SUSCEPTIBILITY OF SOURCE WATER TO COMMUNITY WATER-SUPPLY WELLS IN NEW JERSEY TO CONTAMINATION BY NATURALLY OCCURRING RADIONUCLIDES

Summary

Susceptibility assessment models were developed to predict the susceptibility of source water to community water-supply (CWS) wells in New Jersey to contamination by naturally occurring radionuclides. The models evaluate occurrence of naturally occurring radionuclides. Susceptibility is defined by variables describing hydrogeologic sensitivity and potential contaminant-use intensity within the area contributing water to a well. The models were developed by using water-quality data from ground-water samples collected and analyzed by the U.S. Geological Survey and other agencies. A model was developed for one measure of radioactivity and two radioactive constituents with primary maximum contaminant levels: gross alpha-particle activities, and combined radium (the sum of radium-226 and radium-228) and uranium. A second model and ratings were developed for radon, which has a proposed MCL. The susceptibility ratings for the radionuclides constituent group are based on individual constituent susceptibility assessment models. The constituent group rating for a well is the highest susceptibility rating of the individual constituent ratings for each model. The radionuclide model includes gross alpha-particle activities, combined radium, and uranium. Radon was not included in the radionuclides model because it is chemically unlike other radionuclides. A separate model and ratings were developed for radon. Of the 2,237 community water-supply wells, the susceptibility to contamination by radionuclides was low for 444 (20 percent), medium for 1,004 (45 percent), and high for 789 (35 percent) (figs. 1 and 3). The susceptibility to contamination by radon was low for 584 (26 percent), medium for 858 (38 percent), and high for 795 (36 percent) (figs. 2 and 4). Susceptibility ratings for combined radium were highest in the Coastal Plain Physiographic Province, and may be the result of natural sources and agricultural practices that may chemically mobilize radium. Uranium concentrations were highest in the Piedmont and are associated with geologic sources and with human activities. Radon concentrations are highest in northern New Jersey.

Introduction

The 1996 Amendments to the Federal Safe Drinking Water Act require all states to establish a Source Water Assessment Program (SWAP). New Jersey Department of Environmental Protection (NJDEP) elected to evaluate the susceptibility of public water systems to contamination by inorganic constituents, nutrients, volatile organic and synthetic organic compounds, pesticides, disinfection byproduct precursors, pathogens, and radionuclides. Susceptibility to contamination in ground water is a function of many factors, including contaminant presence or use in or near the water source, natural occurrence in geologic material, changes in ambient conditions related to human activities, and location of the well within the flow system. The New Jersey SWAP includes four steps: (1) delineate the source water assessment area of each ground and surface water source of public drinking water, (2) inventory the potential contaminant sources within the source water assessment area, (3) determine the public water system's susceptibility to contamination, and (4) incorporate public participation and education (http://www.state.nj.us/dep/swap).

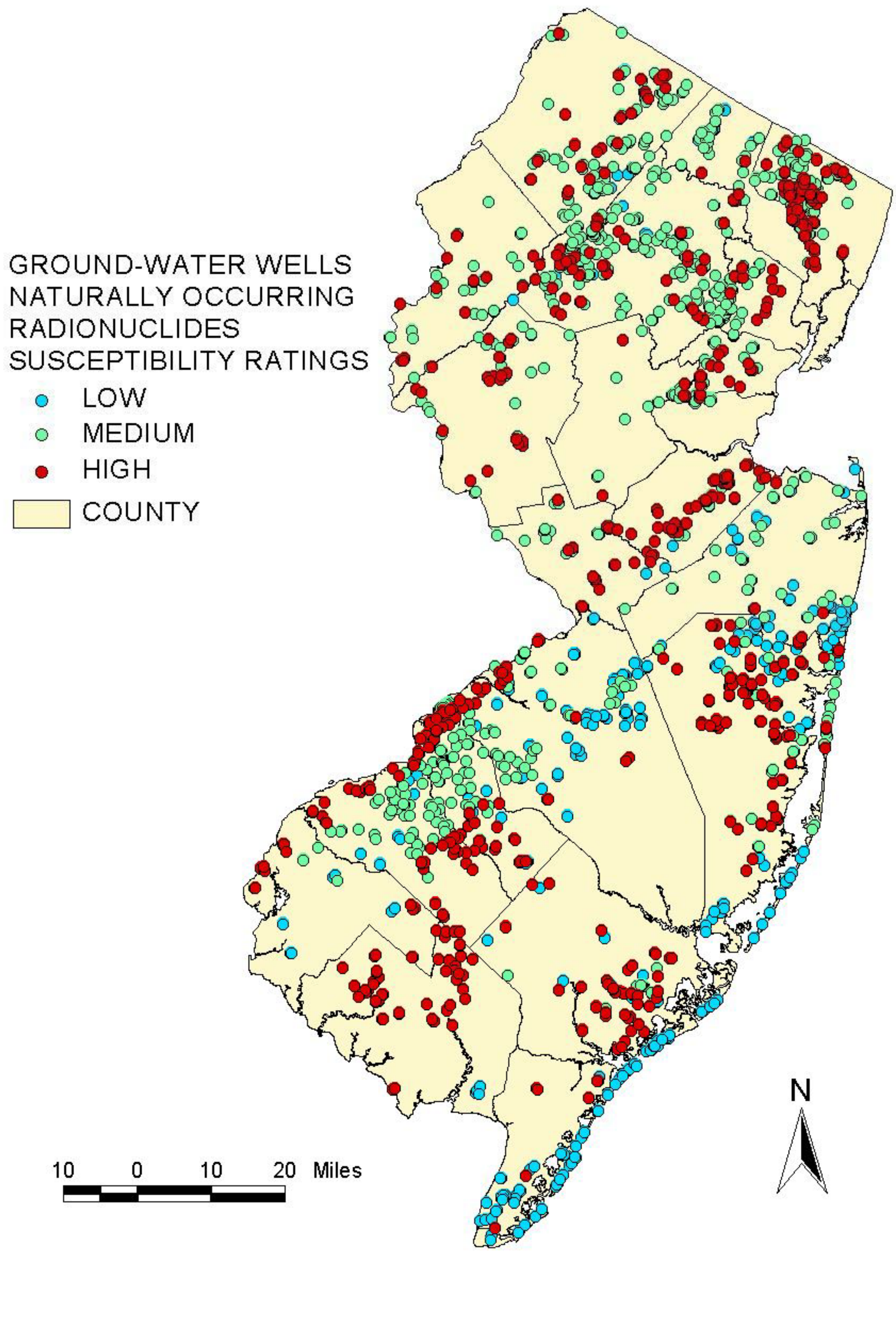

Figure 1. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by naturally occurring radionuclides (excluding radon).

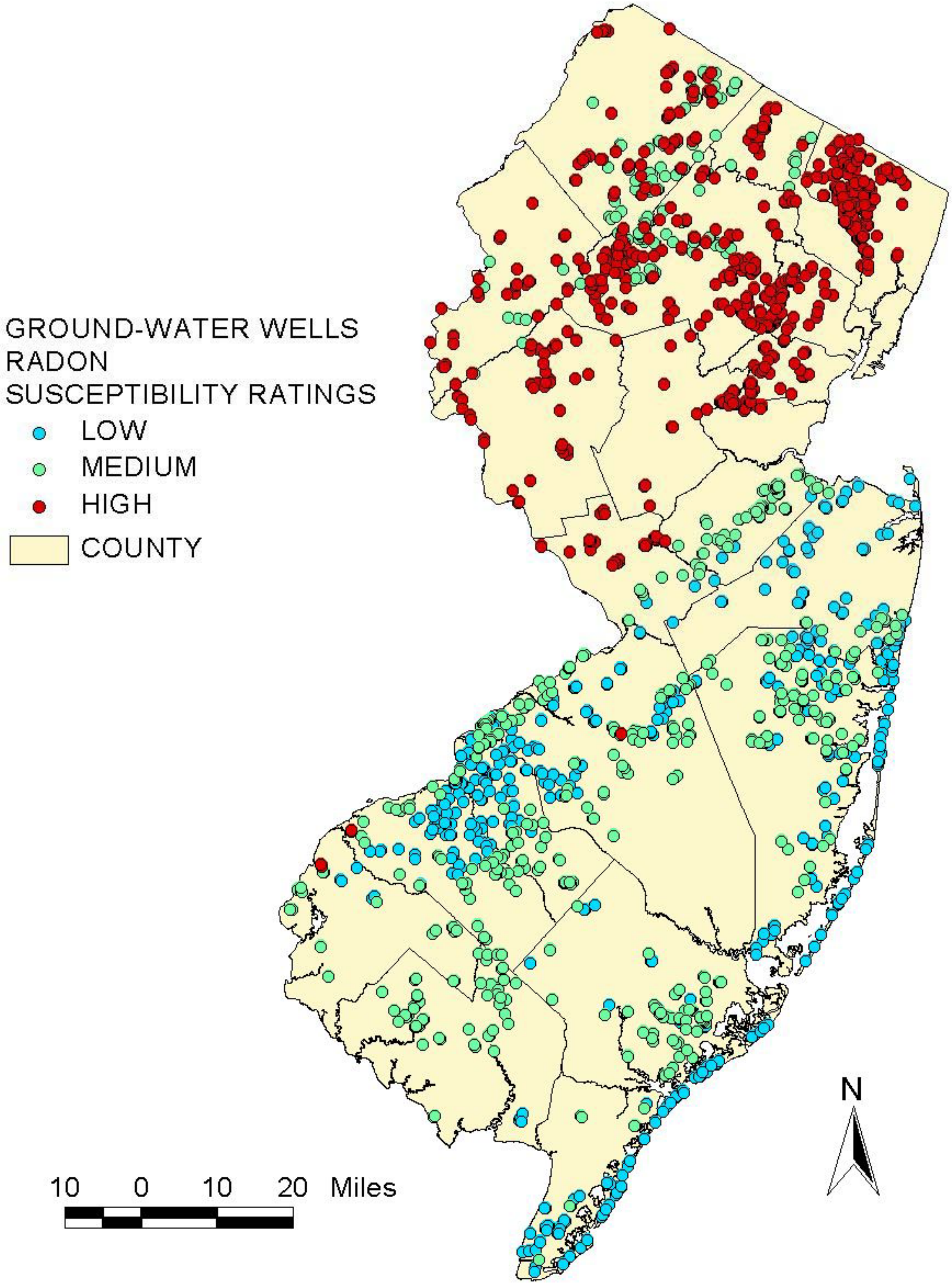

Figure 2. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by radon.

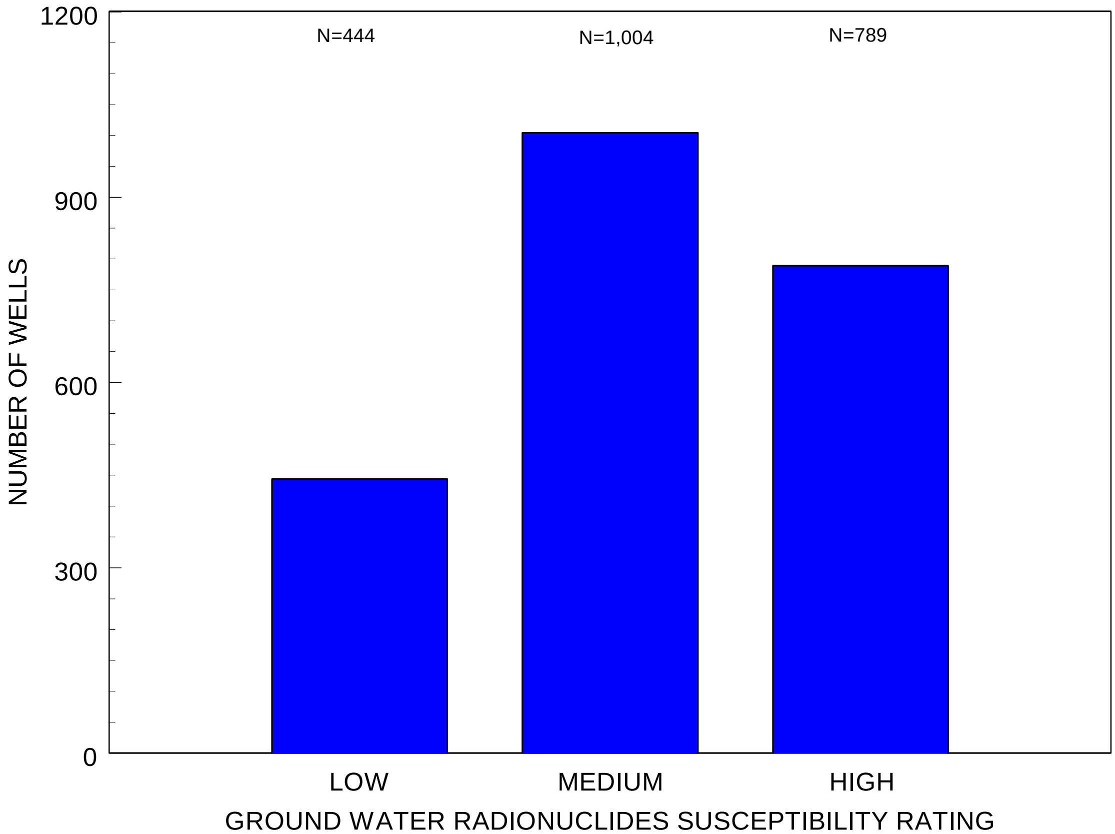

Figure 3. Number of community water-supply wells in New Jersey having low, medium, and high susceptibility to contamination by naturally occurring radionuclides (excluding radon).

Susceptibility assessment models were developed to rate each public ground-water source as having low, medium, or high susceptibility for groups of constituents. This report (1) describes methods used to develop the susceptibility assessment model for radionuclides, (2) presents results of application of the susceptibility model to estimate the susceptibility of source water to CWS wells to these constituents, and (3) documents the distribution of these constituents in water from CWS wells in New Jersey.

Definition of Susceptibility

The susceptibility of a public water supply to contamination by a variety of constituents is defined by variables that describe the hydrogeologic sensitivity and the potential contaminant-use intensity in the area that contributes water to that source. The susceptibility assessment models were developed by using an equation whereby the susceptibility of the source water is equal to the sum of the values assigned to the variables that describe hydrogeologic sensitivity plus the sum of the values assigned to the variables that describe potential contaminant-use intensity within the area contributing water to a well. In the case of naturally occurring radionuclides, contaminant intensity does not represent actual use of these radionuclides, but rather of other manmade compounds which, when discharged to the environment may induce additional mobilization of radionuclides naturally present in soil and rock. Fertilizer may contain minor amounts of radionuclides but these have not been shown to be in ground water.

$$\text{Susceptibility} = \text{Hydrogeologic Sensitivity} + \text{Potential Contaminant-Use Intensity}$$

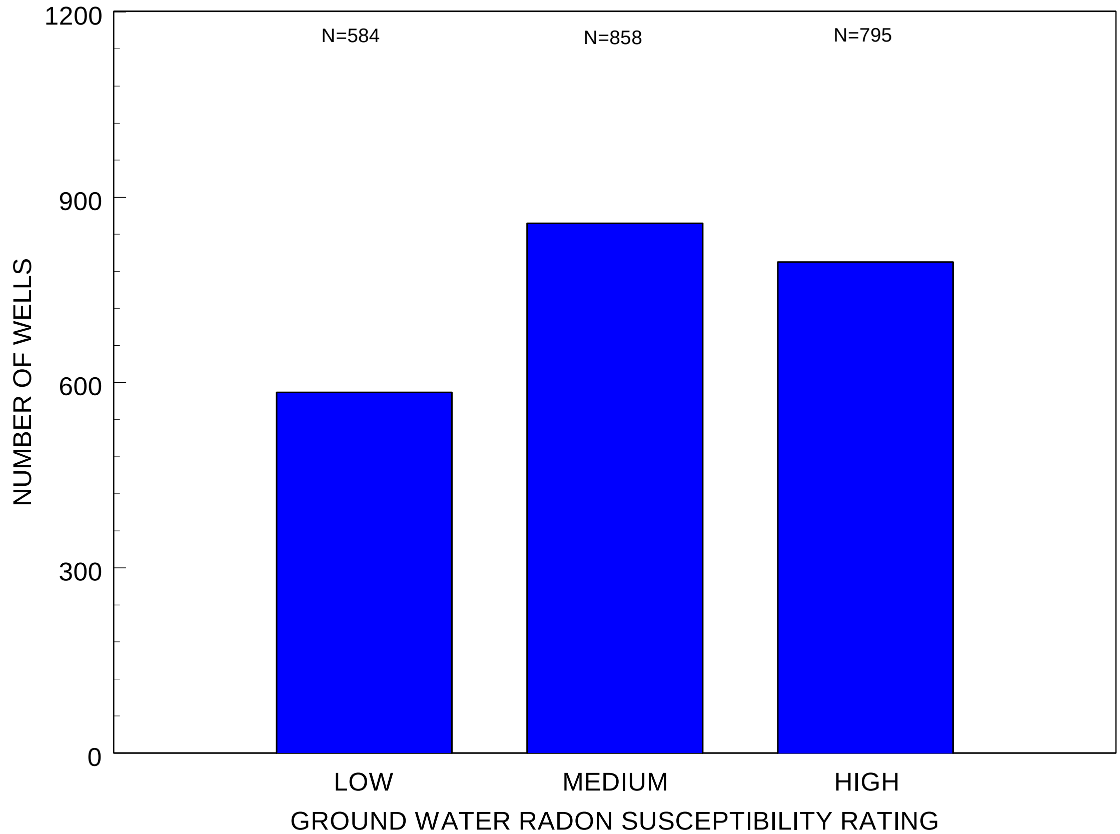

Figure 4. Number of community water-supply wells in New Jersey having low, medium, and high susceptibility to contamination by naturally occurring radon.

The susceptibility models are intended to be a screening tool and are based on water-quality data in the USGS National Water Information System (NWIS) database. The objective is to rate all community water supplies as having low, medium, or high susceptibility to contamination for the groups of constituents by using, as guidance, thresholds developed by NJDEP for the purpose of creating the model. In general, the low-susceptibility category includes wells for which constituent values are not likely to equal or exceed one-tenth of New Jersey's drinking-water maximum contaminant level (MCL), the medium-susceptibility category includes wells for which constituent values are not likely to equal or exceed one-half the MCL, and the high-susceptibility category includes wells for which constituent values may equal or exceed one-half the MCL. The susceptibility ratings for the naturally occurring radionuclide constituents group are based on individual naturally occurring constituent susceptibility assessment models. The constituent group rating for a well is the highest susceptibility rating of the individual constituent ratings.

Susceptibility Model Development

The development of the susceptibility assessment model involved several steps (Hopple and others, U.S. Geological Survey, written commun., 2003): (1) development of source water assessment areas to community water supplies; (2) building of geographic information system (GIS) and water-quality data sets; (3) exploratory data analysis using univariate and multivariate statistical techniques, and graphical procedures; (4) development of a numerical coding scheme for each variable used in the models; and (5) assessment of relations of the constituents to model variables. An independent data set was not available to verify the models. Multiple lines of evidence were used to select the final variables used in the models.

Development of Source Water Assessment Areas

The New Jersey Geological Survey (NJGS) estimated areas contributing water to more than 2,400 community water-supply wells in New Jersey and New York (fig. 5) by using the Combined Model/Calculated Fixed Radius Method. These methods use well depth, water-table gradient, water-use data, well characteristics, and aquifer properties to determine the size and shape of the contributing area. The source water assessment area for a well open to an unconfined aquifer was divided into three tiers based on the time of travel from the outside edge to the wellhead: tier 1 (2-year time of travel), tier 2 (5-year time of travel), and tier 3 (12-year time of travel) (http://www.state.nj.us/dep/njgs/whpaguide.pdf). An unconfined aquifer is a permeable water-bearing unit where the water table forms its upper boundary at the interface between unsaturated and saturated zones. The source water assessment area for a well open to a confined aquifer was defined as the area within a 50-foot radius of the well (http://www.state.nj.us/dep/njgs/whpaguide.pdf). Confined aquifers are permeable water-bearing units between hydrogeologic units with low permeability, known as confining units.

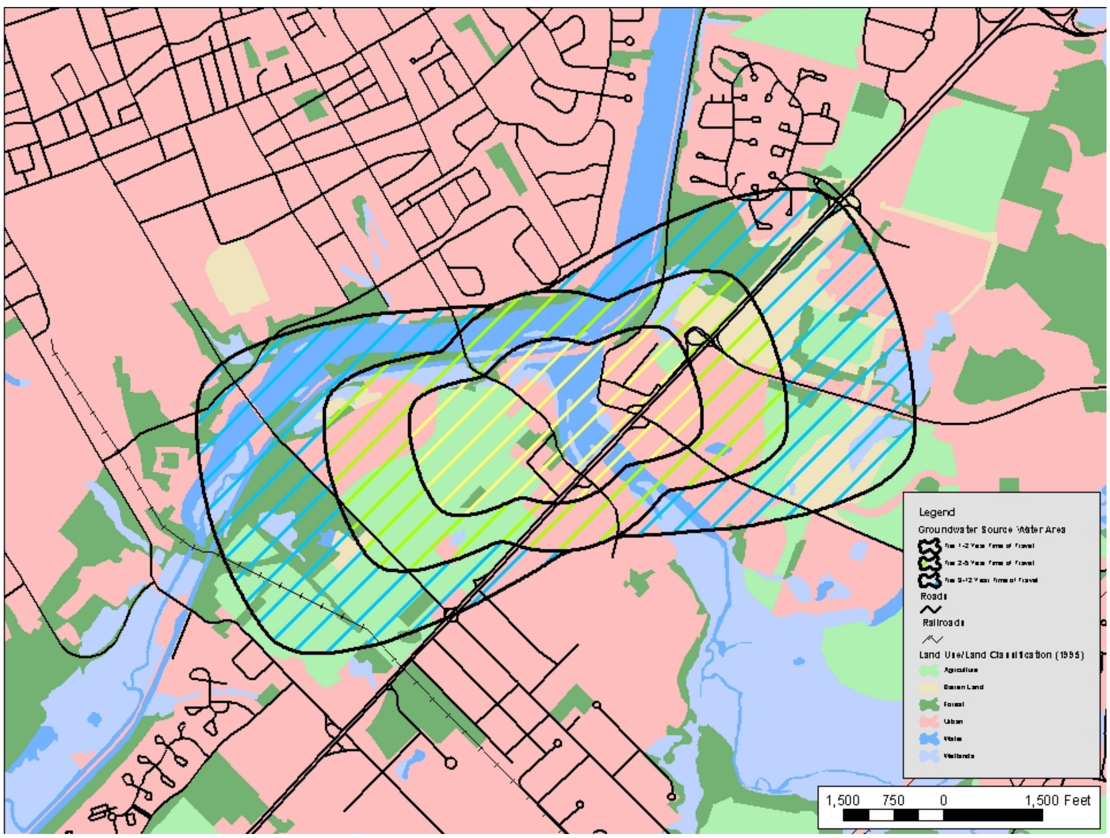

Figure 5. Example of delineated contributing area to a community water-supply well showing time of travel (TOT), land use, roads, and railroads.

Development of Data Sets

Data sets were developed for the GIS and water-quality data to assess the variables used to develop the susceptibility models. A relational database was used to store and manipulate water-quality, hydrogeologic-sensitivity, and intensity variables.

GIS

A GIS was used to quantify hydrogeologic-sensitivity and potential contaminant-use variables that may affect ground-water quality within areas contributing water to wells. The variables were calculated for each of the three ground-water tiers and for the entire source water assessment area for wells open to unconfined aquifers. The variables were calculated for the entire source water assessment area for wells open to confined aquifers. Sensitivity variables used in the statistical analysis include soil properties, aquifer properties, physiographic province, and well-construction characteristics. Intensity variables include land use from coverages based in the early 1970's, 1986, and 1995-97; lengths of roads, railways, and streams; the number of potential contaminant sources; septic-tank, population, and contaminant-site densities; and minimum distances of the well to the various land uses and to potential contaminant sources.

Water-Quality Data

Ground-water-quality data from June 1980 through October 2002 were obtained from the USGS National Water Inventory System (NWIS) database. Data were imported into a relational database and a statistical software package used for exploratory data analysis, statistical testing, and plotting. All water-quality data are from water samples collected prior to treatment, unless otherwise noted. Analyses that were determined by older, less accurate, or less precise methods were excluded. Analyses with known contamination problems also were not used. Sites in northern New Jersey with contributing areas that are predominantly in New York State were eliminated because sensitivity and intensity variables were unavailable.

Three data sets consisting of wells sampled for each constituent were used in the modeling process to test relations to hydrogeologic sensitivity and potential contaminant-use intensity variables: (1) all wells in the NWIS database; (2) all CWS wells, and (3) a subset consisting of unconfined CWS wells. The most recent concentration measured at each well was used in each data set because the most recent sample probably was analyzed using a method with the lowest minimum reporting level (MRL) and with better precision. The number of CWS wells with radionuclides data, the constituents detected, and their corresponding MCLs are shown in table 1.

The pH of water samples was used as a variable in statistical tests and for application of models to CWS wells. The most recent analysis in the NWIS database was used to represent the pH of the wells. If data were unavailable in the NWIS database for pH, the most recent value from the NJDEP water-quality database was used. These analyses are unlike analyses in the NWIS database in that they often time are from samples that were collected from facilities that receive water from more than one well, and the water may be treated. This value was used for all wells that contribute to that facility. If results of analyses were unavailable in either database, no value of pH was used.

If sufficient data were available to run all statistical tests, the subset of unconfined CWS was used to develop the model. If not, the data set with all CWS wells was used. This data set was used to develop all radionuclides models. Typically, statistics were not run on the data set with all wells. Many of the samples are from problem-oriented studies, and the results do not necessarily represent typical ground-water conditions for CWS wells. This data set was used to determine spatial distribution of constituents within New Jersey, find problem areas, and estimate areas where no data for public supplies exists. Source water assessment areas were not generated for all wells; consequently, values for sensitivity and intensity variables were not determined.

Table 1. Number of sites at which selected constituents in samples from community water-supply wells met or exceeded selected criteria related to the MCL, and frequency of detection

Constituent	Standard	Number of sites for which data are available [1]	Number of sites at which constituent was detected	Number of sites at which concentration meets criterion 1[2]	Number of sites at which concentration meets criterion 2[3]	Number of sites at which concentration equals or exceeds standard	Frequency of detection[4]
Alpha radioactivity, filtered, pCi/L[5]	15 pCi/L	11	10	0	0	10	0.91
Alpha radioactivity, filtered, pCi/L as thorium-230	15 pCi/L	165	121	47	29	37	0.73
Gross alpha radioactivity, filtered, pCi/L as americium-241	15 pCi/L	59	46	29	8	1	0.78
Radium-226, filtered, gamma count, pCi/L	5 pCi/L[6]	30	30	18	6	4	1
Radium-226, filtered, pCi/L	5 pCi/L	102	102	50	3	1	1
Radium-226, filtered, planchet count, pCi/L	5 pCi/L	73	37	24	9	2	0.51
Radium-226, filtered, radon method, pCi/L	5 pCi/L	43	42	25	10	1	0.98
Radium-228, filtered, pCi/L	5 pCi/L	160	140	38	22	9	0.88
Radium-228, unfiltered, gamma count, pCi/L	5 pCi/L	22	21	13	5	2	0.95
Radon-222, unfiltered, pCi/L	4000 pCi/L[7]	121	120	21	3	1	0.99
Uranium, filtered, μg/L	30 μg/L	63	30	13	2	0	0.48
Uranium-234, filtered, pCi/L[8]	30 μg/L	32	25	0	0	0	0.78
Uranium-235, filtered, pCi/L	30 μg/L	31	12	0	0	0	0.39
Uranium-238, filtered, pCi/L	30 μg/L	32	23	11	0	0	0.72
Beta radioactivity, filtered, pCi/L[9]	4 mrem/yr	7	7				1
Gross beta radioactivity, filtered, pCi/L as cesium-137	4 mrem/yr	227	187				0.82
Gross beta radioactivity, filtered, pCi/L as Sr-90/ Y-90	4 mrem/yr	42	38				0.90

[1] Number of sites represents all CWS wells in the NWIS database for constituents with primary standards and may be different than the number of sites used to develop the model.
[2] Criterion 1: Concentration is at least equal to one-tenth of the standard, but is less than one-half of the standard.
[3] Criterion 2: Concentration is at least equal to one-half of the standard, but is less than the standard.
[4] Number of sites at which constituent was detected divided by number of sites for which data are available.
[5] Gross alpha-particle activity analyses in New Jersey post 1997 are completed with a 48-hour holding time as a result of studies by the USGS, NJDEP, and the New Jersey Department of Health and Senior Services. Samples analyzed before this date may not have met this holding time criteria and thus do not account for the presence of short-lived alpha-particle-emitting radionuclides (Parsa, 1998).
[6] The maximum contaminant level of 5 pCi/L is for combined radium-226 and radium-228.
[7] Value represents the proposed alternate maximum contaminant level; proposed maximum contaminant level is 300 pCi/L (http://www.epa.gov/safewater/radon/radfr1.html).
[8] Values for uranium in pCi/L were converted to equivalent values in μg/L (Schleien and Terpilak, 1984, table 8.5).
[9] Many naturally occurring and manmade radionuclides emit radiation in the forms of beta particles and/or gamma rays. The standards require identification of individual radioisotope concentrations if elevated beta particle activity is present in order to determined actual compliance. The radioisotopes with current individual regulatory standards are manmade and are typically found in surface water or in the direct vicinity of nuclear facilities and not widely distributed in ground water; the regulatory scheme primarily targets these manmade sources, not routine ground water (U.S. Environmental Protection Agency, 2000a). Furthermore, southern New Jersey is a region of the USA where the primary source of gross beta-particle activity is the naturally occurring radionuclide radium-228, which is directly regulated by the combined radium standard (Welch and others, 1995).

Data Analysis

Federal and State Safe Drinking Water Regulations require routine monitoring for many inorganic constituents at community water systems. For the purpose of modeling, NJDEP determined that concentrations greater than one-half of the MCL would be of greatest concern. Concentrations equal to or greater than one-tenth of the MCL also are considered in this report as an indication of an emerging problem, but health effects at this level are of less concern. The uranium model was developed to determine the variables that best describe the presence or absence of constituents in source waters at concentrations equal to or greater than one-tenth of the MCL. The alpha and radium models were developed at one-half of the MCL, and the radon model was developed at the proposed MCL of 300 pCi/L. The alpha, radium, and radon models were developed at these levels because most concentrations for these constituents in water-quality samples were above one-tenth of the corresponding MCL and statistical tests could not be run at the one-tenth level.

Statistical tests and graphical procedures were used to evaluate the relation between naturally occurring radionuclides and sensitivity and intensity variables. Univariate statistical tests were run on all variables. Univariate tests included the Kruskal-Wallis test and Spearman's rho (Table 2).

Table 2. Results of univariate statistical tests for explanatory variables used in the radionuclides model					
	Kruskal-Wallis rank test		Spearman's rank correlation		
Variables	Kruskal-Wallis score	p-value	Spearman's rho	p-value	Conceptual variable
Gross alpha-particle activity model					
pH	31.26	0.000	-0.575	0.000	No
Percent urban land in 1995-Tier 1	17.40	0.000	0.445	0.000	No
Average soil saturated hydraulic conductivity[2]	1.82	0.177	0.087	0.330	Yes
Depth of well (feet)[2]	0.68	0.411	0.129	0.150	Yes
Distance to agricultural land (feet)[1]	0.54	0.464	-0.102	0.331	Yes
Combined radium model					
pH	38.72	0.000	-0.566	0.000	No
Physiographic Province	26.42	0.000			No
Percent developed land in 1995-Tier 1	13.38	0.000	0.331	0.000	No
Uranium model					
Physiographic Province	57.64	0.000			No
Septic density per square mile in Piedmont	13.78	0.000	-0.511	0.000	No
Percent agricultural land in 1970	3.22	0.073	0.092	0.428	No
Radon model					
Physiographic Province	20.70	0.000			No
Depth to top of open interval (feet)	2.72	0.100	-0.248	0.017	No
Percent agricultural land in 1995	2.41	0.121	0.209	0.034	No
Distance to wetlands (feet)[2]	2.31	0.129	-0.130	0.209	Yes
Average percent soil clay[2]	1.15	0.283	-0.083	0.407	Yes

[1] This conceptual variable shows a graphical relation, improves the model, and is supported by previous scientific investigations.
[2] This conceptual variable shows a graphical relation and improves the model.

The Kruskal-Wallis test was used to determine whether distributions of hydrogeologic sensitivity or intensity variables differed between constituent groups that were below, or equal to or greater than one-tenth of the constituent MCL. The sizes of the Kruskal-Wallis test statistic and corresponding p-value are used as a measure of the strength of differences between the groups. Spearman's rho, the nonparametric equivalent of a correlation coefficient, was used to evaluate linear trends between ranked explanatory and response variables because environmental variables rarely are normally distributed (Helsel and Hirsch, 2002). Correlation coefficients were calculated between the concentration of each modeled constituent and all hydrogeologic-sensitivity and intensity variables, and many water-quality variables. Scatter plots of all variables versus the concentration of the modeled constituent were generated to confirm the results of statistical tests. Boxplots were used to compare the distributions of variables among groups.

Results of univariate statistical tests (Spearman's rho and Kruskal-Wallis) and graphs (scatter plots and boxplots) were used to identify potential predictors of contamination at selected concentration levels relative to the MCL. In some cases, variables thought to be a good predictor of contamination did not produce a significant univariate statistical relation. In this report, conceptual variables are variables with possible graphical relations for which results of univariate statistical tests were not significant but that have been shown in a previous scientific investigation to be related to the concentrations of a constituent. Conceptual variables also are variables for which results of univariate statistical tests were or were not significant but that improve the model and may represent a surrogate for other unidentified variables associated with the concentration of a constituent, although no evidence was found in previous investigations of a relation. Conceptual variables that did not produce significant univariate statistical relations may, however, produce a significant relation when used with other variables in multivariate statistical tests. Selected sensitivity and intensity variables that were either conceptually or significantly related to the presence or absence of a particular constituent were tested for covariance by using Principal Components Analysis. Logistic regression analysis was used to determine the best combination of variables to predict the presence or absence of a constituent at a given concentration. Variables were included in the susceptibility models only if there was a physical basis or explanation for their inclusion, plots showed an apparent graphical relation, or they improved the results of the model.

Some variables that proved to be statistically significant were not used in the model. Some possible reasons for exclusion were (1) the variable was not a known source of the constituent modeled, (2) use of the variable in the model was not supported by scientific investigations, (3) the variable did not show a graphical relation to the constituent, or (4) the variable was found to have a similar relation to the constituent as another variable.

Rating Scheme

A scoring method was developed for each constituent model that gave a maximum of 5 points to each variable for unconfined wells (Table 3). The maximum number of points was given to variables that were the most statistically significant (both univariate and multivariate tests), and graphically approached a linear relation. If, for example, when pH was statistically related (a negative Spearman's correlation, Kruskal Wallis score of 38.72, and p-value of 0.000) to combined radium and the pH for a well was low, a score of 5 was assigned. When the pH for a well was high, a score of 0 was assigned. Fewer points were given to variables that were less significant statistically, that had lower correlation coefficients, that appeared graphically to be grouped, or that did not show changes over the entire range of values. Values of pH were used, if available, to improve the results of the models. If, however, values were not available when applying the model to CWS wells, no points were assigned to the well to increase the susceptibility rating. The graphs presented in this report were used as the starting point for devising the numerical code.

If results of analyses of the most recent samples of a constituent for all confined wells indicated that few detections exceeded one-tenth of the MCL (no more than 1 in 10 samples), 0 points were given to confined CWS wells. For wells in confined aquifers for which no results of analyses were available for a constituent, 0 points were assigned, and the susceptibility could not be determined. If results of analyses indicated that more then 10 percent of samples for wells in an aquifer or geologic unit exceeded one-half of the corresponding MCL, a rating of high was assigned to all wells within that aquifer or geologic unit. If values rarely exceeded one-half of the MCL, but frequently exceeded one-tenth of the MCL, a medium rating was assigned.

Table 3. Susceptibility rating scheme for naturally occurring radionuclides in water from community water-supply wells

Ground Water Gross Alpha-Particle Model

Alpha Rating: 0-3.5 LOW, 4-7.5 MEDIUM, 8-17.5 HIGH

	Sensitivity Points-Unconfined Wells								
Variable	0	0.5	1	1.5	2	2.5	3	4	Conceptual variable
pH	>6		>5.5-6		>5-5.5		>4.5-5	≤4.5	No
Soil saturated hydraulic conductivity[1]	0-15	>15-30	>30-45	>45-60	>60-75	>75			Yes
Depth of well (feet)[1]	>200				≤200				Yes

	Intensity Points-Unconfined Wells						
Variable	0	1	2	3	4	5	
Percent urban land use, 1995 -Tier 1		≤20	>20-40	>40-60	>60-80	>80-100	No
Distance to agricultural land , 1995[2]	>4000	>2000-4000	>1000-2000	>500-1000	≤500		Yes

	Points-Confined Wells	
Variable	0	5
Geologic unit	Everything else	Magothy Formation; Magothy Formation - Old Bridge Sand member; Magothy, Raritan, and Potomac Formations; Potomac Formation; Shark River Formation

[1] This conceptual variable shows a graphical relation and improves the model.
[2] This conceptual variable shows a graphical relation, improves the model, and is supported by previous scientific investigations.

Ground Water Combined Radium Model

Radium Rating: 1-2 LOW, 3-6 MEDIUM, 7-14 HIGH

	Sensitivity Points-Unconfined Wells						
Variable	0	1	2	3	4	5	Conceptual variable
Physiographic Province	Everything else		Piedmont		Coastal Plain		No
pH	>6	>5.5-6	>5-5.5	>4.5-5	>4-4.5	≤4	No

	Intensity Points-Unconfined Wells						
Variable	0	1	2	3	4	5	
Percent developed land, 1995 - Tier 1	0-10	>10-30	>30-50	>50-70	>70-90	>90-100	No

Points-Confined Wells 0

Ground Water Uranium Model

Uranium Rating: 0-6 LOW, 7-8 MEDIUM, 9 HIGH

	Sensitivity Points-Unconfined Wells				
Variable	0	1	2	5	Conceptual variable
Physiographic Province	Everything else		Highlands	Piedmont	No

	Intensity Points-Unconfined Wells				
Variable	0	1	2	5	
Percent agricultural land use, 1970	0-25	>25-50	>50		No
Septic density per square mile in Piedmont	>50		<=50		No

Points-Confined Wells 0

Ground Water Radon Model

Radon Rating: 1-2.5 LOW, 3-6.5 MEDIUM, 7-11 HIGH

	Sensitivity Points-Unconfined Wells						
Variable	0	0.5	1	2	3	5	Conceptual variable
Physiographic Province			Coastal Plain		Everything else	Piedmont	No
Percent soil clay-average[1]	0-5		>5-10	>10			Yes
Depth to top of open interval (feet)	≥150		>75-<150	≤75			No

	Intensity Points-Unconfined Wells						
Variable	0	0.5	1	2	3	5	
Percent agricultural land, 1995	0-10	>10-25	>25				No
Distance to wetlands, 1995 (feet)[1]	>100		≤100				Yes

	Points-Confined Wells	
Variable	0	5
Geologic unit	Everything else	Mount Laurel and Wenonah Formations, Shark River Formation - Toms River member

[1] This conceptual variable shows a graphical relation and improves the model.

Relation of Naturally Occurring Radionuclides in Ground Water to Susceptibility Variables

Relations between concentrations of gross alpha-particle activity; and concentrations of combined radium, uranium, and radon in water from CWS wells and various hydrogeologic sensitivity and potential contaminant-use intensity variables, were investigated to select the variables that best predict the susceptibility of CWS wells in New Jersey to contamination by naturally occurring radionuclides. Concentrations or activities in samples from wells used to develop the models frequently exceeded the MCL for gross alpha activity and combined radium, and the proposed MCL for radon. Concentrations rarely exceeded the MCL for uranium. All naturally occurring isotopes of uranium and radon, and radium-224 and radium-226 emit alpha particles; radium-228 emits beta particles.

The susceptibility ratings for naturally occurring radionuclides are influenced mainly by the sensitivity variables of the model because geology and water chemistry typically are more important than land use in determining the concentration of these constituents. For confined aquifers, little contamination originates from land surface sources and most is due to contributions from the aquifer material surrounding the well and to chemical factors. Radioactive elements are found at low concentrations in all rocks, soil, and water. Aquifer material is a source of naturally occurring radionuclides in water and results from the weathering of the parent rock (http://www.epa.gov/safewater/rads/technicalfacts.html). In New Jersey, radionuclides originate primarily from natural sources. Radionuclides typically are found in higher concentrations in ground water than in surface water (http://www.epa.gov/safewater/rads/technicalfacts.html).

Radon was not included with the other three radionuclides in the radionuclide constituent group model for several reasons. Chemically and physically, radon is unlike all other constituents within the group, or any other contaminant group. It is a noble gas, is nearly inert, is highly soluble relative to other radionuclides, poses an indoor air quality-based health risk, and has a short half-life (3.8 days for radon-222 and 55 seconds for radon-220) which makes concentration variable (Szabo and dePaul, 2000). Currently, there is not a final MCL for radon. However, in November 1999 the USEPA proposed a multimedia framework for this contaminant. As outlined in the USEPA proposal, states can choose to either develop enhanced state programs to address the health risks from radon in indoor air (known as multimedia mitigation programs) while individual water systems reduce radon levels in drinking water to 4,000 pCi/L or lower, or if a state chooses not to develop a multimedia mitigation programs, individual water systems in that state would be required to either reduce radon in their system's drinking water to 300 pCi/L or develop individual local multimedia mitigation programs and reduce levels in drinking water to 4,000 pCl/L. USEPA has not yet finalized this rule. For the purposes of modeling, in order to consider which CWS wells may require immediate action/attention when the proposed 4,000 pCi/L alternate MCL is exceeded, one-half of the proposed alternate MCL was used to apply the radon susceptibility model. With this approach, those wells likely to require immediate action will be the ones rated high susceptibility for the radionuclide constituent group. Many radon concentrations in samples from CWS wells in New Jersey exceeded 300 pCi/L.

Gross Alpha-Particle Radiation

Gross alpha-particle radiation was frequently detected (98 of 126 sites) in water from the CWS wells used for model development (fig. 6), typically in higher concentrations in the Coastal Plain Physiographic Province and southwestern Piedmont than in other areas of the State (fig. 7). Naturally occurring isotopes of uranium, radium-224, radium-226, radon, and other radionuclides emit alpha particles as they decay and are sources of alpha radiation. Measurement of alpha-particle radioactivity indicates that one or more alpha-particle emitting radionuclides are present in the sample, but the identity of the specific radionuclide cannot be determined without specific chemical tests designed to identify the individual nuclide and determine their concentrations. Of the many alpha-particle emitting radionuclides that may occur naturally, a specific standard (MCL) exists for uranium and radium-226 (as combined radium), and a proposed standard exists for radon. Gross alpha-particle activity in the sample may originate from these, or other, radionuclides. The New Jersey and USEPA MCL for gross alpha-particle activity currently is 15 pCi/L. For regulatory compliance purposes, the gross alpha-particle activity MCL of 15 pCi/L includes radium-226, but excludes uranium and radon.

Gross alpha-particle activity is related to the concentration of combined radium in the Coastal Plain of New Jersey. Radium, and consequently, alpha-particle activity often are found in high concentrations in or near agricultural areas (fig. 7), where the ground water is acidic (Szabo and dePaul, 1998). In the Piedmont Province, high alpha-particle activity is most likely from elevated concentrations of uranium and radium in the rock and ground water. High levels of uranium can be found in waters that are oxidizing and high in bicarbonate such that carbonate complexing of the uranium and increased competition for adsorption sites with dissolved ions in mineralized water keep the uranium in solution (Szabo and Zapecza, 1991) and increase alpha-particle activity. Abundant radium-226 is found in iron (and magnesium, manganese, and barium)-rich reducing waters and with low pH waters, especially with high calcium and magnesium content where conditions are unfavorable for the adsorption of radium (Szabo and Zapecza, 1991; Szabo and DePaul, 1998). The radium stays in solution and increases alpha-particle activity.

Typically, the shallower the well, the more likely it is that contaminants will be transported from sources at land surface to the well or that the water quality of the wells will be influenced by human activities that affect the geochemical environment near the well. The depth of the well is a measure of the distance a contaminant would have to travel from sources of the contaminant at land surface to reach the well. Depth of well, a conceptual variable, was used to improve the results of the model (fig. 7C).

Gross alpha-particle activities in confined Coastal Plain aquifers typically were lower than those in unconfined aquifers, but occasionally exceeded one-tenth of the MCL. Median activities in several confined aquifers, including the Potomac Raritan Magothy aquifers and aquifers within the Shark River Formation were near or above this level. In confined aquifers, the median values did not exceed one-half of the MCL. Wells in these units were assigned a medium susceptibility.

The unconfined CWS wells subset contained insufficient data to develop the alpha-particle activity model; consequently, data from all unconfined CWS in the NWIS database wells were used. In this data set, alpha-particle activity was equal to or exceeded the MCL of 15 pCi/L in 35 of 126 wells with analyses, and was equal to or exceeded one-tenth of the MCL in samples from 93 of 126 wells. Variables selected to represent hydrogeologic sensitivity for alpha-particle activity were water pH, average soil saturated hydraulic conductivity (conceptual), and depth of well (conceptual). Variables selected to represent potential contaminant-use intensity for alpha-particle activity were percent urban land in tier 1 in 1995 (conceptual) and distance to agricultural land in 1995. Of the 2,237 CWS wells in New Jersey, 525 were rated as having low susceptibility, 1,144 were rated as having medium susceptibility, and 568 were rated as having high susceptibility for alpha-particle activity (fig. 8).

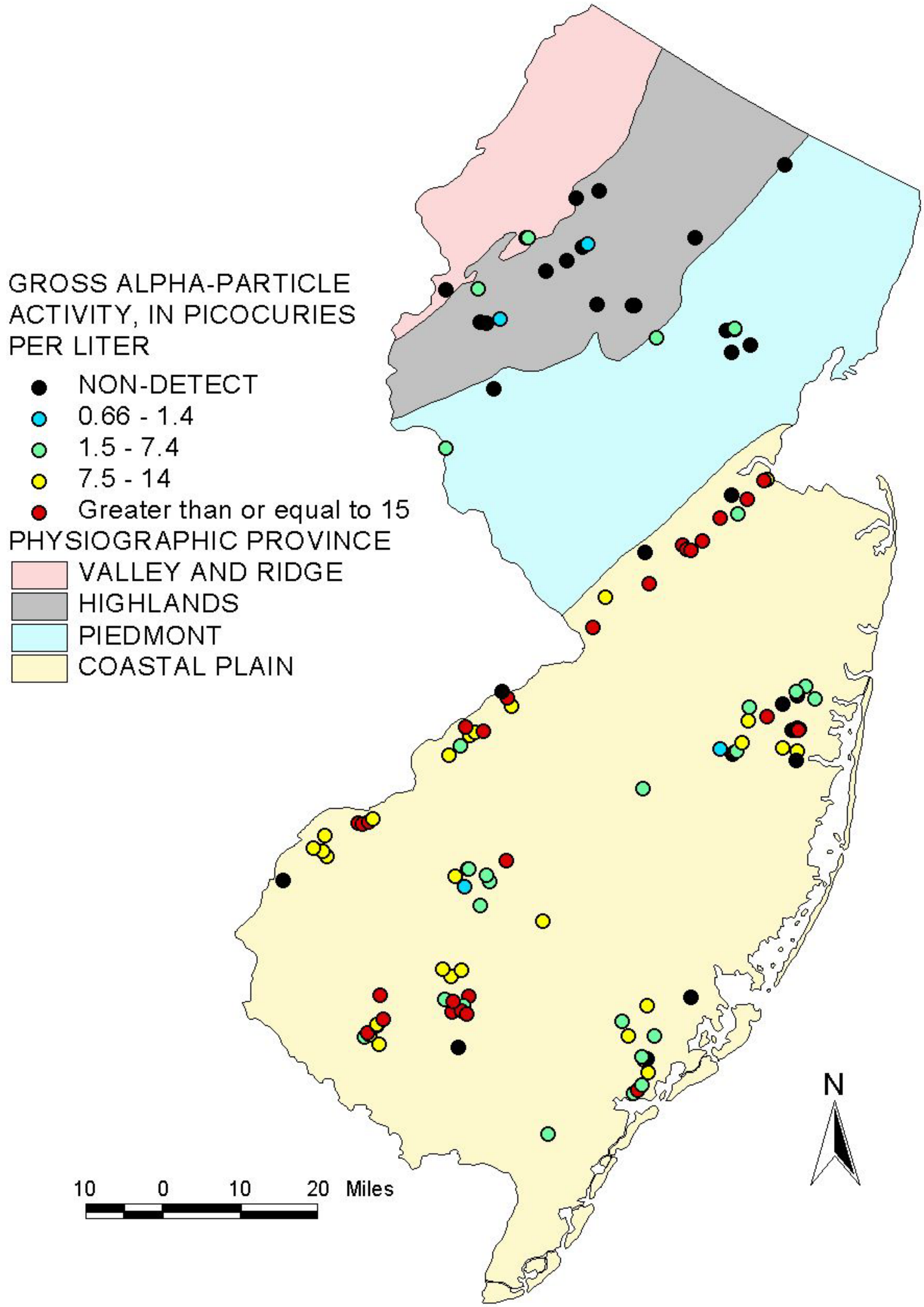

Figure 6. Gross alpha-particle activity in 126 community water-supply wells used for development of the gross alpha-particle activity model.

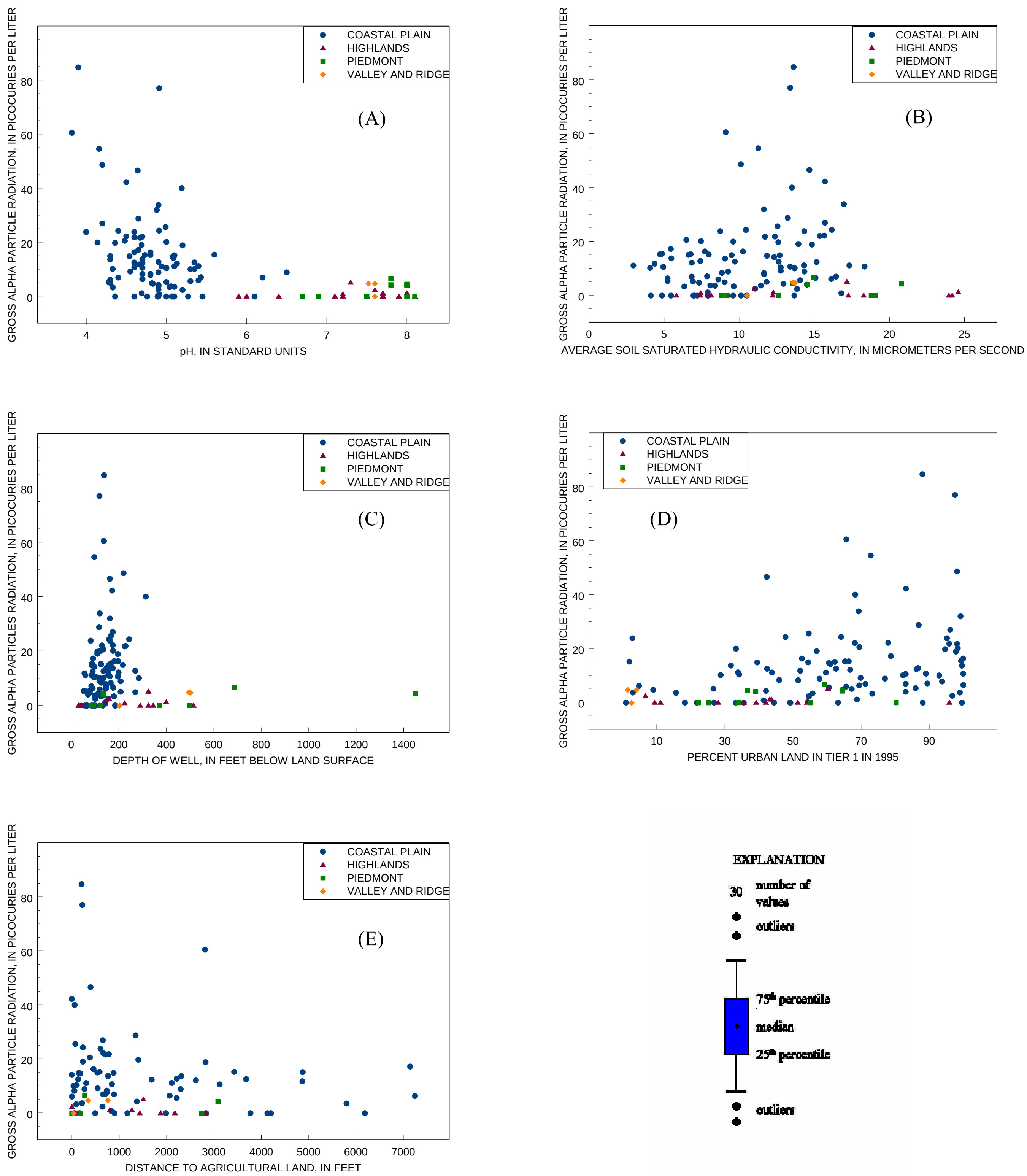

Figure 7. Relation of gross alpha-particle activity to (A) pH, (B) average soil saturated hydraulic conductivity, (C) depth of well, (D) percent urban land, and (E) distance to agricultural land, by physiographic province, for 126 community water-supply wells in New Jersey.

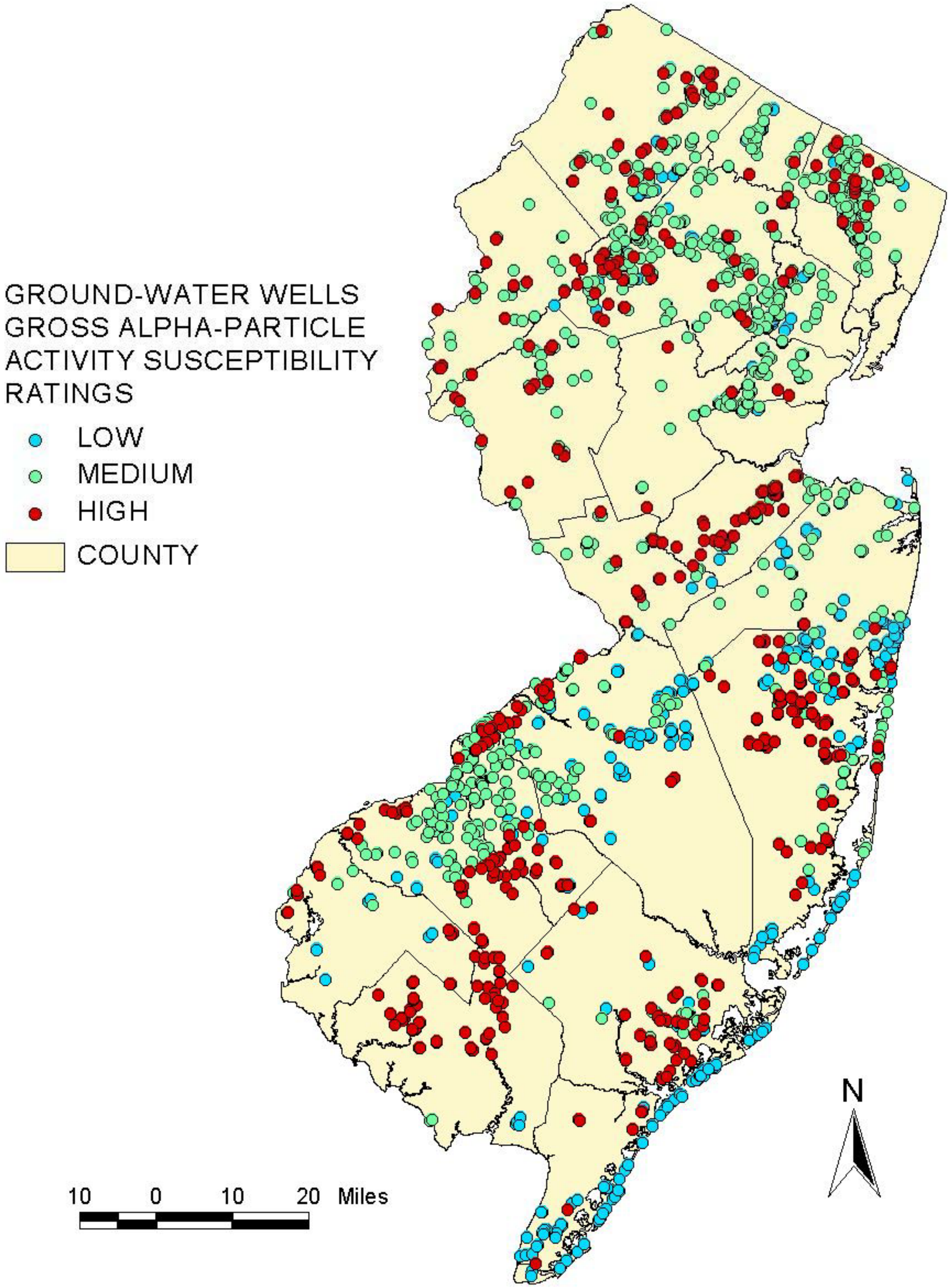

Figure 8. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by gross alpha-particle activity.

Combined Radium

Radium was frequently detected (123 of 126 sites) in water from the CWS wells used for model development (fig. 9), typically in higher concentrations in the Coastal Plain Physiographic Province and southwestern Piedmont than in other areas of the State (fig. 10). Radium can enter the ground-water system by dissolution of minerals in rock or aquifer sediment, desorption from the surfaces of particles within aquifers, and other processes. The New Jersey and USEPA MCL for combined radium-226 and radium-228 currently is 5 pCi/L.

In the Coastal Plain, high radium concentrations frequently occur in areas where the Bridgeton Formation crops out and where nitrate concentrations exceed 5 mg/L (Szabo and dePaul, 1998). The application of agricultural chemicals to crops, and subsequent leaching to the ground-water system, also may result in an increase in the concentration of radium in ground water (Szabo and dePaul, 1998). Iron hydroxides, which are common in rocks of the Piedmont Physiographic Province, can absorb radium (as the Ra^{2+} ion) from solution in ground water. When the water is in a reducing state, the iron hydroxide coatings on mineral surfaces tend to dissolve and are far less abundant (Szabo and Zapecza, 1991), and radium remains in solution in the ground water. Results of statistical tests indicated that radium concentrations were related to developed land (fig. 10C). For this study, developed land includes both agricultural and urban land. The developed land use variable used in statistical tests represents current and historical agricultural land use as well as urban land use (fig. 10B). Radium concentrations typically are higher in or near agricultural areas, where the ground water is acidic, than in other areas (fig. 10). This trend can be seen in both the Coastal Plain and in the northern part of New Jersey (fig. 10A).

The unconfined CWS wells subset contained insufficient data to develop the combined radium model; consequently, data from all unconfined CWS wells in the NWIS database were used. In this data set, combined radium-226 and radium-228 concentrations were equal to or exceeded the MCL of 5 pCi/L in samples from 26 of 126 wells with analyses, and were equal to or exceeded one-tenth of the MCL in samples from 113 of 126 wells. Concentrations of radium rarely were equal to or exceeded one-half of the MCL in samples from 34 wells open to confined aquifers. Variables selected to represent hydrogeologic sensitivity for combined radium were physiographic province and water pH. One variable--percent developed land in tier 1 in 1995--was selected to represent potential contaminant-use intensity for combined radium. Of the 2,237 CWS wells in New Jersey, 846 were rated as having low susceptibility, 767 were rated as having medium susceptibility, and 624 were rated as having high susceptibility (fig. 11). The chemical characteristics of radium-224 are similar to those of radium-226 and radium-228. Although the combined radium model was developed for radium-226 and radium-228, the susceptibility of wells to contamination by radium-224 should be similar.

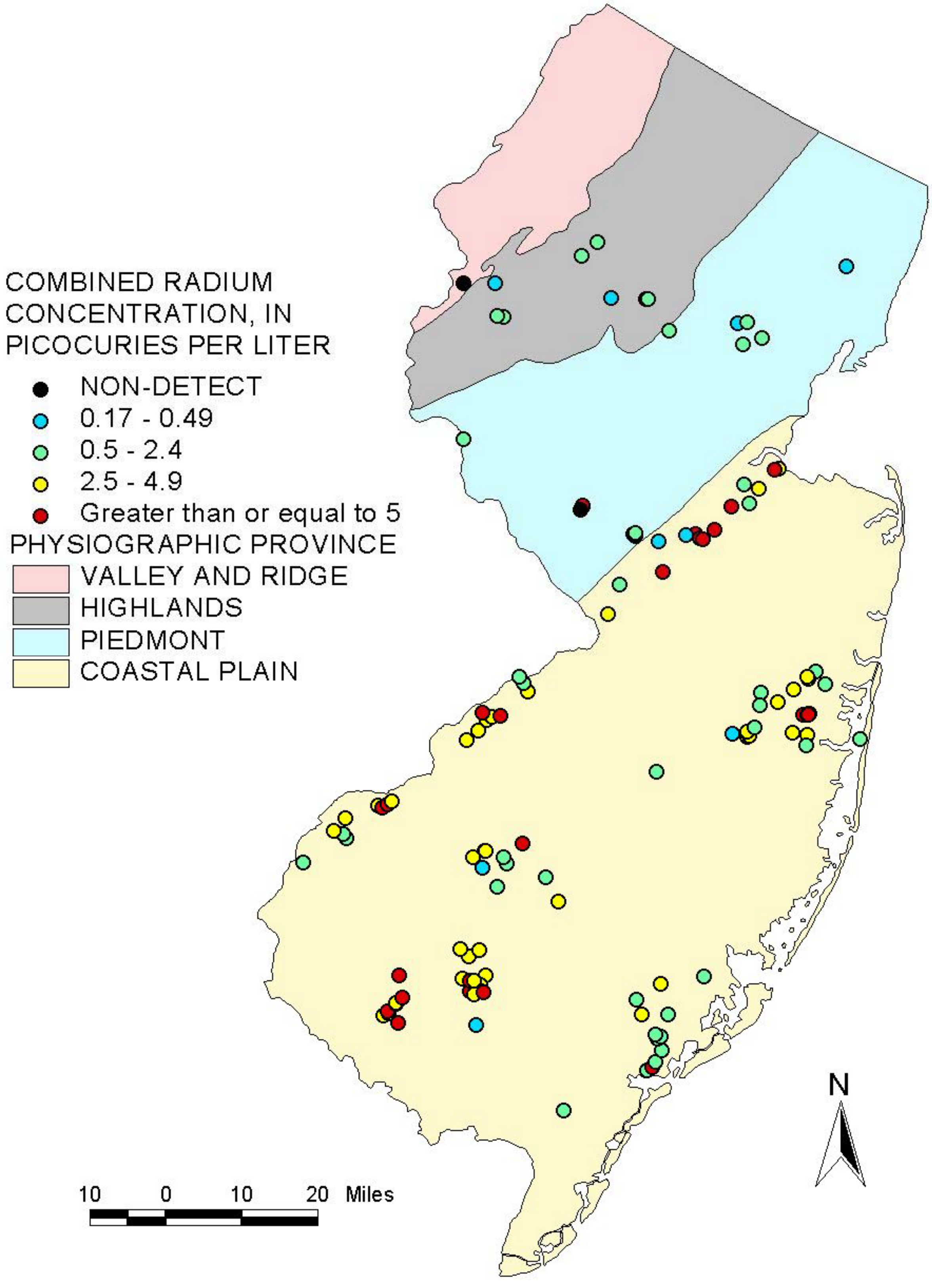

Figure 9. Concentrations of combined radium in 126 community water-supply wells used for development of the combined radium model.

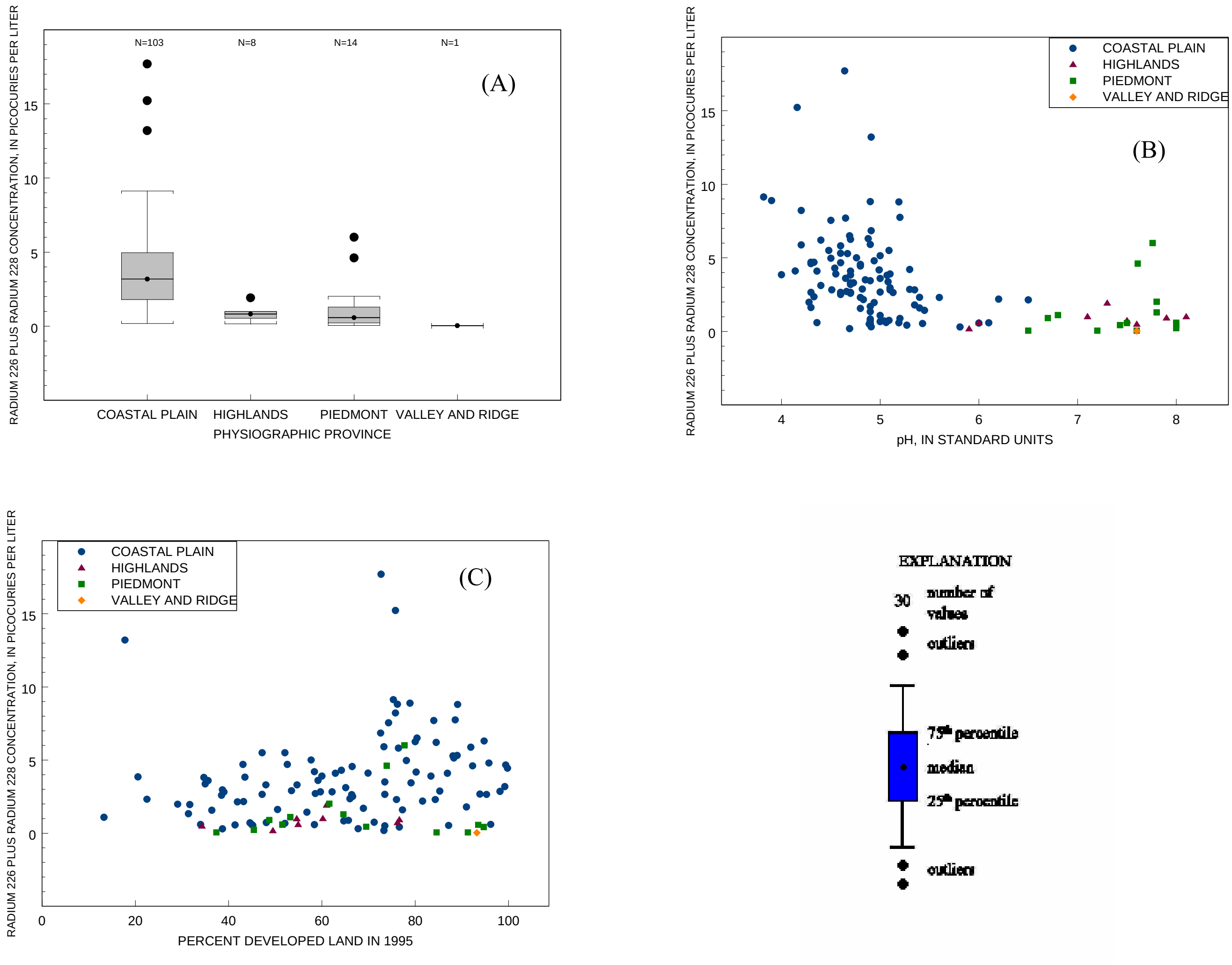

Figure 10. (A) Distribution of combined radium by physiographic province, and relation of combined radium to (B) pH, and (C) percent developed land in tier 1, by physiographic province, for 126 community water-supply wells in New Jersey.

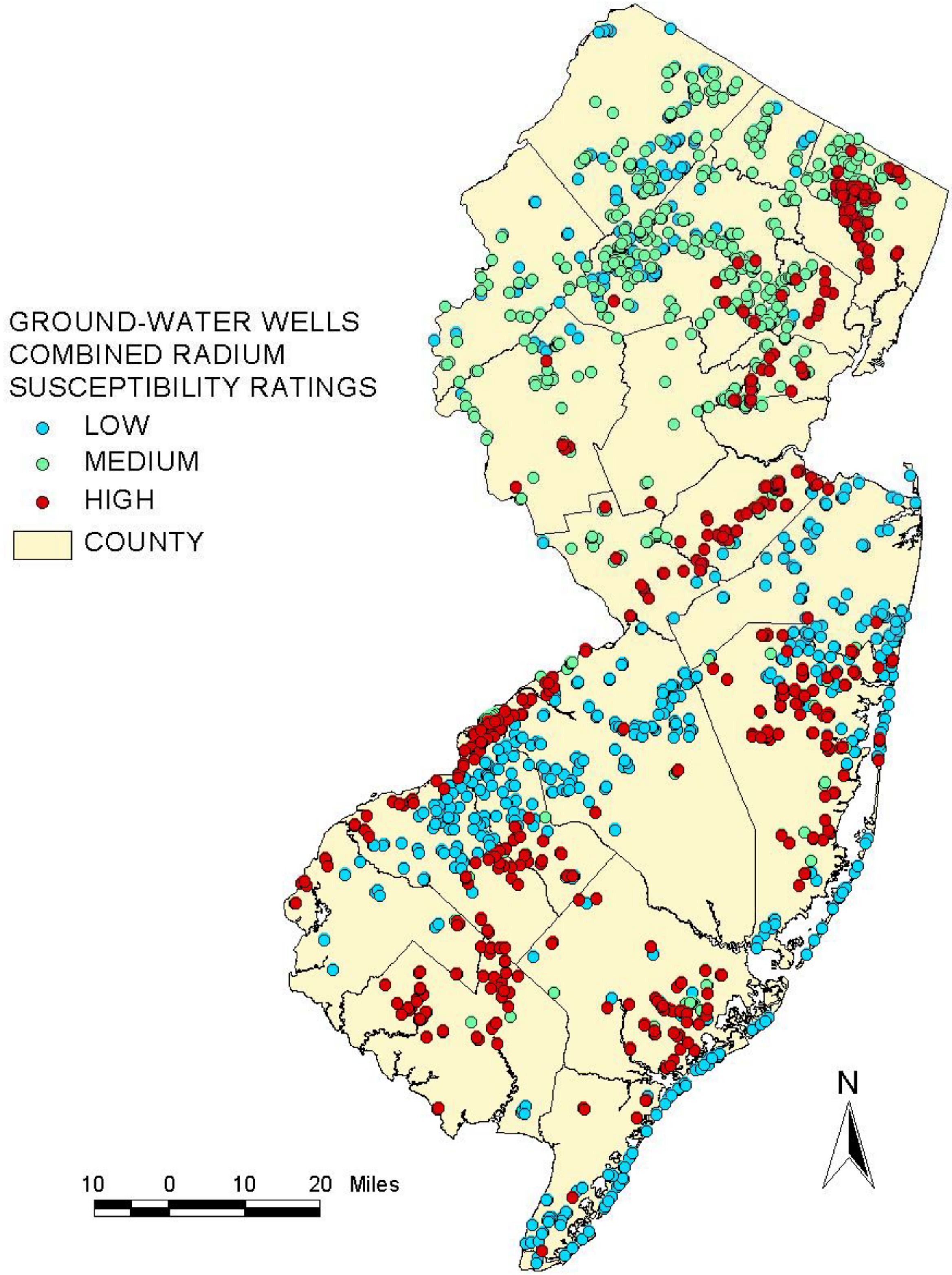

Figure 11. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by combined radium.

Uranium

Uranium was frequently detected (43 of 76 sites) in water from the CWS wells used for model development (fig. 12), typically in higher concentrations in the Piedmont Physiographic Province than in other physiographic provinces of the State (fig. 13). Some concentrations of uranium were determined based on alpha particle emissions of the uranium isotopes and the mass of uranium was computed from the amount of radiation determined. Uranium can enter the ground-water system by dissolution of minerals in rock or aquifer sediment, desorption from the surfaces of particles within aquifers, and other processes. The New Jersey and USEPA MCL for uranium currently is 30 μg/L.

Detection of uranium in water samples is common in wells in the lower part of the Passaic Formation, and in parts of the Lockatong and Stockton Formations located in the Piedmont Physiographic Province. The source of much of the uranium is from minerals, enriched in black mudstones, and dispersed along bedding planes within the mudstone formations (Szabo and Zapecza, 1991).

Uranium concentrations in ground water are controlled partly by its solubility. Uranium is found in ground water in both oxidizing and, in much lower concentrations, reducing geochemical environments. Under reducing conditions, uranium exists predominantly as the U^{4+} ion, which is only slightly soluble in water. However, under oxidizing conditions, the predominant form is the U^{6+} ion, which is highly soluble. The U^{6+} ion is even more soluble in alkaline bicarbonate-rich water because the U^{6+} ion forms a highly soluble carbonate or bicarbonate complex that is also not easily adsorbed onto aquifer sediments. Elevated concentrations of uranium in ground water within the Piedmont are associated with oxidizing and alkaline bicarbonate-rich ground-water conditions, unlike radium, which typically is detected under reducing conditions (Szabo and Zapecza, 1991). Uranium concentrations generally decrease with depth as a result of increasing anoxic conditions (Ivahnenko and others, 1995). Leach fields associated with domestic septic systems can result in reducing ground-water environments. In areas with high densities of septic systems, reducing conditions in ground water may occur. Under these conditions, the predominant form of uranium would be as the relatively insoluble U^{4+} ion. In contrast, agricultural land typically is predominant in areas with well-drained soils where it is likely that ground water will be oxidizing. Agricultural land in 1970 was used as a variable in the model to represent current and historical agricultural land use, and therefore, where well-drained soils are likely to be. The 1995 land use shows more recently developed land where there had been agricultural land. Even if the recently developed land is not sewered, it has not been in existence long enough to change the geochemical environment.

The unconfined CWS wells subset contained insufficient data to develop the uranium model; consequently, data from all unconfined CWS wells were used. In this data set, uranium did not equal or exceed the MCL of 30 μg/L, and was equal to or exceeded one-tenth of MCL in samples from 19 of 76 wells (fig. 12). One variable--physiographic province--was selected to represent hydrogeologic sensitivity for uranium. Variables selected to represent potential contaminant-use intensity for uranium were percent agricultural land in 1970 and septic density in the Piedmont Physiographic Province (fig. 13). Of the 2,237 CWS wells in New Jersey, 1,809 were rated as having low susceptibility, 413 were rated as having medium susceptibility, and 15 were rated as having high susceptibility (fig. 14).

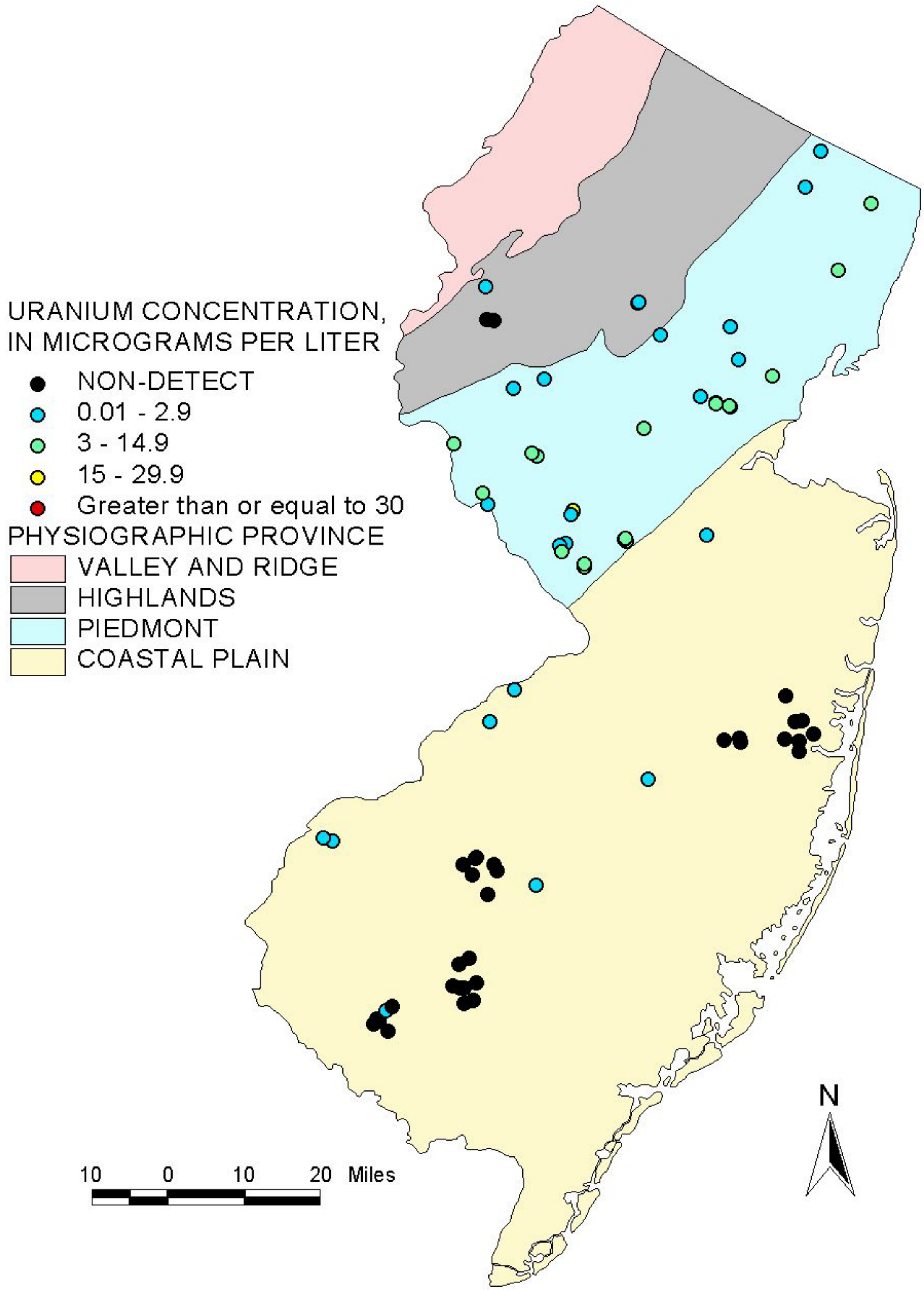

Figure 12. Concentrations of uranium in 76 community water-supply wells used for development of the uranium model.

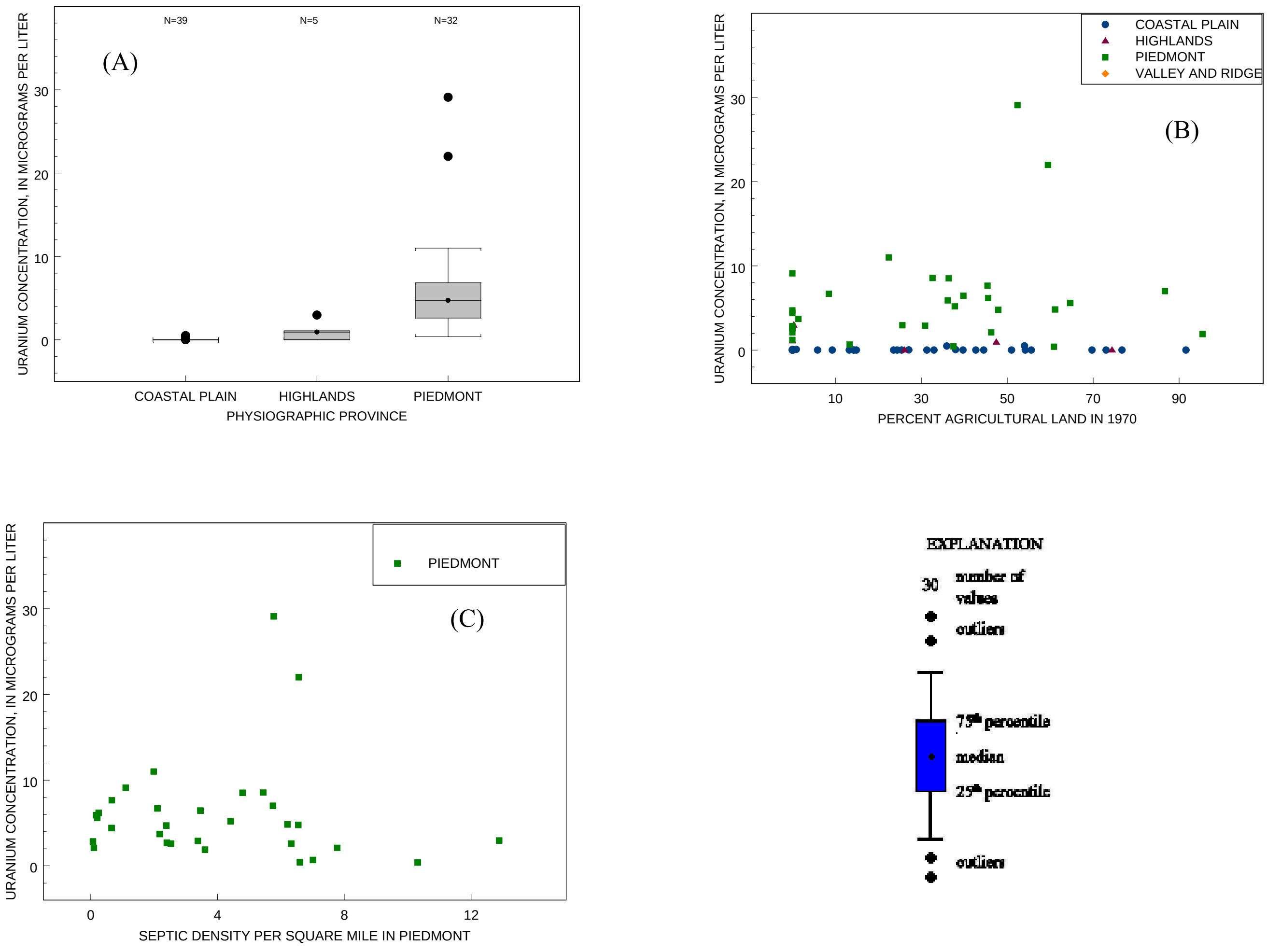

Figure 13. (A) Distribution of uranium concentration by physiographic province, and relation of uranium concentration to (B) percent agricultural land in 1970, by physiographic province, and (C) septic density in the Piedmont, for 76 community water-supply wells in New Jersey.

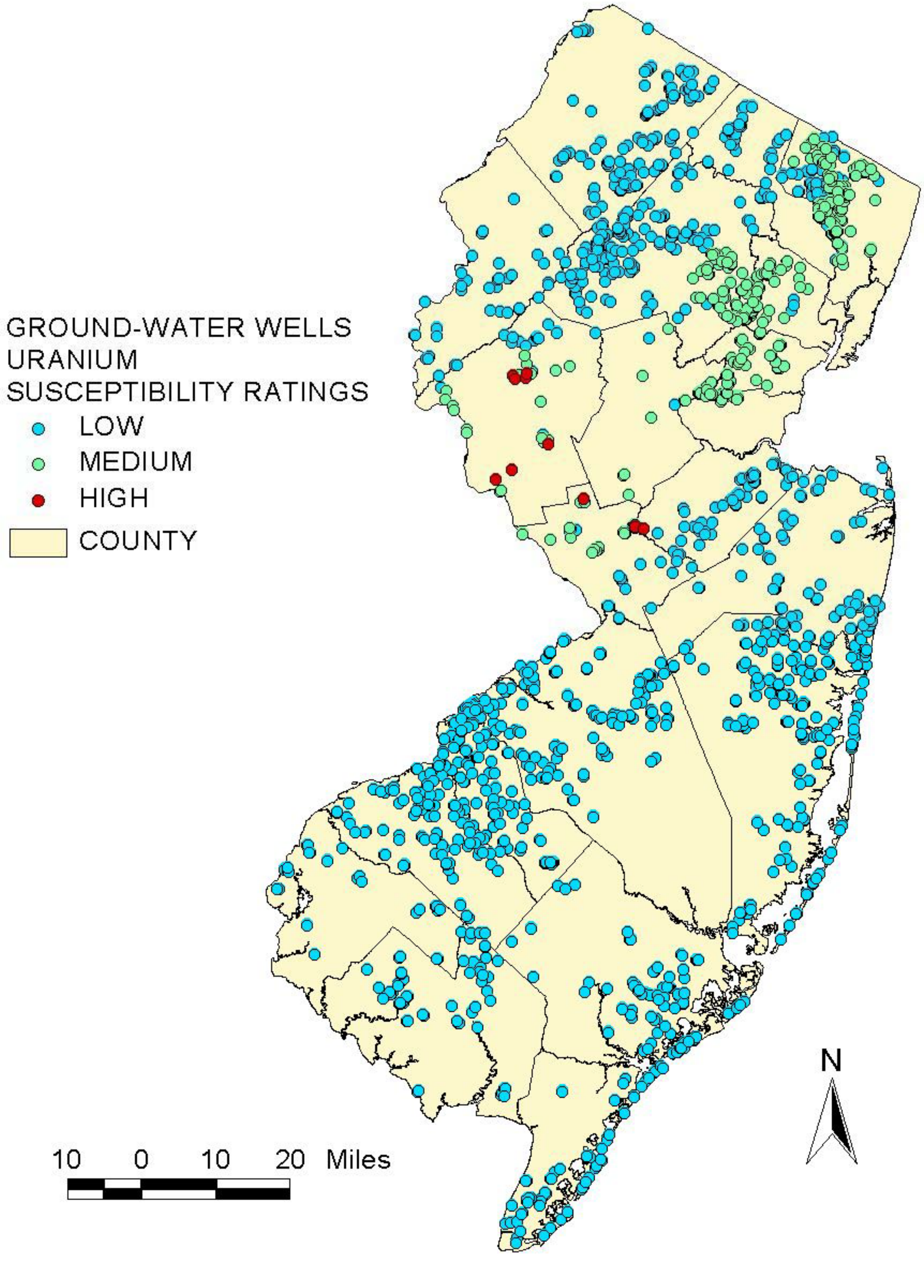

Figure 14. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by uranium.

Radon

Radon was frequently detected (104 of 104 sites) in water from the CWS wells used for model development (fig. 15), typically in higher concentrations in northern New Jersey than in the Coastal Plain Physiographic Province (fig. 16). Few CWS wells in northern New Jersey have results of analyses for radon; however, concentrations of radon in the most recent samples from 44 of 209 sites (including CWS wells and non-CWS wells) in northern New Jersey in the NWIS database were equal to or exceeded 4,000 pCi/L. The maximum concentration detected was 33,000 pCi/L. Radon concentrations in ground water are highly variable, and consistently greater than concentrations of uranium and radium, from which it originates. Radon has a relatively short half-life (3.8 days); consequently, cannot travel far in ground water from where it originated.

Radon in ground water likely originates from both the decay of radium dissolved in ground water, and the decay of radium in the rock matrix. Radon concentrations in ground water are partly controlled by the presence and distribution of radium-226 in rock and sediment material, the distribution of radium-226 in ground water, and the physical characteristics that determine flow patterns within the aquifer (Szabo and Zapecza, 1991). Radium-226 originates indirectly from the decay of uranium-238. Phosphate fertilizers, which are applied to agricultural and residential areas, can carry substantial amounts radioactive material as an impurity, including radium, uranium, and thorium (Menzel, 1968). Radium concentrations typically are higher in or near agricultural areas, where the ground water is acidic, than in other areas.

Radon solubility is not affected much by water chemistry; any relations in this category may be more a result of the effect of increasing radium solubility in some chemical types of water affected by human activities. Average percent soil clay and distance to wetlands in 1995 are conceptual variables that were used to improve the results of the model and may be surrogates for other unidentified variables which affect the concentration of radon in ground water. Ground water in the vicinity of wetlands typically is under reducing conditions, in which radium typically is detected more frequently. In addition, clay, which can be a source of radon, can be present under some types of wetlands.

Concentrations in confined Coastal Plain aquifers typically were similar to those in unconfined Coastal Plain aquifers. Radon concentrations in confined aquifers in the Coastal Plain occasionally exceeded one-tenth of the proposed alternate MCL of 4,000 pCi/L. Median concentrations in several confined aquifers including the Wenonah-Mt. Laurel aquifer and aquifers within the Shark River Formation were near or above this level. Wells in these units were assigned a medium susceptibility.

The unconfined CWS wells subset contained insufficient data to develop the radon model; consequently, data from all unconfined CWS wells were used. In this data set, radon was equal to or exceeded the proposed alternate MCL of 4,000 pCi/L in the sample from 1 of 104 wells with analyses, and was equal to or exceeded one-tenth of the proposed alternate MCL in samples from 23 of 104 wells. Variables selected to represent hydrogeologic sensitivity for radon were physiographic province, average percent soil clay (conceptual), and depth to top of open interval. Variables selected to represent potential contaminant-use intensity for radon were percent agricultural land in 1995 and distance to wetlands in 1995 (conceptual). Of the 2,237 CWS wells in New Jersey, 584 were rated as having low susceptibility, 858 were rated as having medium susceptibility, and 795 were rated as having high susceptibility (fig. 2).

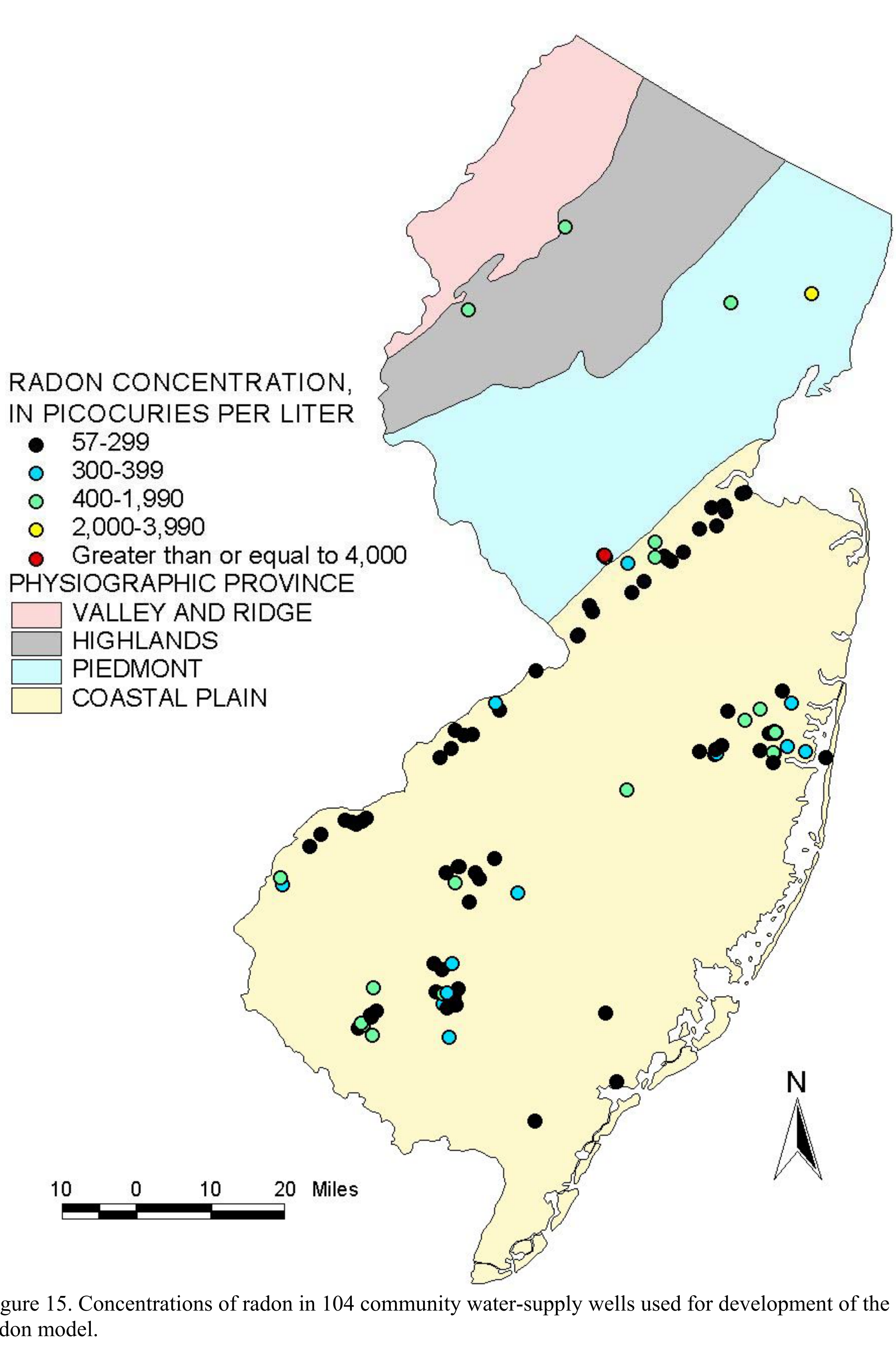

Figure 15. Concentrations of radon in 104 community water-supply wells used for development of the radon model.

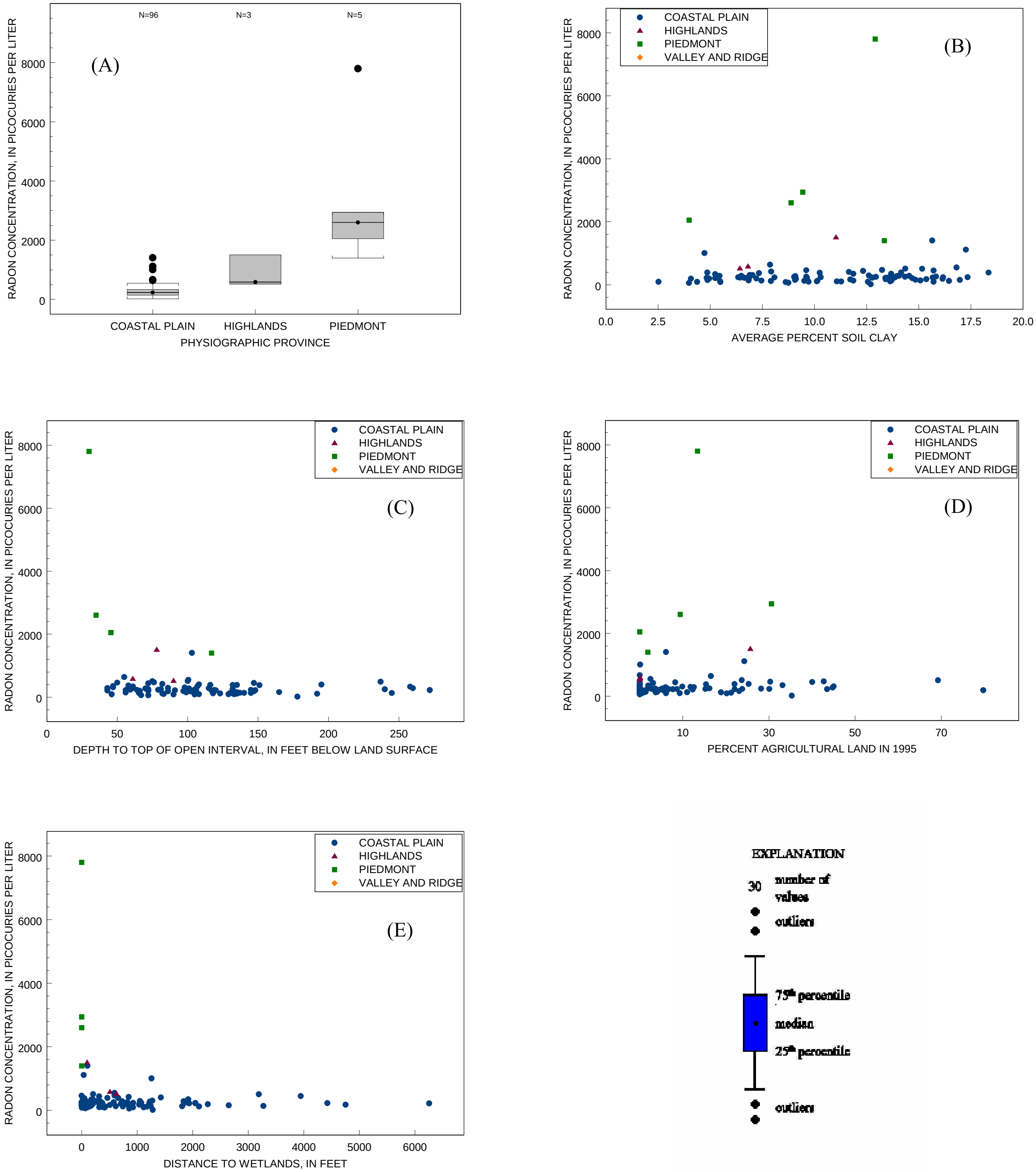

Figure 16. (A) Distribution of radon concentration by physiographic province, and relation of radon concentration to (B) average percent soil clay, (C) depth to top of open interval, (D) percent agricultural land, and (E) distance to wetlands, by physiographic province, for 104 community water-supply wells in New Jersey.

Susceptibility of Ground-Water Sources

The results of the susceptibility assessment models indicate that as sensitivity and intensity increase the concentrations of the constituents increase for all modeled constituents (fig. 17). The numerical rating schemes created during model development were applied to the sensitivity and intensity variables of each CWS well. Of the 2,237 CWS wells, the susceptibility to contamination by radionuclides (excluding radon) was low for 444 (20 percent), medium for 1,004 (45 percent), and high for 789 (35 percent). The susceptibility ratings for the radionuclides constituent group are based on individual constituent susceptibility assessment models. The constituent group rating for a well is the highest susceptibility rating of the individual constituent ratings for each model. Of the 2,237 CWS wells, the susceptibility to contamination by radon was low for 584 (26 percent), medium for 858 (38 percent), and high for 795 (36 percent).

Discussion

Several limitations of the susceptibility assessment models should be noted. These models should only be used as screening tools to identify potential contamination problems. The concentrations used for a well in the analysis were those measured in the most recently analyzed sample, and do not take into account fluctuations in concentrations that may occur. Radon concentrations are known to be especially variable (Szabo and dePaul, 2000). Most of the results of analyses for wells in the NWIS database are from filtered samples. Radionuclides can move in water when adsorbed to colloids, and unfiltered samples can contain substantially higher concentrations than those of filtered samples. Some of the components of the analysis were subjective, especially the coding scheme for the susceptibility assessment model. The method used to determine source water assessment areas and tiers representing times of travel of water to the well is inexact, and produces only estimates of the actual contributing area and the length of time the water is in transit before it reaches the well.

Statistical tests on uranium concentrations were run on groups of samples in which concentrations were below one-tenth of the MCL and on samples in which they were equal to or greater than one-tenth of the MCL. This level is below the NJDEP threshold of concern of one-half the MCL and may not produce the same results as if statistics were run at a higher level. For radon, statistical tests were run at the proposed MCL of 300 pCi/L because few samples had results of analyses that were below the threshold of one-tenth of the proposed MCL of 300 pCi/L. The susceptibility rating represents a combination of both sensitivity and intensity and, in some cases, may be inconsistent with the results of water-quality analyses.

The database, GIS coverages, statistical analysis, and susceptibility assessment models will provide guidance to scientists and managers in their efforts to characterize the effects of hydrogeology and land use on the quality of public-water supplies. The relations between water quality and susceptibility variables developed and illustrated here can be used to help determine monitoring requirements for water purveyors to ensure public health.

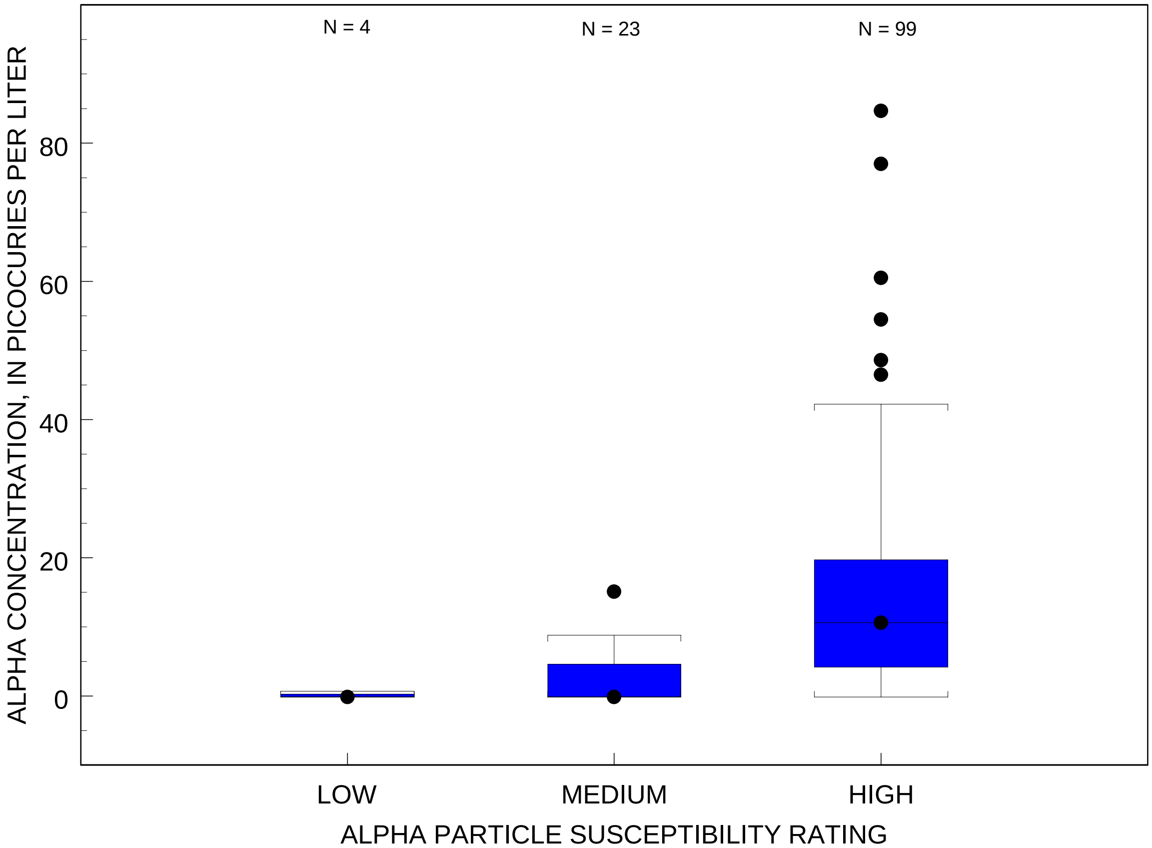

Figure 17A. Results of the gross alpha-particle activity susceptibility assessment model for 126 community water-supply wells in New Jersey showing distribution of gross alpha-particle activity by susceptibility rating.

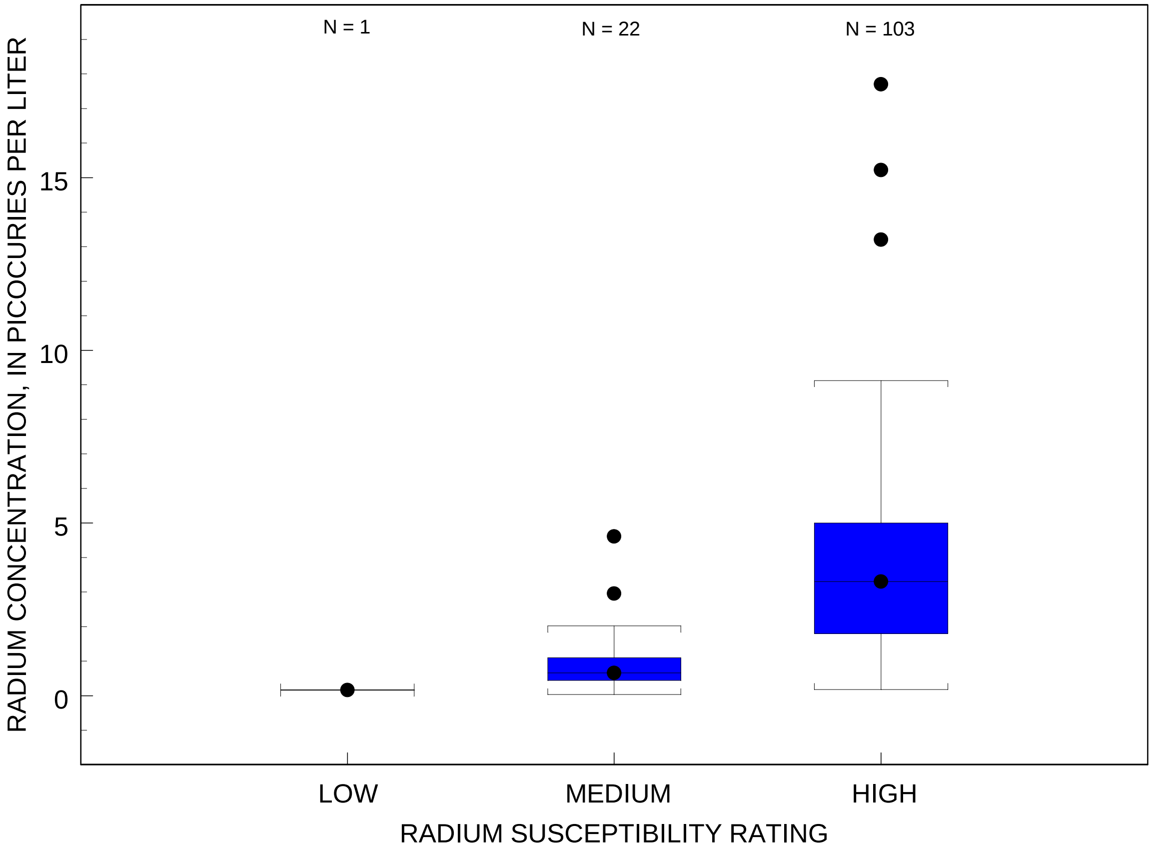

Figure 17B. Results of the combined radium susceptibility assessment model for 126 community water-supply wells in New Jersey showing distribution of combined radium concentration by susceptibility rating.

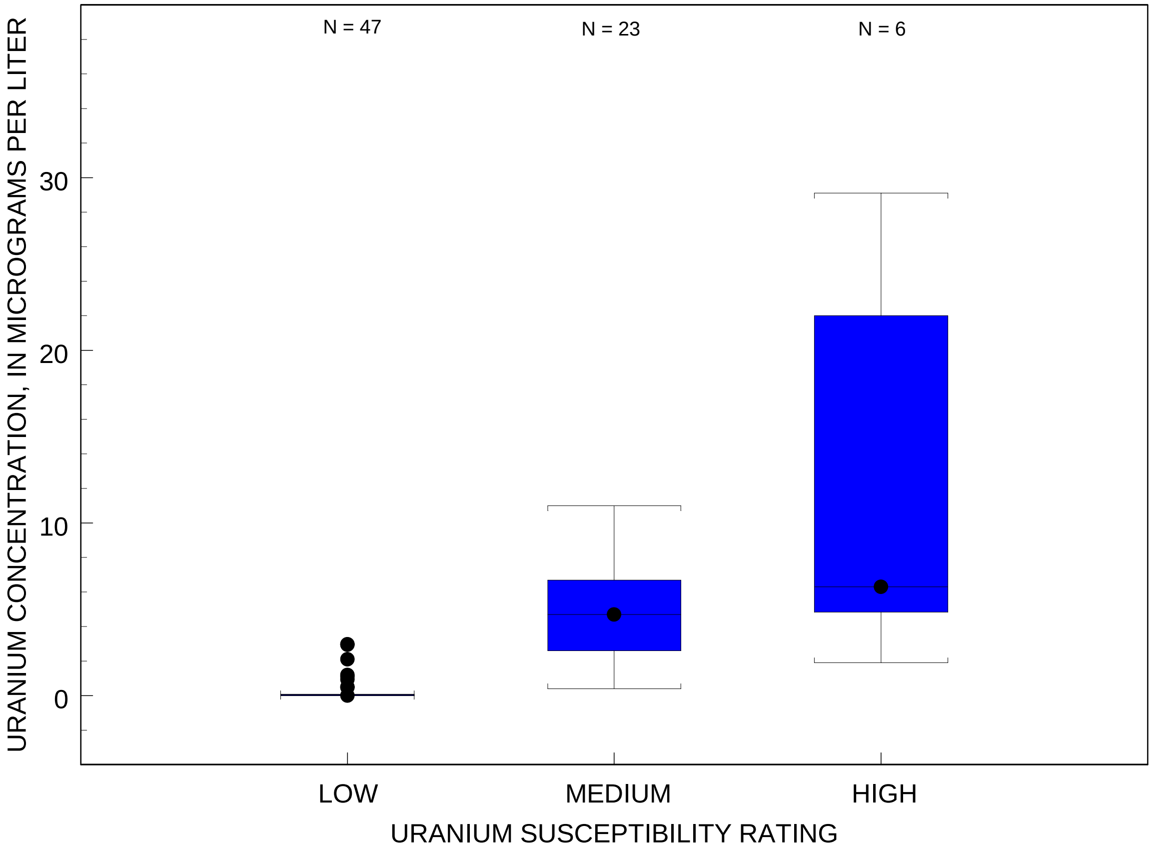

Figure 17C. Results of the uranium susceptibility assessment model for 76 community water-supply wells in New Jersey showing distribution of uranium concentration by susceptibility rating.

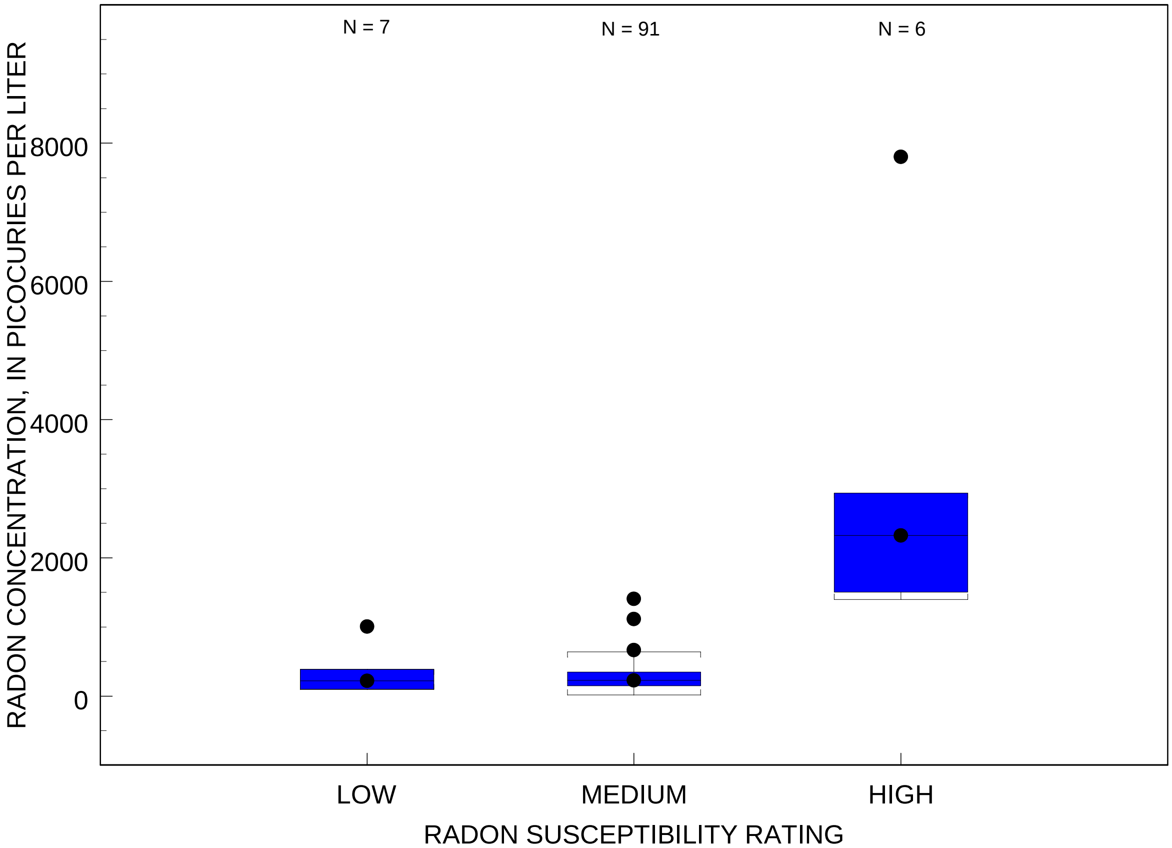

Figure 17D. Results of the radon susceptibility assessment model for 104 community water-supply wells in New Jersey showing distribution of radon concentration by susceptibility rating.

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