polygons on the map. The land-use maps used in this study meet or exceed the 85-percent accuracy criterion specified by Anderson and others (1976). The majority of the photointerpretive errors represent polygons classified under Anderson's level II that are misclassified within a level I category (level II represents a higher degree of detail in land-use classification than level I). Since level II land-use categories are aggregated into groups representing one or more level I categories for the purposes of this study, this error is not expected to significantly influence the results presented here.

Planimetric Errors

The minimum mapping-unit size is a measure of the smallest polygons that are digitized on the land-use maps. Areas of a given land use that are smaller than the minimum mapping unit are included in larger adjacent polygons. The minimum unit mapped on the land-use maps of New Jersey is either 4 or 16 hectares, depending upon the land-use category. Minimum mapping-unit size may induce errors at small buffer sizes where a significant proportion of the land use within the buffer could be misclassified. Sixteen hectares corresponds to a circular buffer of 226-meter radius.

Base-Map Errors

Horizontal accuracy of the Newark, N.J. 1:250,000 quadrangle base map, which includes the study area, was measured to be twice the National Map Accuracy Standard, which specifies that 90 percent of all points on the map lie within 1/50 of an inch of their true location. At this scale, this translates to a distance of 254 meters, which makes base-map accuracy the largest potential source of horizontal error. Other sources of horizontal error include the accuracy of the well locations and the accuracy at which the land use was digitized. Horizontal error may be significant at small buffer sizes, where there is a higher probability that a buffer would contain more incorrect than correct information.

Outdated Information Errors

The age of the land-use data may also introduce errors in the results of the study. Land use in the study area is changing rapidly. Ideally, a series of land-use maps with source dates at several-year intervals would be used in the correlation procedure, and an effort would then be made to relate water quality at a well to land use at the concurrent age. However, these resources are not currently available. The ground water in the Potomac-Raritan-Magothy outcrop area is estimated by Barton and others (1987) to be generally less than 20 years old, which implies that water reaching wells in the study area is between 0 and 20 years of age. Therefore, using a land-use data base that is 15 years old is not unreasonable.

Data Distribution Errors

The distribution of land-use data presents an additional source of error. Many correlation functions have the underlying assumption that the data sets being correlated have normal distributions. Figure 3 contains three box plots showing the percentage of land occupied by urban, agricultural, and undeveloped land within the 1,000-meter buffers surrounding the 41 wells. All three land-use groups have right skewed, non-normal distributions. Land-use data were ranked for use with nonparametric statistical procedures for this study. These procedures have greater power than parametric procedures when skewed data sets are used (Helsel, 1987).

Processing Data with the Geographical Information System

The ARC/INFO[1] geographic information system was used to process all land-use and well-location data for this study. Previously Barton and others (1987) manually aggregated land-use groups, located wells, scribed a buffer around each well, and estimated land-use percentages within those buffers. These tasks were time consuming, not easily reproducible, and subject to a variety of unquantifiable errors. The GIS enabled us to; site and check the locations of all wells in the data set; generate circular buffers with radii of 1, 250, 400, 600, 800, 1,000, and 1,200 meters around each well; and calculate the percentage of each land-use category within each buffer. The results were generated quickly and are accurate and reproducible.

WATER-QUALITY DATA

Thirty-five water-quality constituents were chosen to correlate with land use. These constituents were aggregated into five major categories: (1) field characteristics, (2) major ions, (3) metals, (4) nutrients, and (5) organic compounds (table 2). The wells used in this study were sampled in an effort to investigate the ambient water quality of the Potomac-Raritan-Magothy aquifer system; therefore, known sources of contamination were avoided in this sampling effort. All laboratory analyses were performed at the U.S. Geological Survey central laboratory in Denver, Colo.

The box plots of strontium, manganese, and zinc concentrations shown in figure 4 show the non-normal distribution typical of the constituents analyzed in this study. The concentrations of all water-quality data are summarized in table 2.

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[1] Use of trade names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

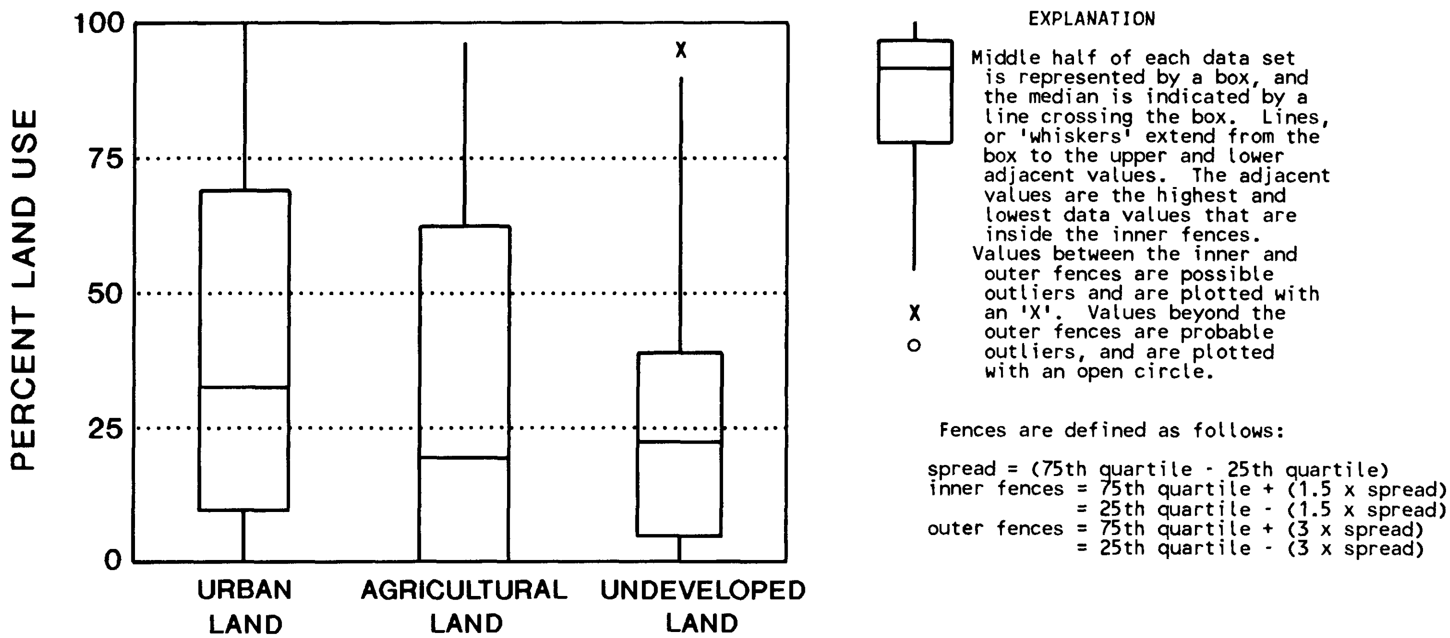

Figure 3.--Box plots showing percentage of urban, agricultural, and undeveloped land within 1,000-meter buffers surrounding the 41 wells.

Table 2.--Water-quality data for a subsample of 41 wells screened in the Potomac-Raritan-Magothy aquifer system

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; all constituents dissolved except where noted]

All analyses performed at the U.S. Geological Survey central laboratory in Denver, Colo.

Constituent	Detection limit and unit		Percentage of samples with concentrations above detection limit[1]	Statistics on censored population		
				Median	Q1	Q3[2]
Field characteristics						
Dissolved oxygen	0.1	mg/L	95	5.7	0.7	8.6
pH	.1	unit	100	5.2	4.8	5.6
Alkalinity as CaCO3	.1	mg/L	76	19.8	4	14
Bicarbonate as HCO3	1	mg/L	76	7	4	16
Specific conductance	1	µS/cm	100	152	99	273
Dissolved solids residue	1	mg/L	98	101	69	170
Major ions						
Chloride	.1	mg/L	100	13	7.7	22.5
Sulfate	.2	mg/L	98	24	4	44.3
Calcium	.02	mg/L	100	7.1	4.4	11.5
Magnesium	.01	mg/L	100	4	2.8	7.1
Potassium	.1	mg/L	100	2	1.3	2.7
Sodium	.2	mg/L	100	6.6	5	10.4
Silica	.006	mg/L	100	10	8.2	12
Metals						
Aluminum	10	µg/L	71	70	10	475
Barium	2	µg/L	100	76	47	140
Beryllium	.5	µg/L	39	2	.9	2
Lithium	4	µg/L	66	8	5	13
Strontium	.5	µg/L	100	72	47	135
Copper	10	µg/L	51	90	20	165
Iron	3	µg/L	98	104	30	2,580
Iron, total recoverable	10	µg/L	100	330	65	2,600
Manganese	1	µg/L	100	49	17	135
Zinc	3	µg/L	93	32	15	65
Chromium	10	µg/L	22	10	10	10
Cobalt	3	µg/L	46	9	4	20
Lead	10	µg/L	32	20	10	25
Nutrients						
Ammonia	.01	mg/L	68	.03	.02	.10
Nitrite	.01	mg/L	12	.02	.01	.03
Ammonia + organic N	.1	mg/L	93	.4	.3	.7
Nitrate	.1	mg/L	80	4.3	1.6	6.7
Phosphorus	.01	mg/L	17	.02	.01	.07
Organics						
Total purgeable organic compounds	3	µg/L	10	17	5	485
Total pesticides	.1	µg/L	17	.2	.1	.5
Total phenol	1	µg/L	54	2	1	3
Dissolved organic carbon	.1	mg/L	95	1	.7	1.3

[1] Percentage above detection limit is calculated by dividing the number of samples with a concentration equal to or exceeding the detection limit by the total number of samples, and multiplying by 100.

[2] Statistics on censored population summarize data in those wells where a constituent occurs at or above the detection limit. Q1 and Q3 represent the first and third quartiles of the censored population.

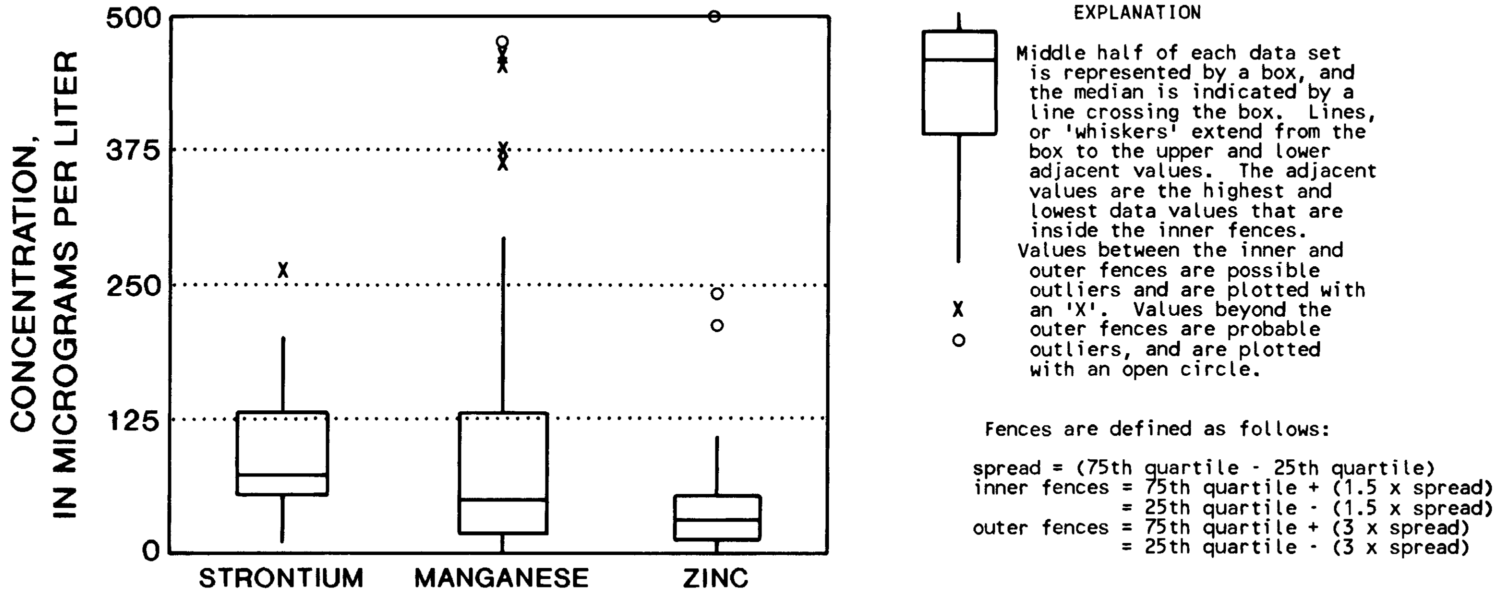

Figure 4.--Box plots showing strontium, manganese, and zinc concentrations at the 41 wells.

STATISTICAL METHOD USED TO DETERMINE THE RELATION BETWEEN LAND USE AND WATER QUALITY

The non-normal nature of the data set required use of Spearman's ranked partial correlations, a nonparametric statistical test, to analyze the relation of ground-water quality to land use in the study area. The basic assumption required for this statistic is that the data be continuous within a defined range (a continuous variable is one that is not restricted to having only isolated values (Siegel, 1956)). The data were ranked to reduce the influence of extreme values on the correlation. Partial correlations were used to eliminate the closure problem in the aggregated land-use data, as explained in the next section. The partial correlation, $p_{1,2/3}$, of three variables is the correlation between variables 1 and 2 with the effects of variable 3 removed by holding it constant (Snedecor and Cochran, 1979).

Closure

Use of aggregated land-use data introduces a bias in the significance of the correlations. The three aggregated land-use classes represent a closed data set because the land-use percentages within each well buffer sum to 100. The percentage of one land use class must be equal to 100 minus the percentage of the other two land use classes. In other words, the aggregated land use classes are not independent of each other destroying an underlying assumption for correlation. Therefore, a high positive correlation between urban land use and a water-quality constituent may be misleading; the high correlation may be caused by either the presence of urban land or the lack of agricultural or undeveloped land. This problem, known as closure, has been shown to lead to spurious correlation and may induce a bias towards negative correlation, even when no relation exists in the data (Chayes, 1971). For a closed data set, the expected value of the correlation coefficient is non-zero, even under the assumption of no association (Aitchison, 1986).

Partial Correlation

Partial correlations are used to control the effects of closure. Closure in the independent variable prevents a pure estimate of the correlation of a single land use with a water-quality constituent. Partial correlations describe land-use contrasts, or ratios, instead of single land-use groups. A partial correlation of urban land with constituent X performed while controlling for undeveloped land is actually a correlation of the urban-agricultural land-use contrast with constituent X. Because the land-use variables are a closed set, the amount of urban land must be related to the amount of agricultural land even though agricultural land appears absent in the above correlation. A positive correlation between the urban-agricultural land-use contrast and X would indicate that a transition from agricultural land to urban land would be associated with an increase in the concentration of constituent X, and a negative correlation would be associated with a decrease in that constituent concentration. Spearman's partial correlation equation for the urban-agricultural land-use contrast with constituent X has the following form:

$$p_{Ur,X/U} = (p_{Ur,X} - (p_{U,X} * p_{Ur,U})) / [((1 - p_{Ur,U}^2) * (1 - p_{U,X}^2))]^{-1/2},$$

where, $p_{Ur,X/U}$ = partial correlation of urban land with constituent X, holding undeveloped land constant;

$p_{Ur,X}$ = the rank correlation of urban land with constituent X;

$p_{U,X}$ = the rank correlation of undeveloped land with constituent X; and

$p_{Ur,U}$ = the rank correlation between urban and undeveloped land.

EFFECTS OF LAND-USE BUFFER SIZE ON SPEARMAN'S PARTIAL CORRELATIONS

Three land-use contrasts were studied: (1) urban-undeveloped, (2) urban-agriculture, and (3) agriculture-undeveloped. The rapid recent urbanization of former agricultural and undeveloped land in the study area makes an analysis of this type of land-use contrast useful.

Tables 3A, 3B, and 3C give results of the Spearman's partial correlations for the urban-undeveloped, urban-agricultural, and agricultural-undeveloped land-use contrast, respectively. Partial correlations that are significant at the 0.05 significance level (probability level less than or equal to 0.05) are underlined, and the significant correlation maxima are underlined and in bold type. This level of significance corresponds to a partial correlation coefficient of 0.308 (Siegel, 1956). Table 4 (p. 18) summarizes the number of significant correlation maxima for each land-use contrast by buffer size; table 5 (p. 18) summarizes the number of significant correlation maxima for each water-quality constituent group by radius; and table 6 (p. 19) indicates the probability levels for select values of Spearman's partial correlations.

Relation Between Buffer Size and Land-Use Contrasts

Similarities in the behavior or occurrence of water-quality constituents in individual land-use categories may result in a pattern in the value of the correlation statistic with respect to buffer size for each land-use contrast.

Table 3A shows the Spearman's partial correlations for the urban-undeveloped land-use contrast. Significant partial correlations (probability level less than or equal to 0.05) occurred for 13 of the 35 constituents. Of these significant correlations, 10 reached their maximum value when land use was quantified within buffers at 600-, 800-, 1,000-, and 1,200-meter radii (table 4). The largest number of significant correlation maxima occurred at the 1,000-meter buffer radius. The field characteristics show no significant correlations. Among the major ions, calcium, magnesium, and potassium had significant positive correlations. Among the metals, beryllium, dissolved iron, total recoverable iron, manganese, zinc, and cobalt had significant negative correlations, and only copper had a significant positive correlation. Among the nutrients, ammonium as n (ammonia), nitrate as n (nitrate), and nitrite as n (nitrite) had significant correlations; ammonia was negative while nitrate was positive. Among the organic compounds, total pesticides had

Table 3A.--Spearman's partial correlations for the urban-undeveloped land-use contrast

[Bold numbers designate highest significant correlations; underlined numbers designate significant correlations for given constituent]

	Buffer radius (meters)						
Constituent	1	250	400	600	800	1,000	1,200
Field characteristics							
Dissolved oxygen	-0.110	-0.110	-0.107	-0.135	-0.160	-0.135	-0.154
pH	.203	.214	.126	.100	.121	.068	.046
Alkalinity as CaCO3	.022	-.158	-.103	-.140	-.142	-.083	-.106
Bicarbonate as HCO3	-.023	-.150	-.117	-.143	-.139	-.100	-.117
Specific conductance	-.010	.054	.095	.133	.293	.275	.267
Dissolved solids residue	.135	-.032	.006	-.018	-.099	.025	-.019
Major ions							
Chloride	.053	.016	.118	.122	.198	.208	.215
Sulfate	-.069	.072	.089	.127	.213	.245	.241
Calcium	.166	.246	.299	.311	.448	**.460**	.408
Magnesium	.091	.148	.174	.239	**.409**	.385	.399
Potassium	-.008	.019	.194	.213	.304	**.337**	.337
Sodium	-.064	-.120	-.046	-.069	.111	.058	.070
Silica	.049	-.084	-.112	-.192	-.140	-.086	-.127
Metals							
Aluminum	-.187	-.187	-.109	-.087	-.111	-.085	-.071
Barium	-.045	-.007	.103	.129	.203	.179	.103
Beryllium	-.291	-**.346**	-.322	-.335	-.239	-.302	-.293
Lithium	.125	.160	.210	.223	.255	.277	.257
Strontium	.061	.035	.082	.093	.200	.252	.214
Copper	.089	.074	.165	.239	.368	.261	**.376**
Iron	-.279	-.316	-.413	-.415	-.401	-**.466**	-.396
Total recoverable iron	-.330	-.300	-.347	-.344	-.313	-**.386**	-.339
Manganese	-**.350**	-.341	-.278	-.261	-.118	-.193	-.159
Zinc	-.208	-**.310**	-.279	-.239	-.245	-.248	-.177
Chromium[1]	-.032	-.004	-.045	-.001	.048	-.023	.006
Cobalt	-.245	-.247	-.288	-**.317**	-.143	-.286	-.198
Lead	-.252	-.120	-.046	-.099	-.068	-.148	-.149
Nutrients							
Ammonia	-.177	-.098	-.211	-.263	-.248	-.324	-**.345**
Nitrite[1]	.254	.263	.275	.213	.166	.137	.106
Ammonia + organic N	.067	-.016	.046	.021	.085	.103	.069
Nitrate	.194	.199	.308	.320	.414	**.469**	.442
Phosphorus[1]	.044	-.019	-.027	-.001	.029	-.029	-.030
Organics							
Total purgeable organic compounds[1]	.222	.083	.082	.042	.123	.114	.142
Total pesticides[1]	.091	.155	.255	.282	.320	.305	**.350**
Total phenol	-.016	-.138	-.118	-.141	-.123	-.065	-.061
Dissolved organic carbon	.218	.211	.199	.213	.116	.153	.207

[1] Partial correlation values may be unstable because of the limited number of detections for these compounds.

Table 3B.--Spearman's partial correlations for the urban-agriculture land-use contrast

[Bold numbers designate highest significant correlation; underlined numbers designate significant correlations for given constituent]

Constituent	Buffer radius (meters)						
	1	250	400	600	800	1,000	1,200
Field characteristics							
Dissolved oxygen	-0.100	-0.082	-0.136	-0.162	-0.112	-0.099	-0.153
pH	.074	.055	-.015	.005	-.006	-.055	-.045
Alkalinity as CaCO3	.007	-.140	-.104	-.144	-.145	-.113	-.134
Bicarbonate as HCO3	-.029	-.155	-.117	-.160	-.156	-.148	-.162
Specific conductance	.061	.060	.159	.192	.291	.276	.274
Dissolved solids residue	.127	-.012	-.075	-.051	-.050	-.006	-.057
Major ions							
Chloride	.095	-.033	.110	.088	.122	.099	.089
Sulfate	.185	.267	.345	.385	.428	**.463**	.454
Calcium	.071	.070	.150	.154	.229	.221	.176
Magnesium	.044	.026	.096	.141	.246	.198	.250
Potassium	-.175	-.252	-.151	-.167	-.115	-.161	-.162
Sodium	.056	-.004	.108	.041	.130	.066	.055
Silica	-.318	-.342	-.350	-.382	-.383	-.377	**-.388**
Metals							
Aluminum	-.018	-.016	.066	.072	.093	.142	.103
Barium	-.001	-.177	-.062	-.062	-.014	-.063	-.095
Beryllium	-.001	-.118	-.031	-.030	.048	.023	-.050
Lithium	.038	.103	.163	.208	.210	.254	.213
Strontium	-.137	-.255	-.177	-.166	-.114	-.124	-.137
Copper	-.091	-.095	-.060	-.034	.097	.022	.083
Iron	.044	.118	.123	.142	.171	.157	.138
Total recoverable iron	.049	.135	.152	.172	.200	.179	.186
Manganese	-.053	-.042	.014	.001	.103	.034	.017
Zinc	.078	-.061	.018	.053	.096	.066	.072
Chromium[1]	.358	.361	.357	**.372**	.370	.353	.345
Cobalt	.052	.070	.116	.141	.275	.190	.212
Lead	.088	.016	.023	-.007	.047	.075	.019
Nutrients							
Ammonia	.039	.054	-.017	-.039	-.033	-.138	-.127
Nitrite[1]	**.332**	.214	.230	.212	.201	.177	.130
Ammonia + organic N	.137	.019	.128	.103	.114	.137	.131
Nitrate	-.157	-.282	-.204	-.240	-.185	-.195	-.185
Phosphorus[1]	.187	.152	.182	.146	.143	.144	.115
Organics							
Total purgeable organic compounds[1]	.293	.299	.332	.299	.330	**.342**	.334
Total pesticides[1]	.213	.133	.139	.155	.174	.173	.198
Total phenol	-.269	-.346	-.399	-.457	-.486	**-.490**	-.449
Dissolved organic carbon	.227	.221	.221	.214	.215	.209	.227

[1] Partial correlation values may be unstable because of the limited number of detections for these compounds.

Table 3C.--Spearman's partial correlations for the agriculture-undeveloped land-use contrast

[Bold numbers designate highest significant correlation; underlined numbers designate significant correlations for given constituent]

Constituent	Buffer radius (meters)						
	1	250	400	600	800	1,000	1,200
Field characteristics							
Dissolved oxygen	0.038	0.175	-0.136	-0.026	0.180	-0.008	-0.027
pH	.143	.188	.137	.100	.125	.098	.060
Alkalinity as CaCO3	-.093	-.151	-.031	-.053	-.101	-.002	.035
Bicarbonate as HCO3	-.081	-.093	-.047	-.081	-.071	-.047	-.028
Specific conductance	-.053	-.043	-.061	-.037	.035	.035	.005
Dissolved solids residue	.068	.179	.178	.186	.175	.185	.197
Major ions							
Chloride	-.016	-.007	.025	.041	.069	.107	.115
Sulfate	-.195	-.221	-.237	-.218	-.224	-.189	-.227
Calcium	.109	.175	.196	.211	.289	.307	.257
Magnesium	.056	.095	.081	.137	.230	.236	.209
Potassium	.118	.215	.338	.371	.433	.461	**.483**
Sodium	-.100	-.192	-.168	-.152	-.045	-.043	-.029
Silica	.273	.221	.170	.097	.203	.220	.193
Metals							
Aluminum	-.166	-.180	-.155	-.134	-.169	-.174	-.133
Barium	-.042	.108	.164	.193	.249	.248	.173
Beryllium	-.276	-.308	-.327	**-.357**	-.287	-.332	-.291
Lithium	.093	.022	.052	.040	.022	.025	.037
Strontium	.153	.219	.208	.209	.299	**.343**	.311
Copper	.148	.157	.221	.287	.338	.255	**.386**
Iron	-.294	-.452	-.546	-.548	-.548	**-.582**	-.523
Total recoverable iron	-.344	-.466	-.509	-.510	-.504	**-.541**	-.523
Manganese	-.302	**-.368**	-.330	-.291	-.198	-.233	-.190
Zinc	-.249	-.273	-.289	-.274	-.282	-.259	-.185
Chromium[1]	-.289	-.328	-.323	-.303	-.311	**-.341**	-.329
Cobalt	-.266	-.344	-.420	-.455	-.380	**-.456**	-.398
Lead	-.296	-.117	-.042	-.091	-.067	-.186	-.157
Nutrients							
Ammonia	-.195	-.146	-.234	-.270	-.246	-.255	-.302
Nitrite[1]	.000	.124	.144	.087	.022	.013	-.010
Ammonia + organic N	-.035	-.073	-.081	-.093	-.053	-.037	-.088
Nitrate	.287	.399	.468	.488	.554	**.592**	.581
Phosphorus[1]	-.093	-.175	-.192	-.136	-.132	-.172	-.158
Organics							
Total purgeable organic compounds[1]	.000	-.180	-.187	-.221	-.206	-.201	-.179
Total pesticides[1]	-.068	.098	.209	.219	.216	.199	.248
Total phenol	.180	.213	.232	.244	.329	.354	**.381**
Dissolved organic carbon	-.001	-.198	-.056	-.089	-.236	-.055	-.171

[1] Partial correlation values may be unstable because of the limited number of detections for these compounds.

Table 4.--Significant partial correlation maxima for the three land-use contrasts

[Dash indicates no significant correlations]

Land-use contrast	Buffer radius (meters)							Total/ possible significant correlations
	1	250	400	600	800	1,000	1,200	
Urban - undeveloped	1	2	-	1	1	5	3	13/35
Urban - agriculture	1	-	-	1	-	3	1	6/35
Agriculture - undeveloped	-	1	-	1	-	6	3	11/35
Totals	2	3	-	3	1	14	7	30/105

Table 5.--Significant partial correlation maxima for the five water-quality-constituent groups

[Dash indicates no significant correlations]

Constituent group	Buffer radius (meters)							Total/ possible significant correlations
	1	250	400	600	800	1,000	1,200	
Field characteristics	-	-	-	-	-	-	-	0/18
Major ions	-	-	-	-	1	3	2	6/21
Metals	1	3	-	3	-	7	2	16/39
Nutrients	1	-	-	-	-	1	2	4/15
Organics	-	-	-	-	-	2	2	4/12
Totals	2	3	-	3	1	13	8	30/105

Table 6.--Probability levels for selected values of Spearman's partial correlations

Probability[1] level	Spearman's partial correlation value
0.1	0.260
.05	.308
.01	.398
.005	.430
.001	.495

[1] Probability levels are for data sets with 41 observations

a significant positive correlation. The highest correlations for the urban-undeveloped land-use contrast were for nitrate (0.469) and dissolved iron (-0.466), both at the 1,000-meter buffer radius (see table 6 for probability levels).

The urban-agricultural land-use contrast shows significant partial correlations for 6 of the 35 constituents (table 3B). Of these significant correlations, five reached their maximum value when land use was quantified within buffers at 600-, 800-, 1,000-, and 1,200-meter radii (table 4). The largest number of significant correlation maxima occurred at the 1,000-meter buffer radius. The only significant correlations among the major ions data were sulfate (positive) and silica (negative). The only significant correlation (positive) among the metals was chromium, and the only significant positive correlation among the nutrients was nitrite. Among the organic constituents, only total purgeable organic compounds (POC's) had a significant positive correlation, and only phenol had a significant negative correlation. The highest correlations for the urban-agricultural land-use contrast were for phenol (-0.490) and sulfate (0.463), both at the 1,000-meter buffer radius (see table 6 for probability levels).

The agricultural-undeveloped land-use contrast shows significant partial correlations for 11 of the 35 constituents (table 3C). Of these significant correlations, 10 reached their maximum correlation value within buffers at 600-, 800-, 1,000-, and 1,200-meter radii (table 4). The largest number of significant correlation maxima occurred at the 1,000-meter buffer radius. The field characteristics showed no significant correlations. Among the major ions, only potassium had a significant positive correlation. Among the metals, strontium and copper had significant positive correlations, whereas beryllium, dissolved iron, total recoverable iron, manganese, chromium, and cobalt had significant negative correlations. Among the nutrients, only nitrate had a significant positive correlation. Among the organic compounds, only phenol had a significant positive correlation. The highest correlations for the agricultural-undeveloped land-use contrast were for nitrate (0.592) and dissolved iron (-0.582), both at the 1,000-meter buffer radius. The correlations for nitrate and dissolved iron, within the agricultural-undeveloped land-use contrast, were the highest for all water-quality constituents and land-use contrasts (see table 6 for probability levels).

Relation Between Buffer Size and Water-Quality-Constituent Group

Similarities among the behavior of constituents grouped into each of the five major water-quality categories described earlier and listed in tables 3A, 3B, and 3C may result in a pattern in the value of the correlation statistic with respect to buffer size for each water-quality category as described below.

Field Characteristics

When six constituents from the field-characteristics group were correlated with the three land-use contrasts, none of the 18 correlations were significant at the 0.05 significance level (tables 3A, 3B, and 3C).

Major Ions

When seven constituents from the major-ions group were correlated with the three land-use contrasts, 6 of 21 possible correlations were significant at the 0.05 significance level (tables 3A, 3B, and 3C). All six of these correlations reached their maximum value when land use was quantified within buffers at 600-, 800-, 1,000-, and 1,200-meter radii (table 5). The largest number of significant correlation maxima for the major-ions group occurred at the 1,000-meter buffer radius.

Metals

When 13 constituents from the metals group were correlated with the three land-use contrasts, 16 of 39 possible correlations were significant at the 0.05 significance level (tables 3A, 3B, and 3C). Of the 16 significant correlations, 12 reached their maximum value within buffers at 600-, 800-, 1,000-, and 1,200-meter radii (table 5). The largest number of significant correlation maxima for the metals group occurred at the 1,000-meter buffer radius.

Nutrients

When five constituents from the nutrients group were correlated with the three land-use contrasts, only 4 of 15 possible correlations were significant at the 0.05 significance level (tables 3A, 3B, and 3C). Three of the four significant correlations reached their maximum value when land use was quantified within buffers at 600-, 800-, 1,000-, and 1,200-meter radii (table 5). The largest number of significant correlation maxima for the nutrients group occurred at the 1,200-meter buffer radius.

Organic Compounds

When four constituents from the organic compounds group were correlated with the three land-use contrasts, 4 of 12 possible correlations were significant at the 0.05 significance level (tables 3A, 3B, and 3C). All four of the significant correlations reached their maximum value when land use was quantified within buffers at 600-, 800-, 1,000-, and 1,200-meter radii (table 5). The largest number of significant correlation maxima for the organic compounds group occurred at the 1,000- and 1,200-meter buffer radius.

Partial correlations for some constituents in the metals, nutrients, and organic compounds groups may be influenced by the small number of detections within the data set. For example, only four of 41 wells had detectable purgeable organic compounds, and only seven of 41 wells had detectable pesticides. The number of detections for these two organic compounds is insufficient to insure consistent, stable results. Other statistical tests, such as the Fisher's exact test, would be better suited to analyze the relation between land use and water quality in terms of these constituents (D. Dunn, Sachs Group, Philadelphia, Pa., oral commun., 1988).

Spearman's Partial Correlations by Buffer Size

Figures 5 through 8 plot Spearman's partial correlations of constituents and land use in relation to buffer size for all of the water-quality constituents and land-use contrasts that showed significant correlations (probability level less than or equal to 0.05). Many of the plots show an increase in correlation that reached a maximum when land use was quantified within buffers at 600-, 800-, 1,000-, and 1,200-meter radii, and then decrease or level off. This pattern of reaching a maximal value or leveling off was evident for 25 of the 32 correlations that were significant at the 0.05 significance level.

Relation Between Results and Errors in the Land-Use Data

Limitations or inaccuracies in the land-use variable may influence the results of correlations between land use and water quality. The error that is likely to be the most significant in this respect is the minimum mapping unit (planimetric errors). Minimum mapping unit may induce errors within buffer with small radii, where a significant percentage of the land use within the buffer could be misclassified. Errors resulting from the horizontal accuracy of the base map would also tend to increase the likelihood that smaller buffers would contain incorrect land-use data.

In contrast, spurious correlations resulting from buffer overlap would be more likely within buffers with large radii. This form of spurious correlation, called autocorrelation, is similar to the problem of spatial non-independence of the land-use variable mentioned previously. In an earlier study, Barton and others (1987) examined the water quality of wells in the Potomac-Raritan-Magothy study area. Later, correlagrams of percent land use within the buffer area in relation to distance between wells indicated that autocorrelation of the land-use variate was causing error for wells that had overlapping buffer areas (Barringer and others, 1988). This resulted in some biased correlation values. A subset of the data used in the Barton study was used here to avoid autocorrelation from overlapping buffers. Correlagrams of percent land use against distance between wells generated for the 41-well data set indicate little or no error from autocorrelation in this data set for any of the selected buffer radii. At 1,000-meter radii, less than 1 percent of the total buffered area was overlapping, and the largest individual buffer overlap was equivalent to 11 percent of a 1,000-meter buffer. At 1,200-meter radii, about 3.5 percent of the total buffered area was overlapping, and the largest individual buffer overlap was equivalent to 23 percent of a 1,200-meter buffer. By contrast, at 1,000 meters, about 33 percent of the total buffer area was overlapping in the 71-well data set used by Barton and others (1987), in which autocorrelation has been evident (Barringer and others, 1988). The largest individual buffer overlap in the Barton and others (1987) data set was nearly 100 percent of a 1,000-meter buffer.

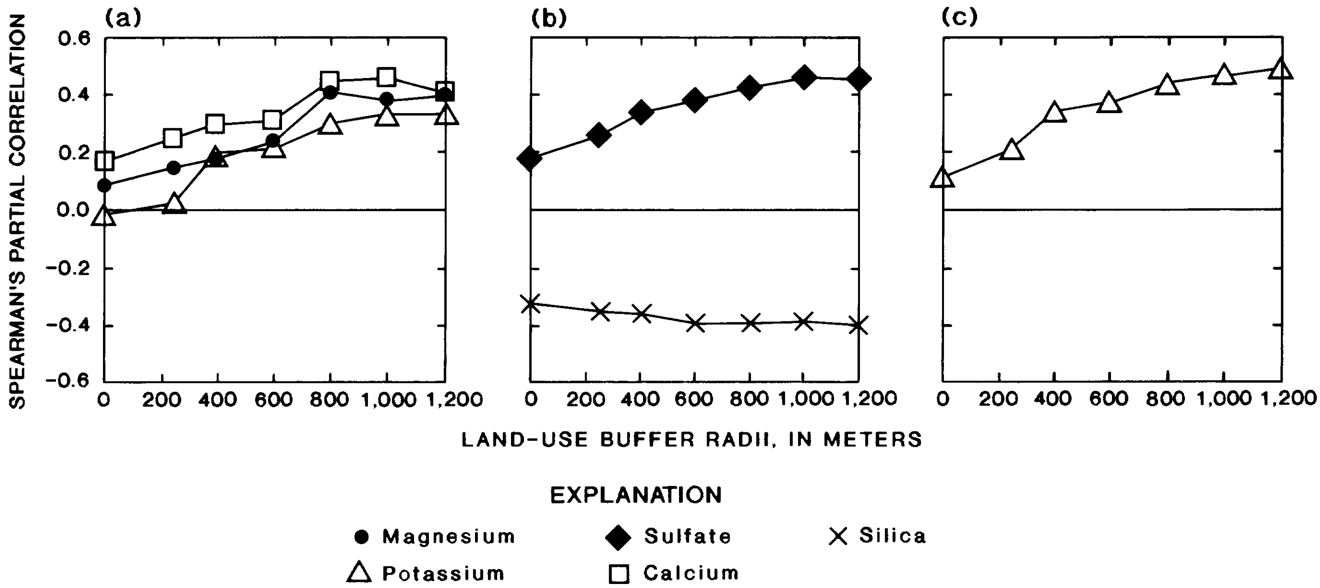

Figure 5.--Spearman's partial correlations by buffer size for the (a) urban-undeveloped, (b) urban-agriculture, and (c) agriculture-undeveloped land-use contrast, for the major-ions data.

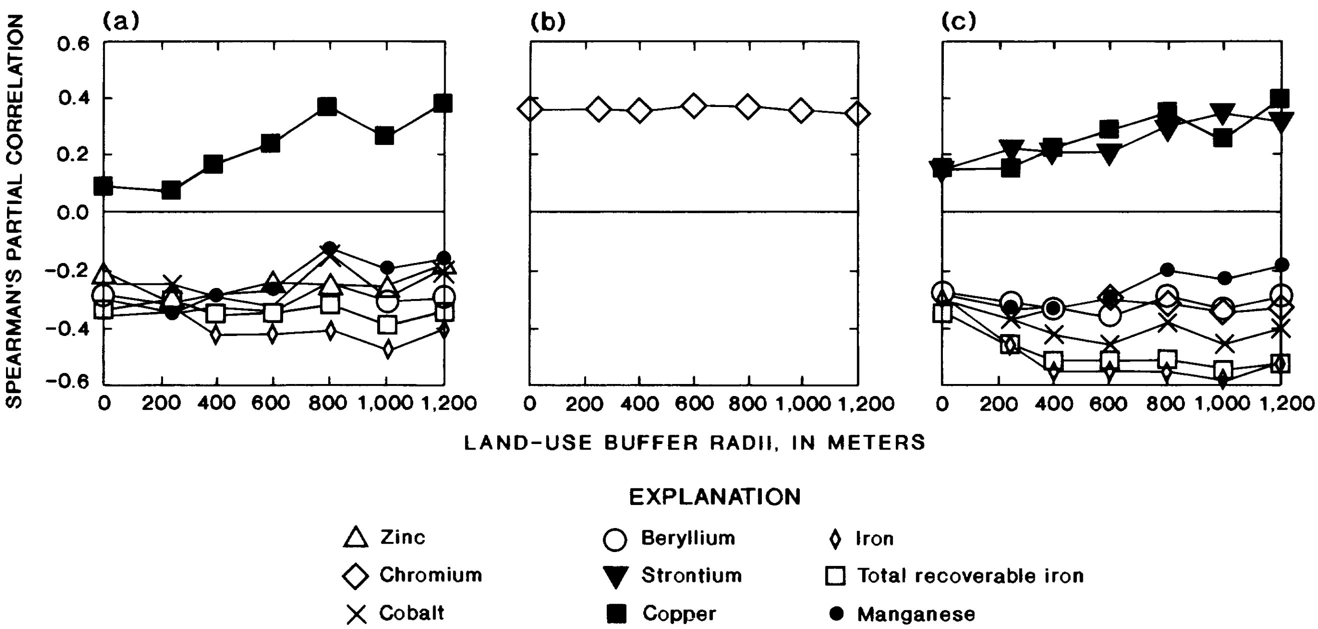

Figure 6.--Spearman's partial correlations by buffer size for the (a) urban-undeveloped, (b) urban-agriculture, and (c) agriculture-undeveloped land-use contrast, for the metals data.

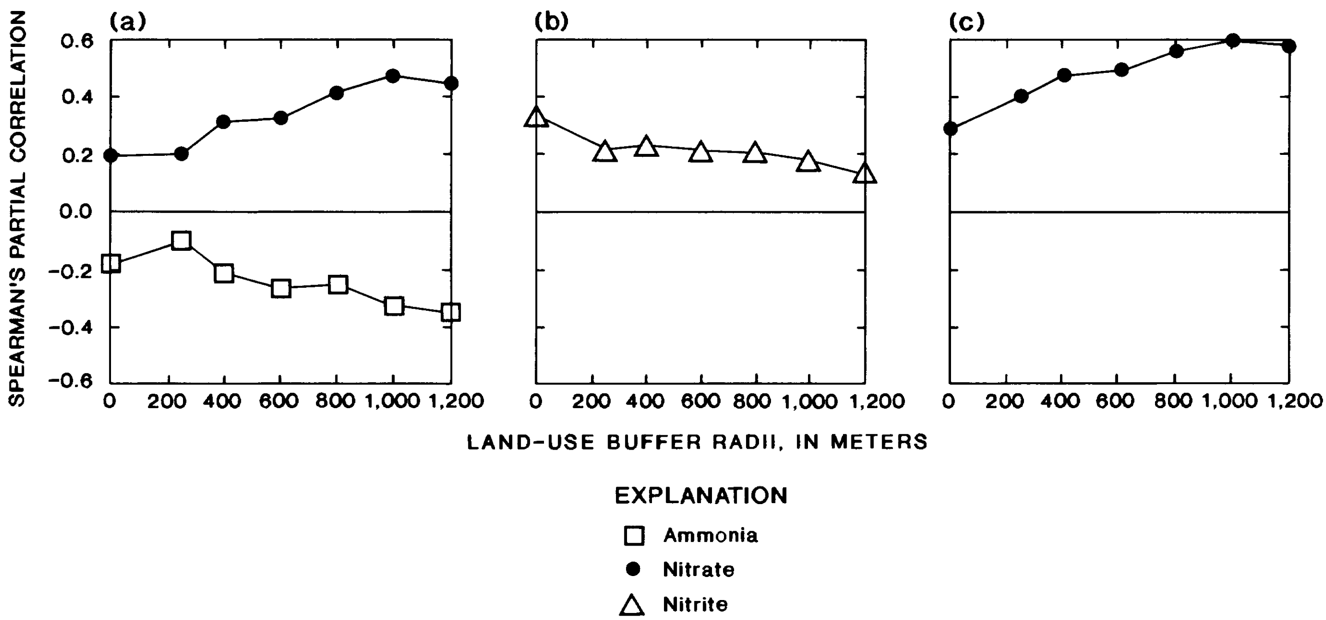

Figure 7.--Spearman's partial correlations by buffer size for the (a) urban-undeveloped, (b) urban-agriculture, and (c) agriculture-undeveloped land-use contrast, for the nutrients data.

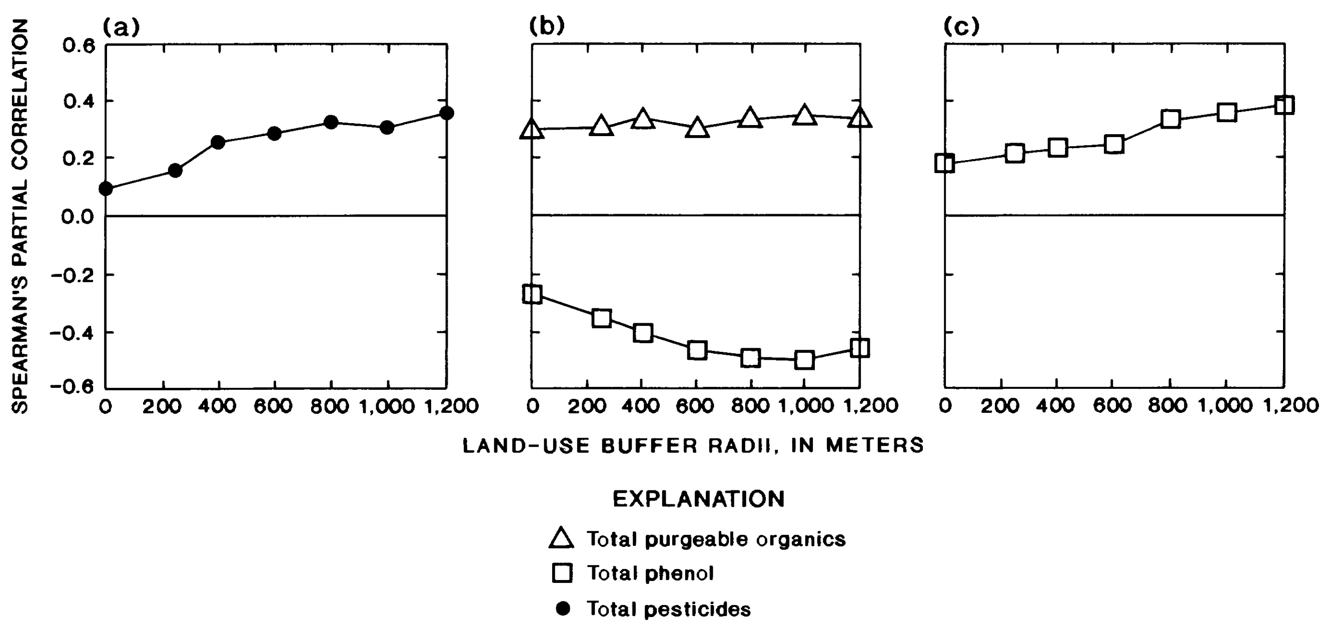

Figure 8.--Spearman's partial correlations by buffer size for the (a) urban-undeveloped, (b) urban-agriculture, and (c) agriculture-undeveloped land-use contrast, for the organic-compounds data.

SUMMARY AND CONCLUSIONS

The relation between land use and shallow ground-water quality in the northern outcrop area of the Potomac-Raritan-Magothy aquifer system in central New Jersey was investigated through a ranked partial correlation technique. Circular buffers with 1-, 250-, 400-, 600-, 800-, 1,000-, and 1,200-meter radii were generated around 41 wells. The percentage of each of three land-use categories (urban, agriculture, and undeveloped) within each buffer was calculated for each well. Concentration data for 35 water-quality constituents at the 41 wells were related to the land-use data through use of a Spearman's partial correlation test. The Spearman's partial correlation test uses ranked water-quality data to account for its non-normal distribution and land-use partials or contrasts to eliminate errors caused by closure in the land-use data set.

A significant relation (probability level less than or equal to 0.05) was found between land-use contrasts and water-quality for 30 of 105 tests, or about 30 percent of the possible correlations. Of the relations with significant correlations, 83 percent reached their maximum correlation value, or the correlation value showed no significant increase, when land use was quantified within buffers at 600-, 800-, 1,000-, and 1,200-meter radii. The largest number of significant correlation maxima (14) occurred at the 1,000-meter buffer radius.

Three land-use contrasts were studied; (1) urban-undeveloped, (2) urban-agriculture, and (3) agriculture-undeveloped. Similarities in the behavior or occurrence of water-quality constituents in individual land-use categories may produce a pattern in the value of the correlation statistic with respect to buffer size for each land-use contrast.

In the urban-undeveloped land-use contrast, 13 of 35 correlations with water-quality constituents reached the 0.05 significance level, and 10 of these 13 reached their maximum correlation value within buffers with 600-, 800-, 1,000-, and 1,200-meter radii. The largest number of significant correlation maxima (5) occurred at the 1,000-meter buffer radius.

In the urban-agricultural land-use contrast, 6 of 35 correlations with water-quality constituents reached the 0.05 significance level, and 5 of these 6 reached their maximum correlation value when land use was quantified within buffers at 600-, 800-, 1,000-, and 1,200-meter radii. The largest number of significant correlation maxima (3) occurred at the 1,000-meter buffer radius.

In the agriculture-undeveloped land-use contrast, 11 of 35 correlations with water-quality constituents reached the 0.05 significance level, and 10 of these 11 reached their maximum correlation value within buffers with 600-, 800-, 1,000-, and 1,200-meter radii. The largest number of significant correlation maxima (7) occurred at the 1,000-meter buffer radius.

Concentration data for 35 water-quality constituents were correlated with the three land-use contrasts. Constituents were classified into five major groups: (1) field characteristics, (2) major ions, (3) metals, (4) nutrients, and (5) organic compounds. Similarities in the behavior of water-quality constituents within each of these groups may produce a pattern in the value of the correlation statistic with respect to buffer size for each land-use contrast.

Within the field-characteristics group, none of the 18 possible relations between land use and water quality were significant at the 0.05 significance level.

Within the major-ions group, 6 of 21 possible relations between land use and water quality were significant at the 0.05 significance level. All of these reached their maximum correlation value within buffers with 600-, 800-, 1,000-, and 1,200-meter radii. The largest number of significant correlation maxima (3) occurred at the 1,000-meter buffer radius.

Within the metals group, 16 of 39 possible relations between land use and water quality were significant at the 0.05 significance level. Twelve of these 16 reached their maximum correlation value when land use was quantified within buffers at 600-, 800-, 1,000-, and 1,200-meter radii. The largest number of significant correlation maxima (7) occurred at the 1,000-meter buffer radius.

Within the nutrients group, 4 of 15 possible relations between land use and water quality were significant at the 0.05 significance level. Three of these 4 reached their maximum correlation value within buffer with 600-, 800-, 1,000-, and 1,200-meter radii. The largest number of significant correlation maxima (2) occurred at the 1,200-meter buffer radius.

Within the organic compounds group, 4 of 12 possible relations between land use and water quality were significant at the 0.05 significance level. All four of these reached their maximum correlation value when land use was quantified within buffers at 600-, 800-, 1,000-, and 1,200-meter radii. The largest number of significant correlation maxima (2) occurred at the 1,000- and 1,200-meter buffer radii.

The majority of significant correlation maxima occurred at the 600-, 800-, 1,000-, and 1,200-meter buffer radii. Within this range, the 1,000-meter buffer radius consistently had the largest number of significant correlation maxima associated with it. This analysis suggests a possible size of buffers for detecting correlations. The circular buffer area does not represent the zone of contribution to a well.

REFERENCES

Aitchison, J., 1986, The statistical analysis of compositional data: London, Chapman and Hall, 416 p.

Anderson, J. R., Hardy, E. E., Roach, J. T., and Witmer, R. E., 1976, A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 28 p.

Appel, C. A., 1962, Salt-water encroachment into aquifers of the Raritan Formation in the Sayreville area, Middlesex County, New Jersey, with a section on a proposed tidal dam on the South River: New Jersey Department of Conservation and Economic Development Special Report 17, 47 p.

Barksdale, H. C., Johnson, M. E., Schaefer, E. J., Baker, R. C., and DeBuchananne, G. D., 1943, The ground-water supplies of Middlesex County, New Jersey: New Jersey State Water Policy Commission Special Report 8, 160 p.

Barringer, T. H., Dunn, D., Battaglin, W. A., and Vowinkel, E. F., Problems and Methods involved in relating land use to ground-water quality: Water Resources Bulletin, in press.

Barton, Cynthia, Vowinkel, E. F., and Nawyn, J. P., 1987, Preliminary assessment of water quality and its relation to hydrogeology and land use: Potomac-Raritan-Magothy aquifer system, New Jersey: U.S. Geological Survey Water-Resources Investigations Report 87-4023, 2 p.

Chayes, Felix, 1971, Ratio correlation: a Manual for students of petrology and geochemistry: Chicago, University of Chicago Press, 99 p.

Farlekas, G. M., 1979, Geohydrology and digital-simulation model of the Farrington aquifer in the northern Coastal Plain of New Jersey: U.S. Geological Survey Water-Resources Investigations Report 79-106, 55 p.

Fegeas, R. G., Claire, R. W., Guptill, S. C., Anderson, K. E., and Hallem, C. A., 1983, Land use and land cover digital data: U.S. Geological Survey Circular 895-E, 21 p.

Fusillo, T. V., and Hochreiter, J. J., Jr., 1982, Relationship of organic contamination in ground water to land use--A case study in the New Jersey Coastal Plain [Abstract]: American Geophysical Union Transactions, v. 63, p. 317.

Fusillo, T. V., Hochreiter, J. J., Jr., and Lord, D. G., 1984, Water-quality data for the Potomac-Raritan-Magothy aquifer system in southwestern New Jersey, 1923-83: U.S. Geological Survey Open-File Report 84-737, 127 p.

Fusillo, T. V., and Voronin, L. M., 1981, Water-quality data for the Potomac-Raritan-Magothy aquifer system, Trenton to Pennsville, New Jersey, 1980: U.S. Geological Survey Open-file Report 81-814, 38 p.

Greenberg, Michael, Anderson, Richard, Keene, Jennifer, Kennedy, Anne, Page, G.W., and Schowgurow, Sandy, 1982, Empirical test of the association between gross contamination of wells with toxic substances and surrounding land use: Environmental Science and Technology, v. 16, no. 1, p. 14-19.

Helsel, D. R., and Ragone, S. E., 1984, Evaluation of regional ground-water quality in relation to land use--U.S. Geological Survey Toxic Waste-Ground-Water Contamination Program: U.S. Geological Survey Water-Resources Investigations Report 84-4217, 33 p.

Helsel, D. R., 1987, Advantages of nonparametric procedures for analysis of water quality data: Hydrological Sciences Journal, v. 32, no. 2, p. 179-190.

Schaefer, F. L., 1983, Distribution of chloride concentrations in the principal aquifers of the New Jersey Coastal Plain, 1977-81: U.S. Geological Survey Water-Resources Investigations Report 83-4061, 60 p.

Siegel, Sidney, 1956, Nonparametric statistics for the behavioral sciences: New York, McGraw-Hill, 312 p.

Snedecor, George W., and Cochran, William G., 1979, Statistical Methods: Ames, Iowa, Iowa State University Press, p. 400.

U.S. Environmental Protection Agency, 1987, Guidelines for delineation of wellhead protection areas: Washington, D.C., 16 p.

Vowinkel, E. F., and Battaglin, W. A., 1988, Hydrogeological, well construction, and land-use factors that can affect the evaluation of regional ground-water quality, in Ragone, S., ed., Regional characterization of water quality: Wallingford, United Kingdom, International Association of Hydrological Sciences, no. 182, p. 69-78.

Zapecza, O. S., 1984, Hydrogeologic framework of the New Jersey Coastal Plain: U.S. Geological Survey Open-File Report 84-730, 61 p.

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