SUSCEPTIBILITY OF SOURCE WATER TO COMMUNITY WATER-SUPPLY WELLS IN NEW JERSEY TO CONTAMINATION BY INORGANIC CONSTITUENTS

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 inorganic constituents. In this report, inorganic constituents are metals and major constituents. A separate report and model is available for nitrate. 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 well samples collected and analyzed by the U.S. Geological Survey. Models were developed for 6 of 14 constituents with primary maximum contaminant levels: arsenic, barium, beryllium, fluoride, lead, and mercury. The susceptibility ratings for the inorganic constituents 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. Of the 2,237 community water supply wells, the susceptibility to inorganic constituents was low for 789 (35 percent), medium for 851 (38 percent), and high for 597 (27 percent) (figs. 1 and 2). Susceptibility ratings for arsenic were highest in the Piedmont Physiographic Province and are likely associated with geologic sources rather than with human activities. Barium concentrations also were highest in the Piedmont, and may be the result of natural sources and agricultural practices. Beryllium, lead, and mercury were frequently detected in low pH water typical of the Coastal Plain aquifers of 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).

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 inorganic constituents, (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.

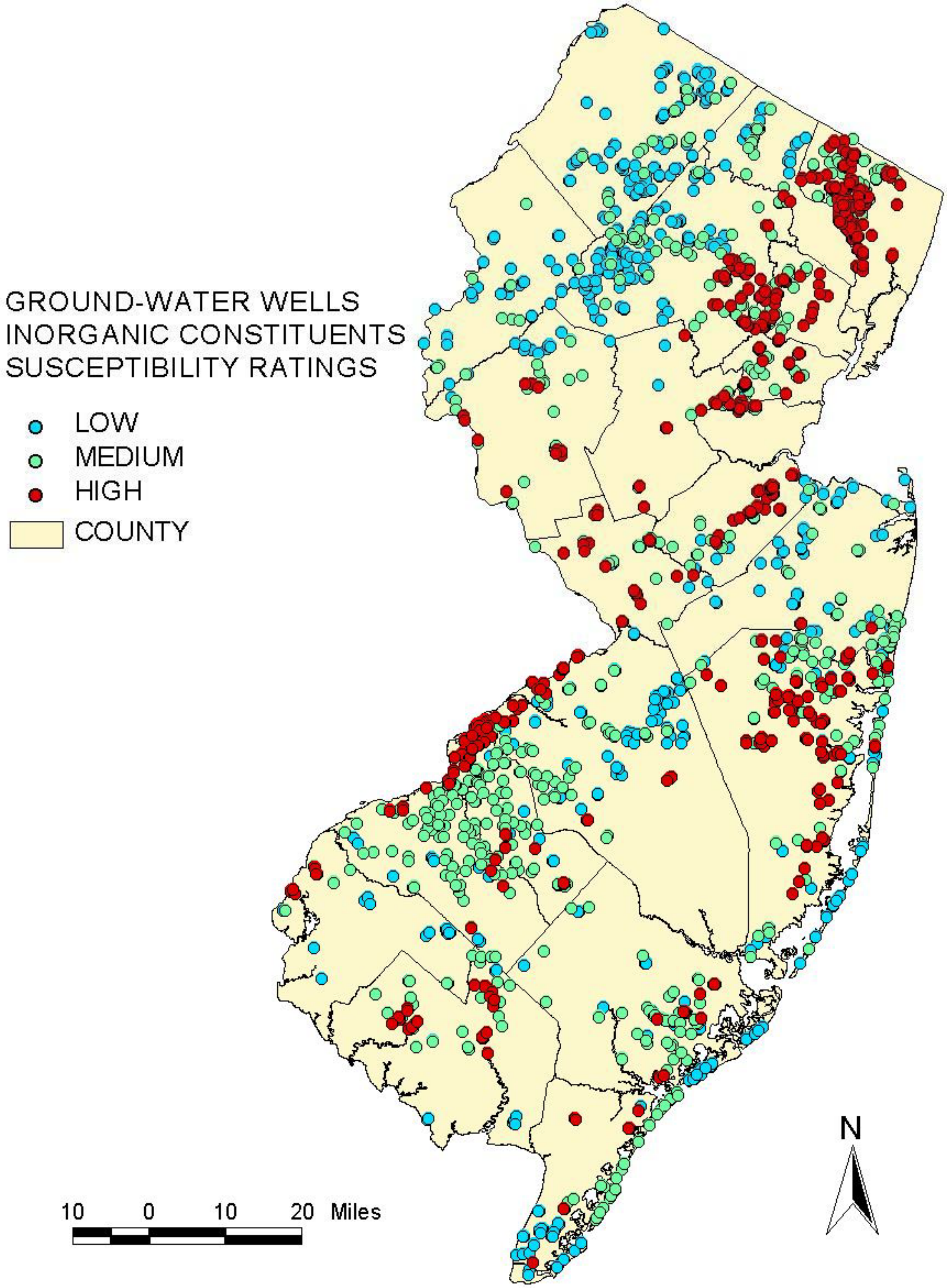

Figure 1. Susceptibility of 2,237 community water supply wells in New Jersey to contamination by inorganic constituents.

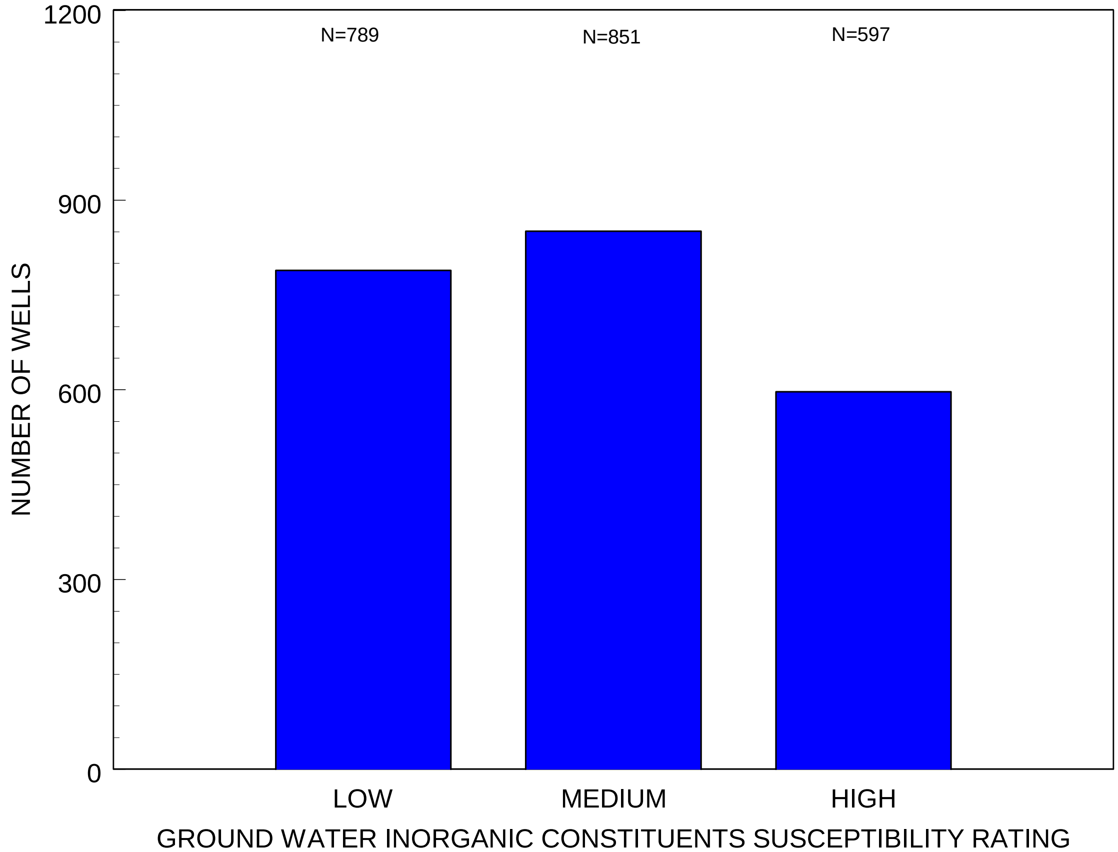

Figure 2. Number of community water-supply wells in New Jersey having low, medium, and high susceptibility to contamination by inorganic constituents.

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 of, 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.

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

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 inorganic constituents 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.

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. 3) 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.

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 areas 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.

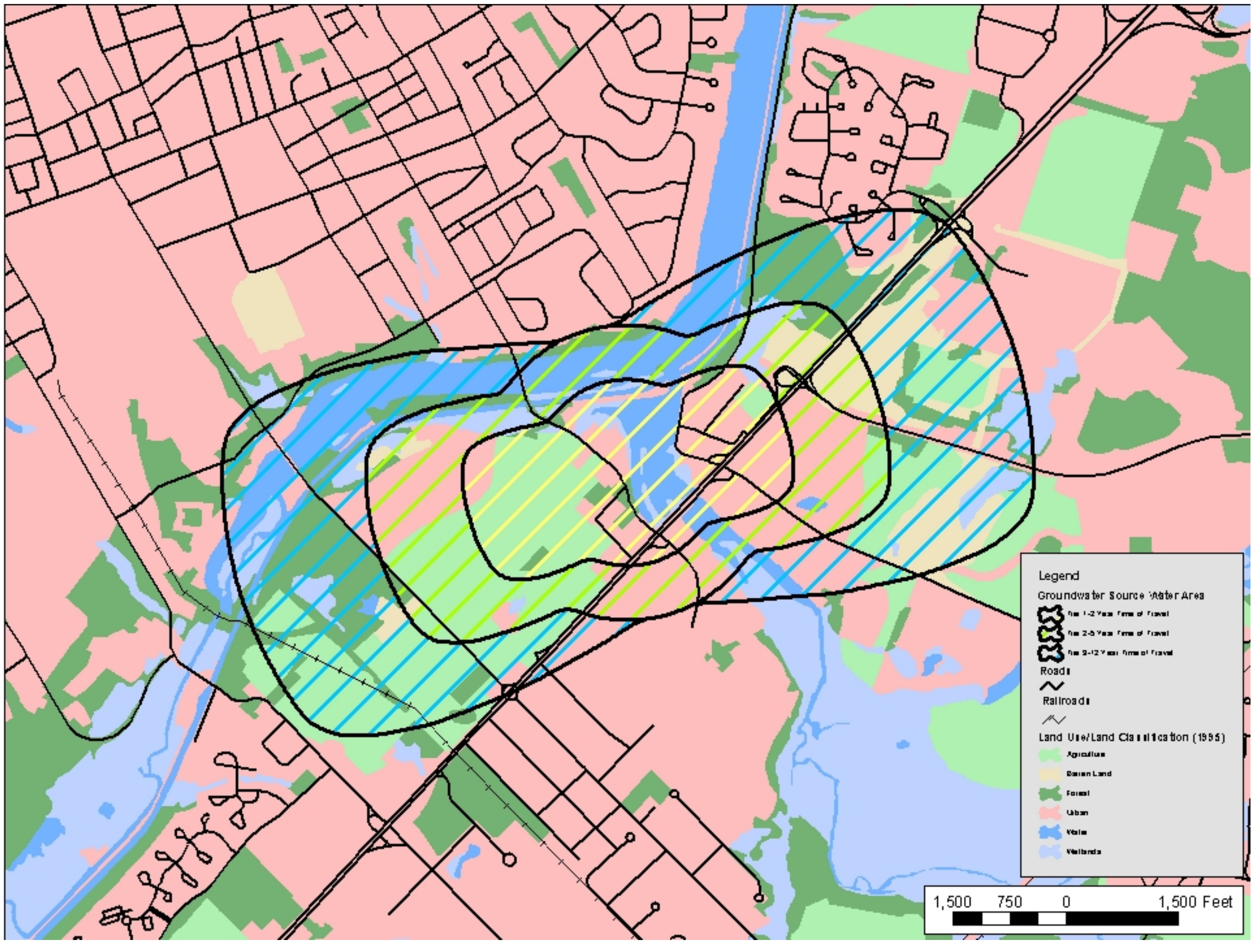

Figure 3. Example of delineated contributing area to a community water-supply well showing time of travel (TOT), land use, roads, and railroads.

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 by the USGS 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 inorganic constituents data, the constituents detected, and their corresponding MCLs are shown in table 1.

The pH and dissolved oxygen concentration of water samples were used as variables in statistical tests and for application of models to CWS wells. The most recent analyses in the NWIS database were used to represent the pH and dissolved oxygen 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. NJDEP does not require water suppliers to provide dissolved oxygen concentration data; consequently, only data from the NWIS database were used. If results of analyses were unavailable in either database, no value of pH or dissolved oxygen concentration 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. 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[1]	Standard, in micrograms per liter	Number of sites for which data are available[2]	Number of sites at which constituent was detected	Number of sites at which concentration meets criterion 1[3]	Number of sites at which concentration meets criterion 2[4]	Number of sites at which concentration equals or exceeds standard	Frequency of detection[5]
Antimony	6	58	1	1	0	0	0.02
Arsenic	10	319	106	96	5	1	0.33
Barium	2000	498	443	23	0	0	0.89
Beryllium	4	371	88	70	12	6	0.24
Cadmium	5	52	1	1	0	0	0.02
Chromium	100	52	4	0	0	0	0.08
Cyanide	200	97	0	0	0	0	0
Fluoride	4000	443	244	42	3	0	0.55
Lead	15	59	26	10	2	1	0.44
Mercury	2	33	9	4	1	1	0.27
Selenium	50	54	7	0	0	0	0.13
Thallium	2	17	0	0	0	0	0

[1] All samples are filtered unless otherwise noted.
[2] 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.
[3] Criterion 1: Concentration is at least equal to one-tenth of the standard, but is less than one-half of the standard
[4] Criterion 2: Concentration is at least equal to one-half of the standard, but is less than the standard
[5] Number of sites at which constituent was detected divided by number of sites for which data are available.

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. Models were 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.

Statistical tests and graphical procedures were used to evaluate the relation between inorganic constituents 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).

The Kruskal-Wallis test was used to determine whether distributions of hydrogeologic-sensitivity or potential contaminant-use intensity variables differed between sites where the constituent concentration was either less than one-tenth of the MCL or greater than or equal to one-tenth of the 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, intensity variables, and many water-quality variables. Scatter plots of all variables versus the modeled constituent were generated to confirm the results of statistical tests. Boxplots were used to compare the distributions of variables among groups.

Table 2. Results of univariate statistical tests for explanatory variables used in the inorganic constituents models

	Kruskal-Wallis rank test		Spearman's rank correlation		
Variables	**Kruskal-Wallis score**	**p-value**	**Spearman's rho**	**p-value**	**Conceptual variable**
Arsenic					
Physiographic Province	43.29	0.000			No
pH	27.29	0.000	0.479	0.000	No
Dissolved oxygen concentration	10.21	0.001	-0.352	0.001	No
Density of potential contaminant sites	9.72	0.002	0.317	0.001	No
Barium					
Physiographic Province	35.05	0.000			No
Distance to agricultural land (feet)	4.64	0.031	-0.257	0.001	No
Population density-Tier 1	2.26	0.133	0.143	0.073	No
Beryllium					
Physiographic Province	22.33	0.000			No
Percent barren land, 1995	10.85	0.001	0.297	0.001	No
Average percent soil clay	9.53	0.002	-0.279	0.002	No
Depth to top of open interval (feet)	3.98	0.046	0.177	0.057	No
Fluoride					
Physiographic Province	31.95	0.000			No
Sewage treatment plants per square mile	11.46	0.001	0.222	0.007	No
Distance to sewage treatment plant (feet)	10.99	0.001	-0.221	0.007	No
Average soil saturated hydraulic conductivity	4.80	0.028	-0.347	0.000	No
Percent urban land, 1970	3.58	0.058	0.168	0.041	No
Depth to top of open interval (feet)[2]	1.10	0.295	-0.026	0.757	Yes
Lead					
Distance to nearest DOT road	6.69	0.010	0.323	0.036	No
pH	2.44	0.118	-0.218	0.115	No
Length of railroads (feet)	1.99	0.159	0.269	0.053	No
Depth to top of open interval (feet)[2]	1.57	0.210	0.223	0.115	Yes
Average percent soil clay[1]	1.03	0.310	-0.087	0.530	Yes
Mercury					
Population density per square mile	8.37	0.004	0.405	0.022	No
Physiographic Province[2]	1.60	0.449			Yes
Average percent soil organic matter[1]	0.96	0.330	0.188	0.287	Yes
Average percent soil clay[1]	0.07	0.800	-0.054	0.758	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.

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 appeared to work best statistically (both univariate and multivariate tests), and graphically approached a linear relation. If, for example, when the average percent soil clay was statistically related (a negative Spearman's correlation, Kruskal Wallis score of 9.5, and p-value of 0.002) to the concentration of beryllium and the percent soil clay within the contributing area for a well was small, a score of five was assigned. When the percent soil clay was large for a well, a score of zero 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 did not show change over the entire range of values. Values of pH and dissolved oxygen 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 most recent samples for all confined wells indicated that few detections exceeded one-tenth of the MCL (no more than 1 in 10 samples), zero points were given to confined CWS wells. For wells in confined aquifers for which no results of analyses were available, zero points were assigned, and the susceptibility could not be determined. If results of analyses indicated that more then ten percent of samples for wells in a confined 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 inorganic constituents in water from community water-supply wells

Ground Water Arsenic Model

Arsenic Rating: 0-5 LOW, 6-8 MEDIUM, 9-11 HIGH

	Sensitivity Points-Unconfined Wells			
Variable	0	2	5	Conceptual variable
Physiographic Province	Everything else		Piedmont	No
Dissolved oxygen concentration	>3	≤3		No
pH	<7	≥7		No

	Intensity Points-Unconfined Wells			
Variable	0	2		
Density of potential contaminant sites[1]	≤9	>9		No

	Points-Confined Wells	
Variable	0	6
Geologic unit	Everything else	Magothy Formation, Raritan Formation, Potomac Formation, Shark River Formation - Toms River member, Englishtown Formation, Kirkwood Formation - lower member (sand facies), Vincentown Formation

[1] Potential contaminant sites in this model include the following; sites on the Known Contaminant Sites List; solid-waste landfills; NJPDES ground-water, surface-water, and storm-water discharge sites; Class C compost facilities; resource recovery facilities; solid-waste transfer facilities; Class B recycling facilities; Discharge Prevention and Countermeasure Plan and Cleanup & Removal Plan sites; and underground storage tanks.

Ground Water Barium Model

Barium Rating: 0-6 LOW, 7-9 MEDIUM

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

	Intensity Points-Unconfined Wells				
Variable	0	1	2	5	
Distance to agricultural land, 1995 (feet)	>4,000	>1,000-4,000	0-1,000		No
Population density-Tier 1	0-<1,500	>=1,500-<4,000	>=4,000		No

Points-Confined Wells 0

Ground Water Beryllium Model

Beryllium Rating: 0-7 LOW, 8-10 MEDIUM, 11-17 HIGH

	Sensitivity Points-Unconfined Wells						
Variable	0	1	2	3	4	5	Conceptual variable
Physiographic Province	Everything else					Coastal Plain	No
Depth to top of open interval (feet)	≥150	>75-<150	≤75				No
Percent soil clay-average	>15	>12.5-15	>10-12.5	>7.5-10	>5-7.5	≤5	No

	Intensity Points-Unconfined Wells						
Variable	0	1	2	3	4	5	
Percent Barren land, 1995[2]	≤2	>2-4	>4-8	>8-12	>12-16	>16	No

Points-Confined Wells 0

[2]Barren land use category includes lands that are characterized by thin soil, or sand or rock; and that lack vegetation or have widely spaced vegetation. Barren land can be found in nature or result from human activities. Barren land includes surface and subsurface extractive mining operations; stone quarries; gravel, sand, and clay pits; solid waste disposal areas and landfills.

Ground Water Fluoride Model

Fluoride Rating: 0-16 LOW, 17-19 MEDIUM

	Sensitivity Points-Unconfined Wells						
Variable	0	1	2	3	4	5	Conceptual variable
Physiographic Province	Coastal Plain		Everything else				No
Average soil saturated hydraulic conductivity	>50	>40-50	>30-40	>20-30	>10-20	≤10	No
Depth to top of open interval (feet)[3]	>150	>125-150	>100-125	>80-100	>60-80	≤60	Yes

	Intensity Points-Unconfined Wells						
Variable	0	1	2	3	4	5	
Percent urban land, 1970	0-<10	10-<20	20-<30	30-<40	40-<60	≥60	No
Distance to sewage treatment plant (feet)	>1,000		≤1,000				No
STPs per square mile	<1		≥1				No

	Points-Confined Wells	
Variable	0	17
Geologic unit	Everything else	Magothy Formation, Raritan Formation, Potomac Formation, Shark River Formation - Toms River member

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

Ground Water Lead Model

Lead Rating: 0-5.5 LOW, 6-9.5 MEDIUM, 10-14 HIGH

	Sensitivity Points-Unconfined Wells							
Variable	0	0.5	1	1.5	2	3	4	Conceptual variable
pH	>5.5		>5.0-5.5		>4.75-5.0	>4.5-4.75	≤4.5	No
Percent soil clay-average[4]	>20	>15-20	>10-15	>5-10	≤5			Yes
Depth to top of open interval (feet)[3]	≥150		>90-<150		≤90			Yes

	Intensity Points-Unconfined Wells					
Variable	0	1	2	3	4	
Distance to DOT road (feet)	>300		≤300			No
Length of railroads (feet)	0-<2,000	2,000-<5,000	5,000-<10,000	10,000-<20,000	≥20,000	No

Points-Confined Wells 0

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

Ground Water Mercury Model

Mercury Rating: 0-7 LOW, 8-9 MEDIUM, 10-14 HIGH

	Sensitivity Points-Unconfined Wells						
Variable	0	1	2	3	4	5	Conceptual variable
Physiographic Province[3]	Everything else		Coastal Plain				Yes
Percent soil clay-average[4]	>15	>10-15	0-10				Yes
Percent soil organic matter-average[4]	>2	>1-2		>.5-1		≤0.5	Yes

	Intensity Points-Unconfined Wells						
Variable	0	1	2	3	4	5	
Population density	0-<500	500-<1,000	1,000-<1,500	1,500-<2,500	2,500-<5,000	>=5,000	No

Points-Confined Wells 0

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

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

Relation of Inorganic Constituents in Ground Water to Susceptibility Variables

Relations between concentrations of arsenic, barium, beryllium, fluoride, lead, and mercury 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 inorganic constituents. Concentrations in wells used to develop the models rarely exceeded the maximum contaminant level for any of the six constituents. The remaining eight constituents with primary standards—antimony, asbestos, cadmium, chromium, copper, cyanide, selenium, and thallium—were not modeled for various reasons including (1) lack of data for CWS wells, (2) lack of or few detections above one-tenth of the constituent MCL for CWS wells, and (3) poor distribution of sites with data in New Jersey.

The susceptibility ratings for inorganic constituents 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 a constituent for inorganic 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 chemical factors.

Arsenic

Arsenic was detected (31 of 104 sites) in water from the unconfined CWS wells subset used for model development (fig. 4). Arsenic in ground water may result from either natural sources or human activities and from point or nonpoint sources. Arsenic occurs naturally in rock and soil. Most arsenic used by industry is used for wood preservation. Arsenic also is used in paint, drugs, dyes, soaps, metals, and semi-conductors. Arsenic previously was used in making pesticides, weed killers, and embalming fluids; however, these uses are now banned (http://www.epa.gov/safewater/ars/prop_techfs.html). The current USEPA MCL for arsenic is 50 μg/L, but will be lowered 10 μg/L effective January 2006. As a result, the model was developed using 10 μg/L as the MCL.

Arsenic is found in ground water in both oxidizing and reducing geochemical environments, and over a range of pH's. Arsenic occurs primarily as inorganic oxyanions, reduced trivalent arsenite (As (III)), and oxidized pentavalent arsenate (As (V)). The former is the more toxic form. At acidic pH's, the oxyanions may adsorb to clays, organic matter, or hydroxides, but are more likely to be in solution at alkaline pH's

(Smedley and Kinniburgh, 2002). By far the highest concentrations of arsenic in ground water in New Jersey are found in the Piedmont Physiographic Province and are associated with sources in the bedrock material. Within the Piedmont, arsenic in ground water typically is found in higher concentrations in the sedimentary rock, especially in shales with organic rich (black) beds (Serfes and others, 2000, and Serfes, New Jersey Geological Survey, oral commun., 2003), with lower concentrations in the intrusive basalt and diabase units.

Minor contribution of arsenic in CWS wells may be the result of specific contamination sites (fig. 5D) or changes in water chemistry that mobilize the arsenic. The density of potential contaminant sites was used in the model to represent the likelihood that a well may be affected by contamination from point sources. Contamination of wells may result from the use of arsenic at these sites or because of changes to the geochemical environment associated with activities at these sites. Potential contaminant sites in this model include the following: sites on the Known Contaminant Sites List; solid-waste landfills; NJPDES ground-water, surface-water, and storm-water discharge sites; Class C compost facilities; resource recovery facilities; solid-waste transfer facilities; Class B recycling facilities; Discharge Prevention and Countermeasure Plan and Cleanup & Removal Plan sites; and underground storage tanks.

Concentrations in confined Coastal Plain aquifers typically are lower than concentrations in unconfined aquifers. Detection of arsenic in confined aquifers in the Coastal Plain greater than or equal to one-tenth of the MCL occasionally does occur (35 of 113 sites). Several confined aquifers had median concentrations near or above this level and included the Potomac Raritan Magothy, Englishtown, Vincentown, Atlantic City 800 foot Sand, and Piney Point aquifers. Wells in these units were given a medium susceptibility. The presence of arsenic in aquifer material and the high pH and low dissolved oxygen are likely responsible for the slightly elevated arsenic concentrations in these aquifers since these aquifers should be unaffected by contaminants that originate at land surface (figs. 5B and 5C). Greensands and clays within aquifers and confining units of the Coastal Plain contain higher arsenic concentrations (J.L. Barringer, U.S. Geological Survey, written comm., 2002).

Arsenic was equal to the MCL of 10 μg/L in a sample from 1 well of 104 wells in the unconfined CWS wells subset with analyses, and was equal to or exceeded one-tenth of MCL in samples from 29 of 104 wells. Variables selected to represent hydrogeologic sensitivity for arsenic were Physiographic Province, dissolved oxygen concentration, and water pH. One variable--density of potential contaminant sites--was selected to represent potential contaminant-use intensity for arsenic. Of the 2,237 CWS wells in New Jersey, 1,441 were rated as having low susceptibility, 534 were rated as having medium susceptibility, and 262 were rated as having high susceptibility (fig. 6).

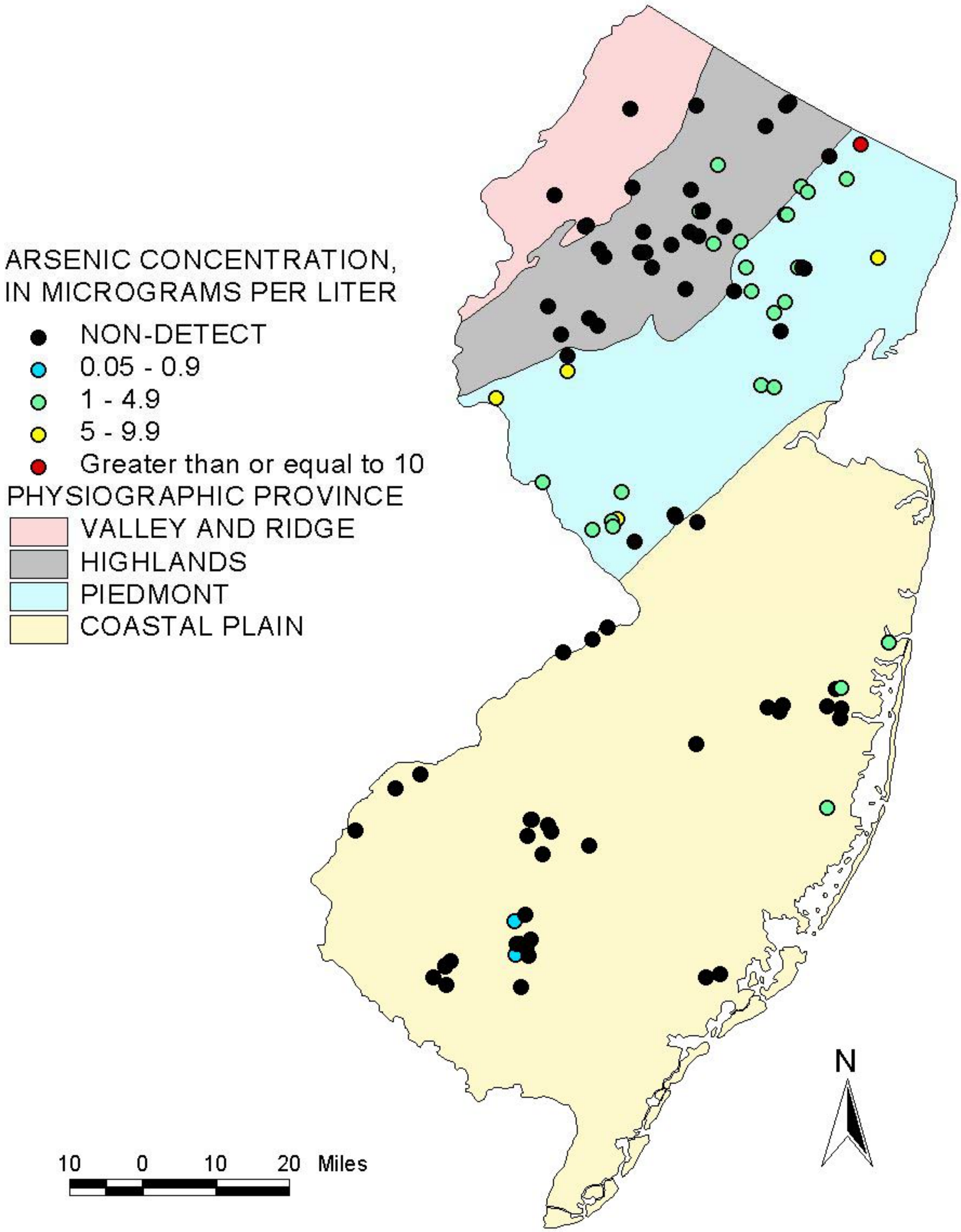

Figure 4. Concentrations of arsenic in 104 community water-supply wells used for development of the arsenic model.

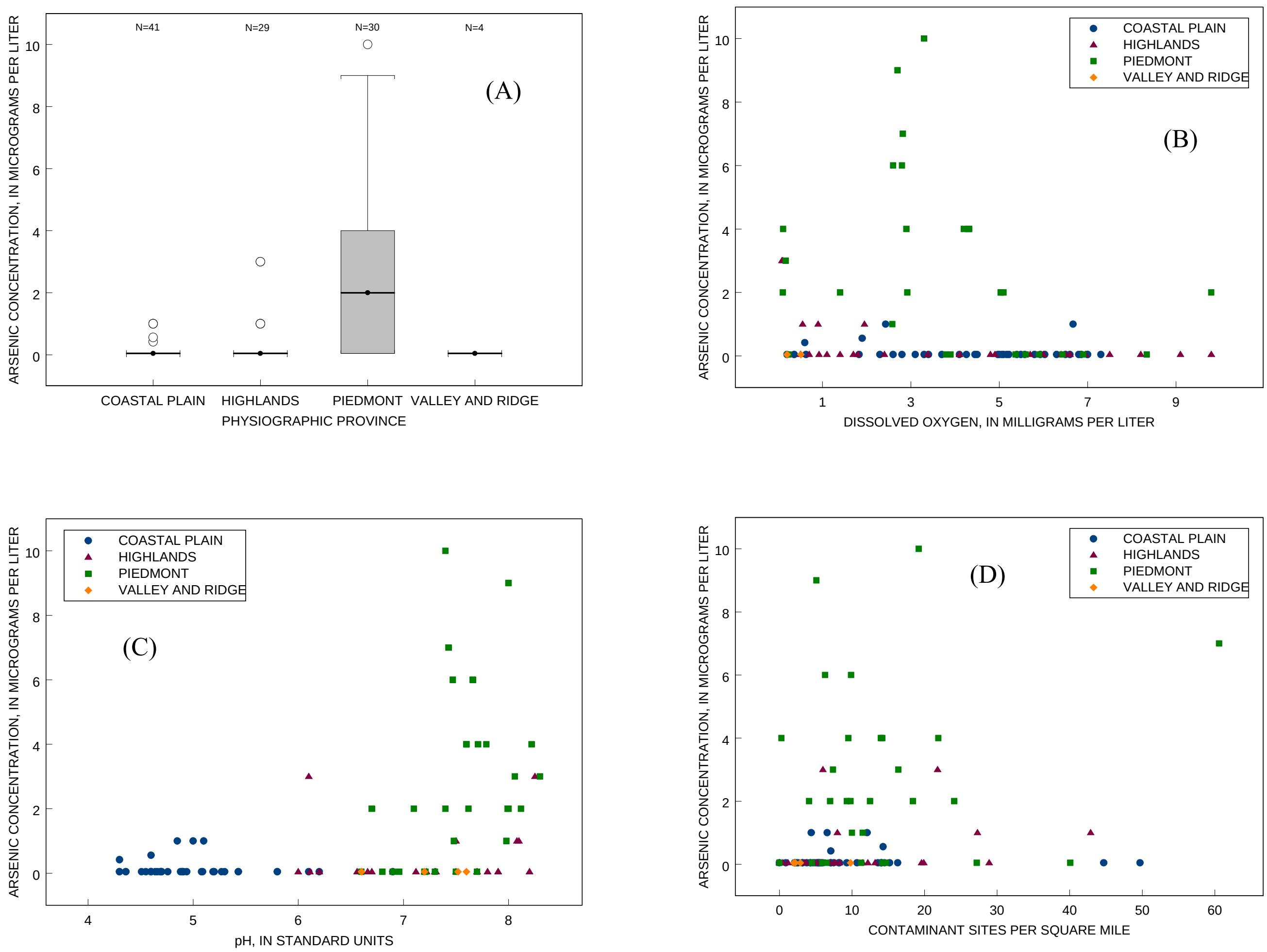

Figure 5. (A) Distribution of arsenic concentration by physiographic province, and relation of arsenic concentration to (B) dissolved oxygen, (C) pH, and (D) density of potential contaminant sites, by physiographic province, for 104 community water-supply wells in New Jersey.

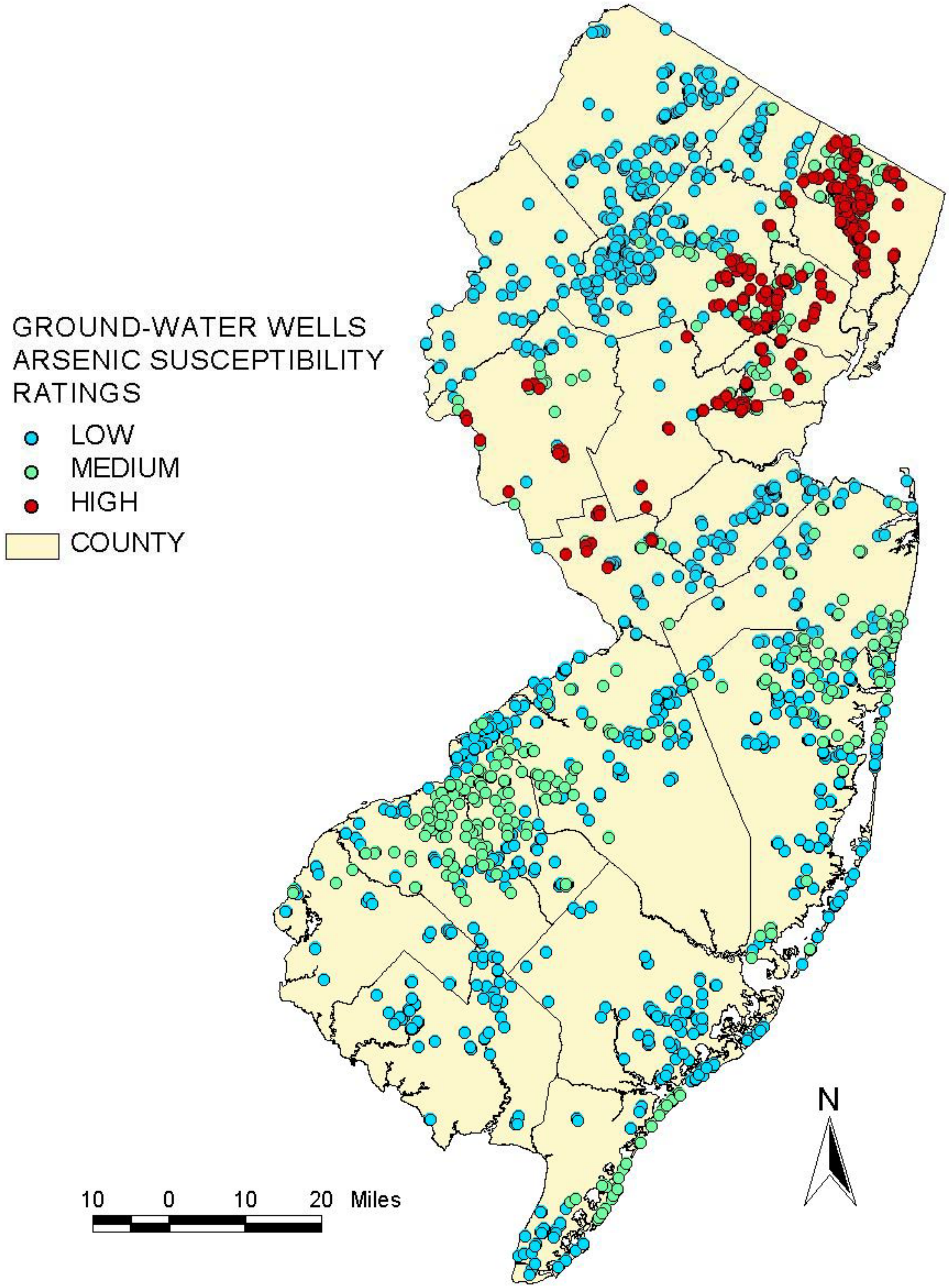

Figure 6. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by arsenic.

Barium

Barium was detected (148 of 159 sites) in water from the unconfined CWS wells subset used for model development (fig. 7); it may result from either natural sources or human activities. Barium is used in the making of a wide variety of electrical components; in the manufacture of steel, copper, and metal alloys; in bleaches, dyes, fireworks, explosives, and matches; in glass, ceramics, and clay products; and in the manufacture of motor-vehicle parts and accessories. Barium is released to water and soil in the discharge and disposal of drilling wastes (http://www.epa.gov/safewater/dwh/t-ioc.html). It is estimated that more than 725,000 pounds of barium was released to land or water in New Jersey during 1987-93 (http://www.epa.gov/safewater/dwh/t-ioc.html). Barium also is used in batteries, lubricating oils and greases, and is a component of detergent in motor oil. Barium is released to the environment from copper smelting (http://www.epa.gov/safewater/dwh/t-ioc.html). Population density was used as a variable to improve the results of the model because barium is widely used in industry, agriculture, and other uses, and releases to the environment are common. Population density, like urban land use, represents a surrogate for specific activities which can release barium to the environment, but for which specific variables were not available for statistical testing. The New Jersey and USEPA MCL for barium currently is 2000 μg/L.

Barium commonly is added to agricultural land in liming agents (dolomite) where it is present as an impurity that substitutes for calcium (Kozinski and others, 1995). Barium may migrate to ground water because it does not tend to bind to most soils (http://www.epa.gov/safewater/dwh/c-ioc.html). Barium salts are likely to precipitate out of solution in the presence of sulfate or carbonate (http://www.epa.gov/safewater/dwh/t-ioc.html).

Barium occurs naturally in rock and soil, and is commonly found in shale, sandstones, and igneous rock (Hem, 1985). The highest concentrations of barium in ground water in New Jersey are found in the Piedmont Physiographic Province and may be associated with sources in the bedrock material, as well as agricultural areas (fig. 8A). Detection of barium in confined aquifers in the Coastal Plain greater than or equal to one-tenth of the MCL is rare (2 of 171); consequently, confined wells are not considered to be susceptible.

Barium did not equal or exceed the MCL of 2000 μg/L in samples from 159 wells in the unconfined CWS wells subset with analyses, and was equal to or exceeded one-tenth of MCL in samples from 15 of 159 wells. The variable selected to represent hydrogeologic sensitivity for barium was Physiographic Province. Variables selected to represent potential contaminant-use intensity for barium were distance to agricultural land (1995 land use) and population density-tier 1. Of the 2,237 CWS wells in New Jersey, 1,978 were rated as having low susceptibility, 259 were rated as having medium susceptibility, and none were rated as having high susceptibility (fig. 9).

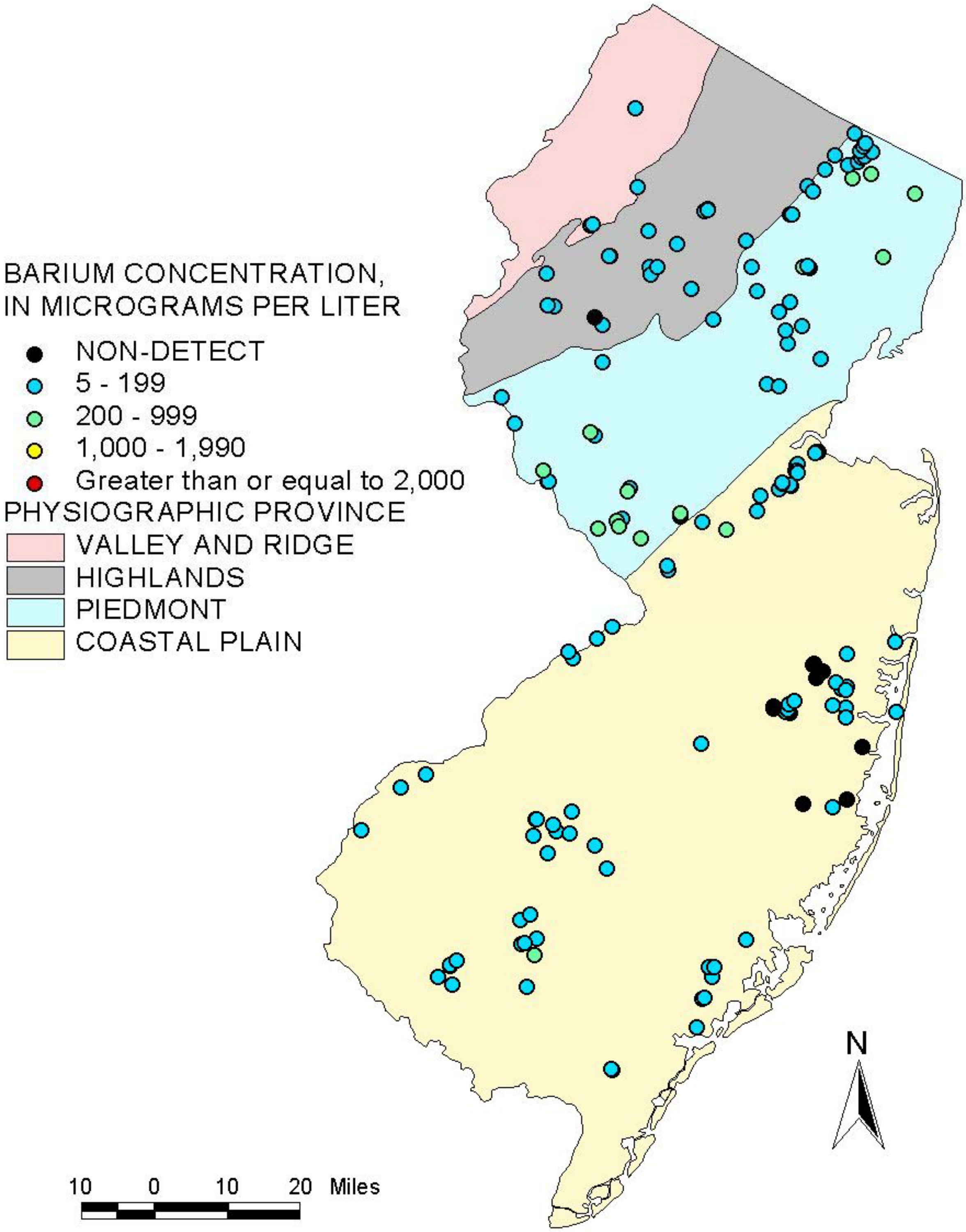

Figure 7. Concentrations of barium in 159 community water-supply wells used for development of the barium model.

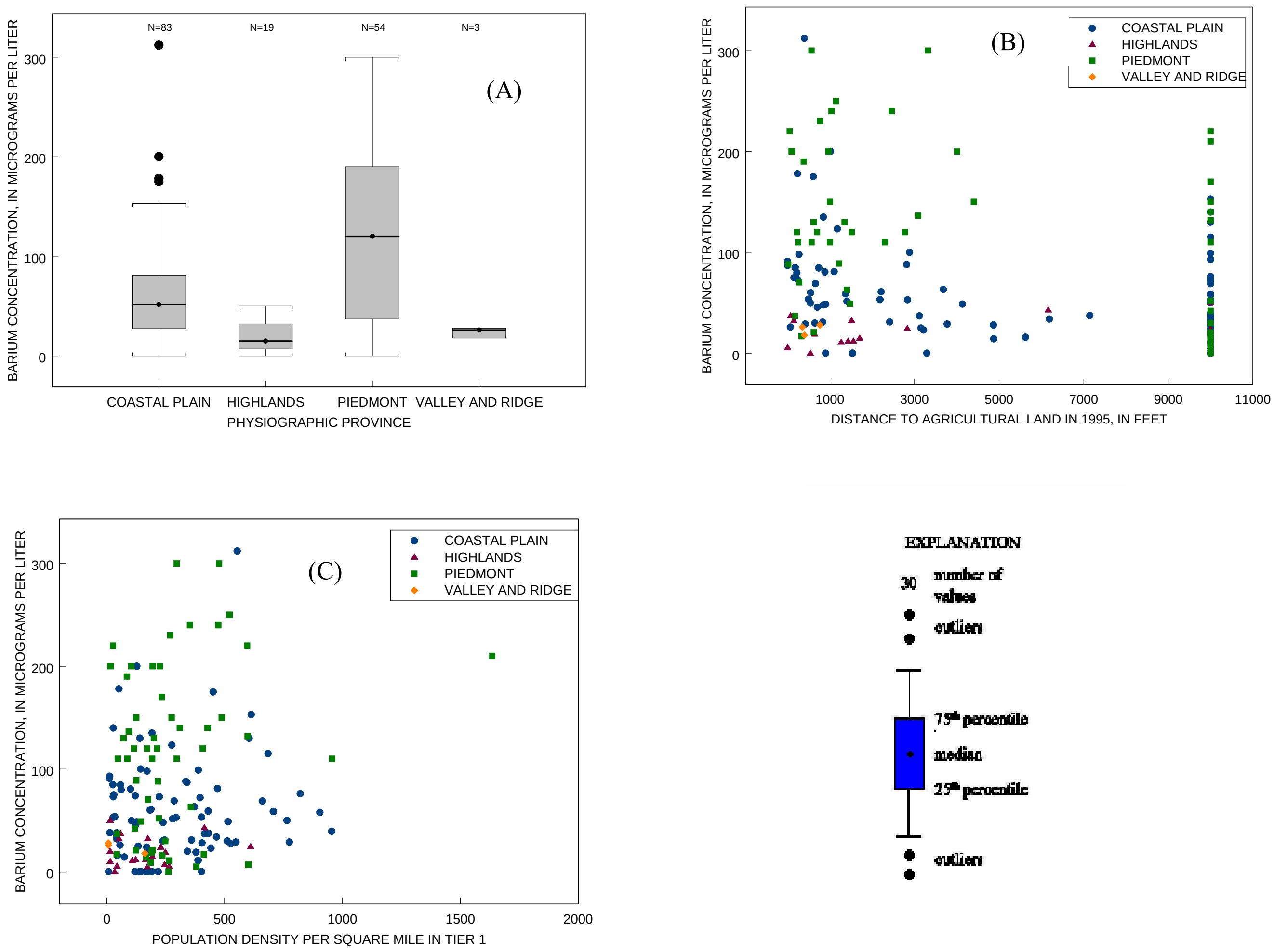

Figure 8. (A) Distribution of barium concentration by physiographic province, and relation of barium concentration to (B) distance to agricultural land, and (C) population density per square mile in tier 1, by physiographic province, for 159 community water-supply wells in New Jersey.

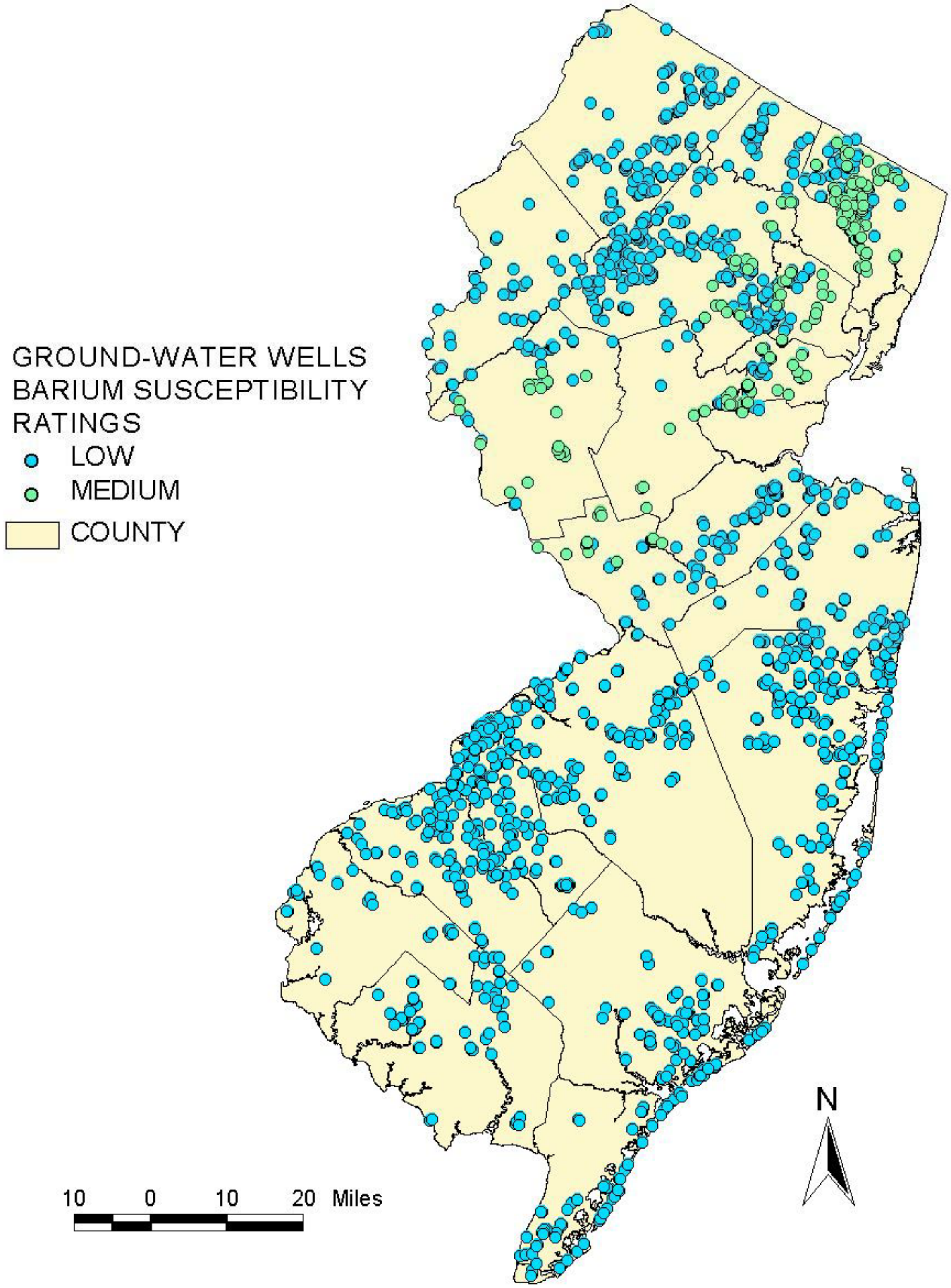

Figure 9. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by barium.

Beryllium

Beryllium was detected (19 of 124 sites) in water from the unconfined CWS wells subset used for model development (fig. 10); it may result from either natural sources or human activities. Elevated concentrations of beryllium may result from point or nonpoint sources. Some fossil fuels contain beryllium compounds and beryllium may enter the environment from combustion, principally of coal. Beryllium is used as an alloy and metal in nuclear reactors and the aerospace industry, in electrical equipment and components, and in navigation and optical equipment. Beryllium also is used as a catalyst and intermediate in chemical manufacture, in glass and ceramics, and in microwave oven components (http://www.epa.gov/safewater/dwh/t-ioc.html). The New Jersey and USEPA MCL for beryllium currently is 4 μg/L.

Typically, the shallower the open interval of a 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 top of the open interval of a 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 to the top of the open interval was used to improve the results of the model (fig. 11C).

Percent barren land in 1995 was used as a variable to improve the results of the model (fig. 11D). Barren land may represent a surrogate for specific activities within this land use category which can release beryllium to the environment, but for which specific variables were not available for statistical testing. Barren land use category includes lands that are characterized by thin soil, or sand or rock; and that lack vegetation or have widely spaced vegetation. Barren land can be found in nature or result from human activities. Barren land includes surface and subsurface extractive mining operations; stone quarries; gravel, sand, and clay pits; and solid waste disposal areas and landfills.

Beryllium is found in igneous rocks. Beryllium is not typically found in natural water above trace levels because it is relatively insoluble at normal pH ranges. It is however more soluble in low pH water typical in the Coastal Plain of New Jersey (fig. 11A). Beryllium compounds that adsorb to clay or organic matter in soil typically have low solubility (http://www.epa.gov/safewater/dwh/t-ioc.html). Detection of beryllium in confined aquifers in the Coastal Plain greater than or equal to one-tenth of the MCL do frequently occur (33 of 115 sites), however, because they are generally near the method reporting level, results may be inaccurate/imprecise. Consequently, the data for confined wells were inconclusive and susceptibility of confined wells was not determined.

Beryllium was equal to or exceeded the MCL of 4 μg/L in samples from 3 of 124 wells in the unconfined CWS wells subset with analyses, and was equal to or exceeded one-tenth of MCL in samples from 19 of 124 wells. Variables selected to represent hydrogeologic sensitivity for beryllium were Physiographic Province, depth to the top of the open interval, and average percent soil clay. Variables selected to represent potential contaminant-use intensity for beryllium were percent barren land (1995 land use). Of the 2,237 CWS wells in New Jersey, 1,788 were rated as having low susceptibility, 266 were rated as having medium susceptibility, and 183 were rated as having high susceptibility (fig. 12).

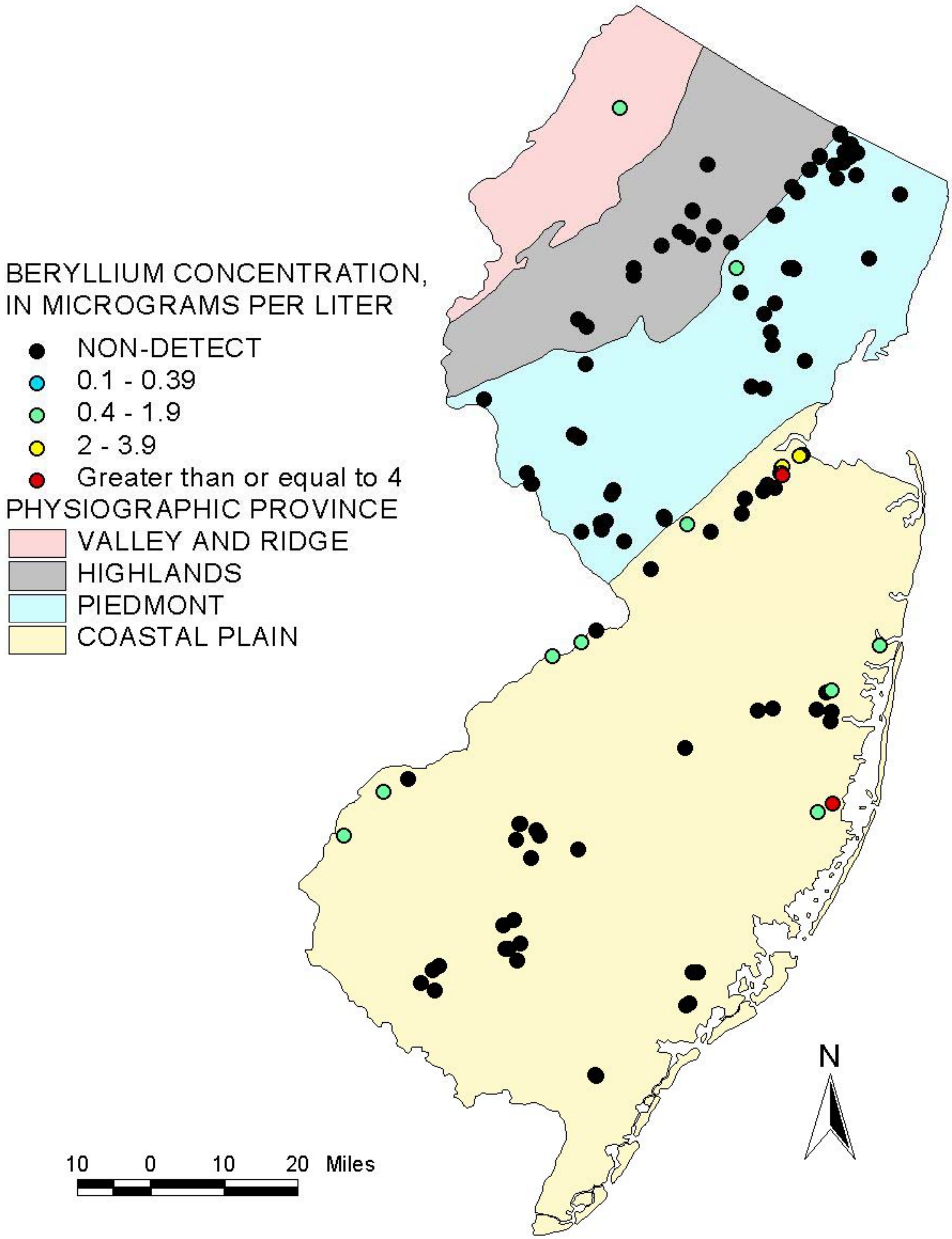

Figure 10. Concentrations of beryllium in 124 community water-supply wells used for development of the beryllium model.

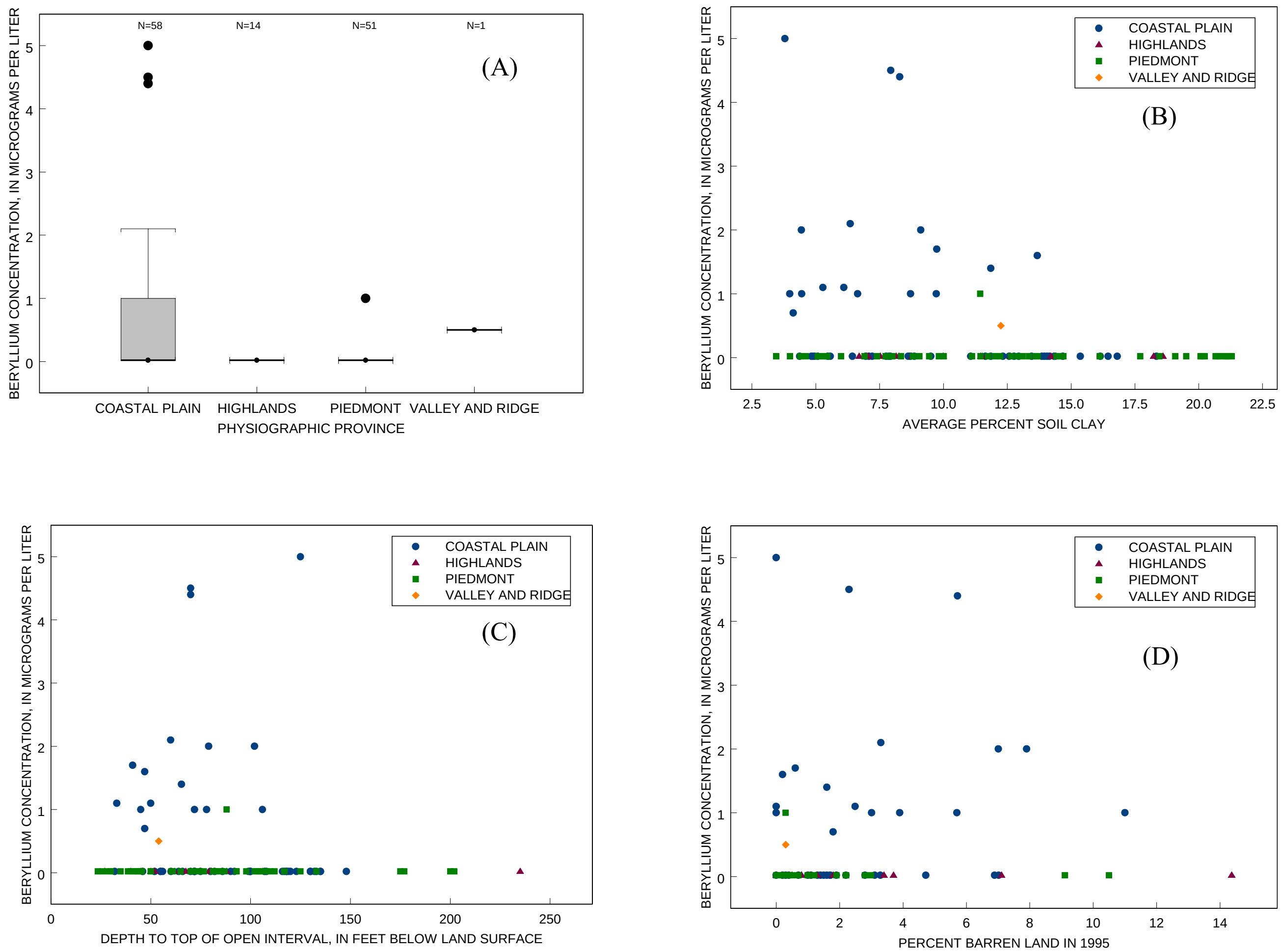

Figure 11. (A) Distribution of beryllium concentration by physiographic province, and relation of beryllium concentration to (B) average percent soil clay, (C) depth to top of open interval, and (D) percent barren land in 1995, by physiographic province, for 124 community water-supply wells in New Jersey.

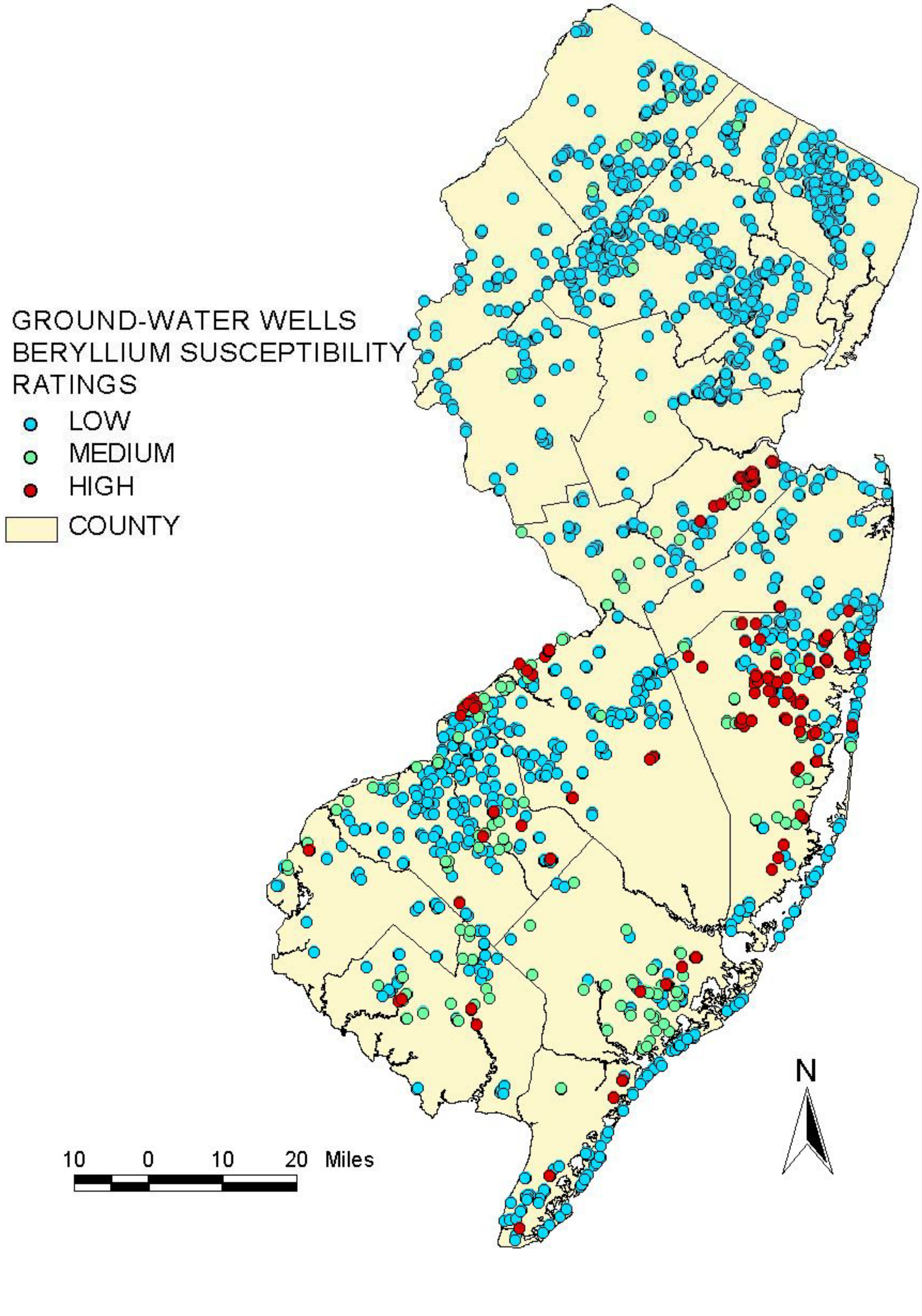

Figure 12. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by beryllium.

Fluoride

Fluoride was detected (66 of 149 sites) in water from the unconfined CWS wells subset used for model development (fig. 13); it may be from either natural sources or human activities. Fluoride is common in igneous and sedimentary rock (Hem, 1985). Fluorine has many industrial uses, and is used in the production of aluminum and CFCs, chemical and electronics industries, is used for glass etching, and is associated with the phosphate fertilizer industry. Fluoride is used in some dental procedures (http://www.epa.gov/safewater/dwh/t-ioc.html). The New Jersey and USEPA MCL for fluoride currently is 4000 μg/L. Fluoride is an essential element for humans and is present in the structure of bones and teeth. Fluoride also is added to many public water supply systems and is present in effluent from wastewater treatment facilities.

Typically, the shallower the open interval of a 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 top of the open interval of a 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 to the top of the open interval, a conceptual variable, was used to improve the results of the model (fig. 14A).

Fluoride has been widely dispersed in the environment by human activities. Percent urban land in 1970 was used as a variable to improve the results of the model to represent historical urban land use. Urban land represents a surrogate for specific activities within the land use category which can release fluoride to the environment, but for which specific variables were not available for statistical testing.

Minimum distance to sewage treatment plant (fig. 14E) and sewage treatment plants per square mile (fig. 14F) were used as variables to improve the results of the model. Effluent from sewage treatments plants can contain fluoride from sources such as domestic use and disposal of products that contain fluoride, fluoridated water from community water supplies, or industrial and commercial discharges that are treated in municipal treatment plants. Both variables were included because the concentration of fluoride in surface water a given point depends on many factors including the volume of the discharge and the distance the treatment plant is from that point. Large CWS wells typically draw water from larger areas than other types of wells, and often time their contributing areas intercept surface-water bodies. Thus, part of the water withdrawn from these wells may come directly from surface water bodies.

Fluoride typically is found in lower concentrations in unconfined Coastal Plain wells than in wells in the other Physiographic Provinces in New Jersey (fig. 14A). Detection of fluoride in confined aquifers in the Coastal Plain greater than or equal to one-tenth of the MCL, however, does occur frequently (28 of 153 sites). Several aquifers had median concentrations near or above this level and included the Potomac Raritan Magothy aquifers, principally in Salem, Gloucester, and Camden Counties, and the Shark River Formation (part of the Composite Confining Unit). Wells in these units were given a medium susceptibility.

Fluoride did not equal or exceed the MCL of 4000 μg/L in samples from 149 wells in the unconfined CWS wells subset with analyses, and was equal to or exceeded one-tenth of MCL in samples from 6 of 149 wells. Variables selected to represent hydrogeologic sensitivity for fluoride were Physiographic Province, average saturated hydraulic conductivity of the soil, and depth to the top of the open interval (conceptual). Variables selected to represent potential contaminant-use intensity for fluoride were percent urban land (1970 land use), distance to sewage treatment plant, and sewage treatment plants per square mile. Of the 2,237 CWS wells in New Jersey, 1,956 were rated as having low susceptibility, 281 were rated as having medium susceptibility, and none were rated as having high susceptibility (fig. 15).

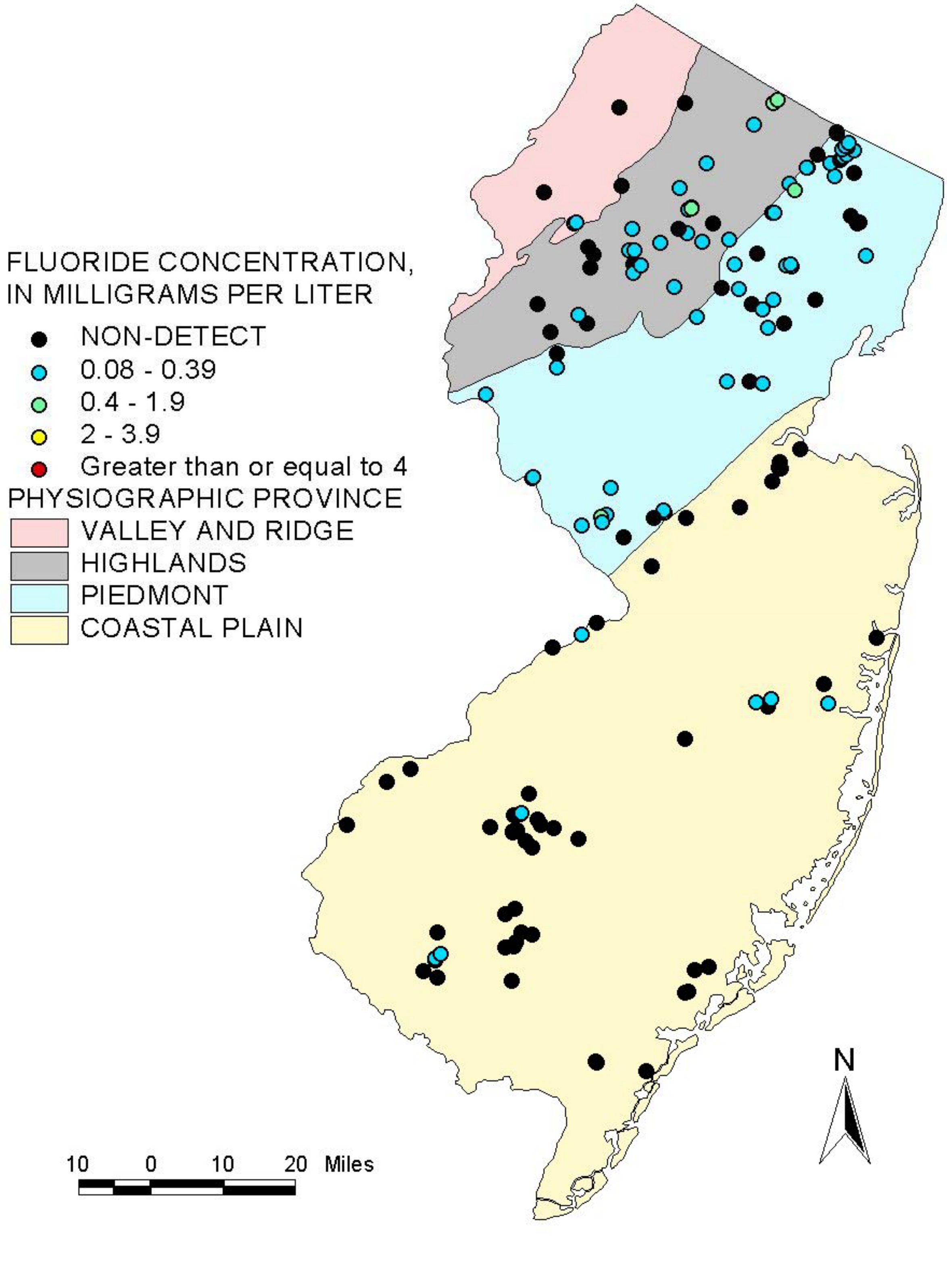

Figure 13. Concentrations of fluoride in 149 community water-supply wells used for development of the fluoride model.

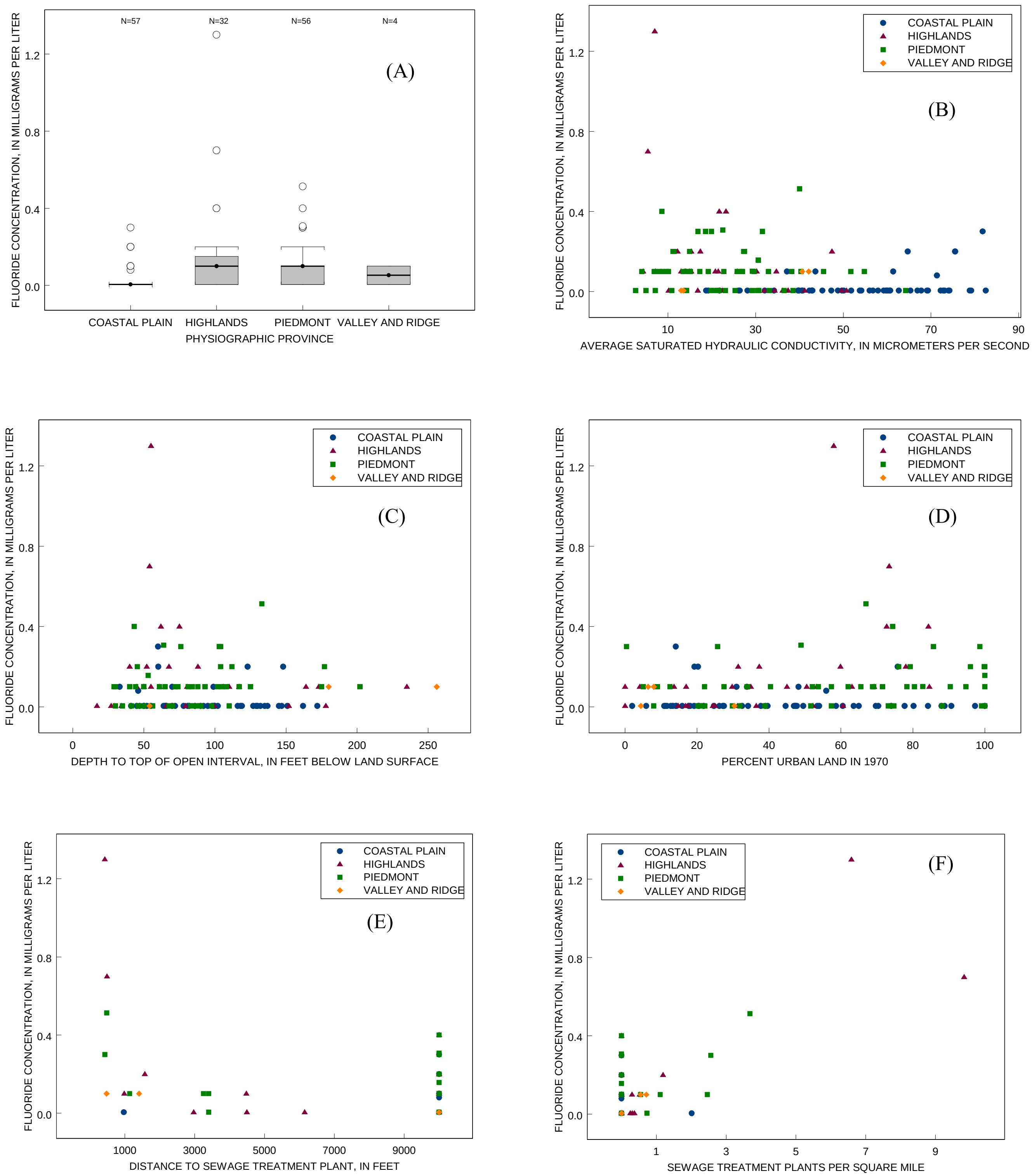

Figure 14. (A) Distribution of fluoride concentration by physiographic province, and relation of fluoride concentration to (B) average soil saturated hydraulic conductivity, (C) depth to top of open interval, (D) percent urban land in 1970, (E) distance to sewage treatment plant, and (F) sewage treatment plants per square mile, by physiographic province, for 149 community water-supply wells in New Jersey.

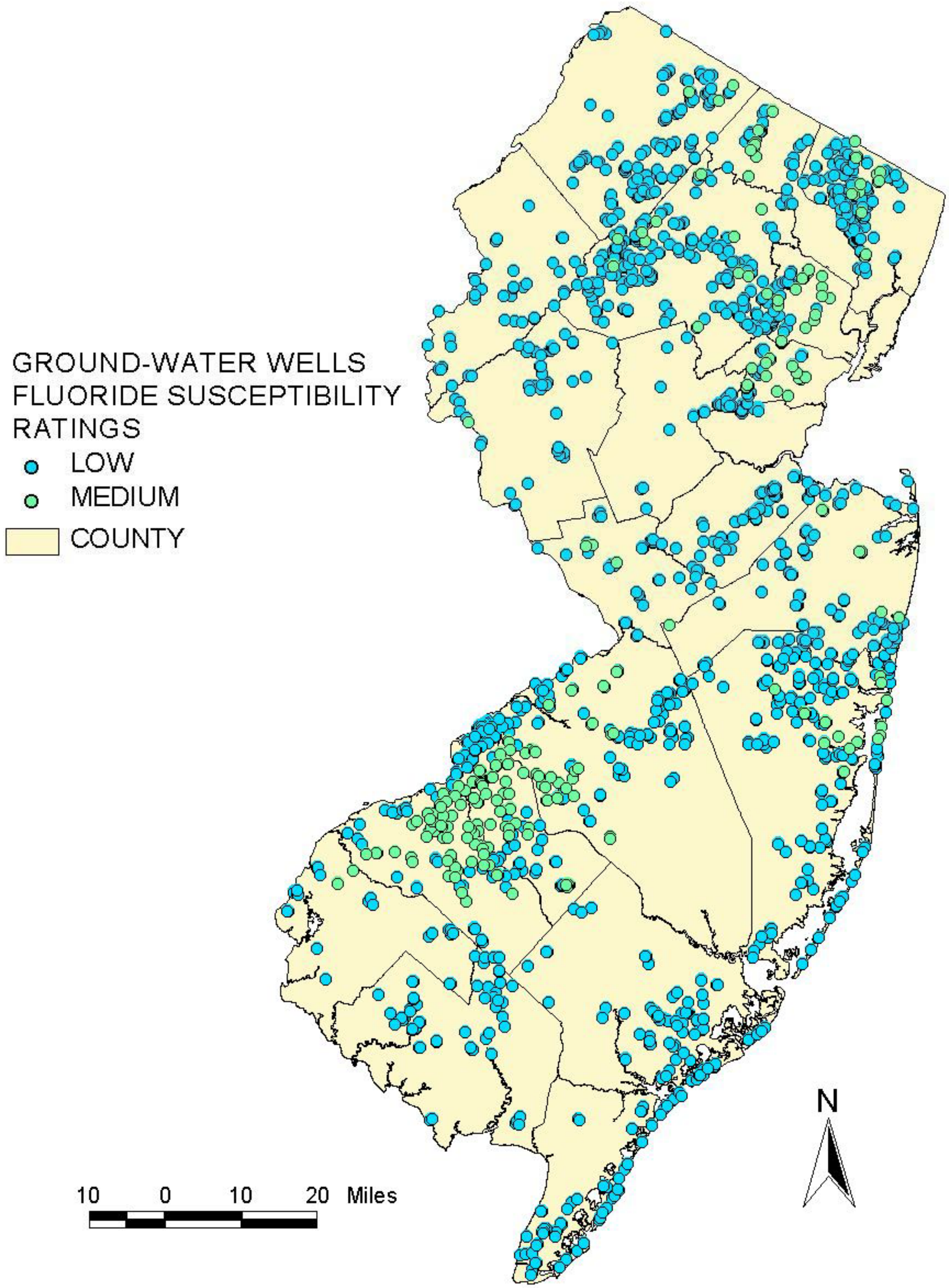

Figure 15. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by fluoride.

Lead

Lead was detected (26 of 53 sites) in water from the CWS wells used for model development (fig. 16); and it may result from either natural sources or human activities. Elevated concentrations of lead may result from point or nonpoint sources. Lead occurs naturally in rock and soil, and is common in sedimentary rock. Lead has been widely dispersed in the environment by human activities. It is released to the environment by mining, ore processing, lead and copper smelting, refining use, recycling, and waste disposal (http://www.epa.gov/safewater/dwh/t-ioc.html). Lead also is released by the combustion of coal. Tetraethyl lead was used in gasoline to promote more efficient combustion, although it has since been removed from gasoline (Hem, 1985). The USEPA action level for lead currently is 15 μg/L.

The natural mobility of lead is low due partly to its low solubility. Lead can adsorb onto organic and inorganic sediment surfaces (Hem, 1985) such as clay. Average percent soil clay, a conceptual variable, was used to improve the results of the model. Lead occurs in drinking water primarily from two sources, from corrosion of plumbing materials in water distribution systems (lead pipes or copper pipe with lead solder), and to a lesser extent, from raw water supplies. Water having low alkalinity and pH can retain large concentrations of lead (fig. 17A).

Typically, the shallower the open interval of a 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 top of the open interval of a 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 (fig. 17C). Depth to the top of the open interval, a conceptual variable, was used to improve the results of the model. Length of railroads within the area contributing water to a well was used to improve the results of the model and may be a surrogate for other unidentified variables associated with railroads or urban land which affect the concentration of lead in ground water (fig. 17E).

Lead is detected more frequently, and at higher concentrations in unconfined Coastal Plain wells, likely because of the low pH and poorly buffered conditions that exist in this area. Detection of lead in confined aquifers in the Coastal Plain greater than or equal to one-tenth of the MCL is rare (0 of 4 sites); consequently, confined wells are not considered to be susceptible.

The unconfined CWS wells subset contained insufficient data to develop the lead model; consequently, data from all unconfined CWS wells were used. In this data set, lead concentration was equal to or exceeded the action level of 15 μg/L in a sample from 1 of 53 wells with analyses, and was equal to or exceeded one-tenth of MCL in samples from 13 of 53 wells. Few CWS wells in confined aquifers or in Northern New Jersey had results of analyses for lead. Variables selected to represent hydrogeologic sensitivity for lead were water pH, average percent soil clay (conceptual), and depth to top of open interval (conceptual). Variables selected to represent potential contaminant-use intensity for lead were distance to DOT road and length of railroads. Of the 2,237 CWS wells in New Jersey, 1,757 were rated as having low susceptibility, 455 were rated as having medium susceptibility, and 25 were rated as having high susceptibility (fig. 18).

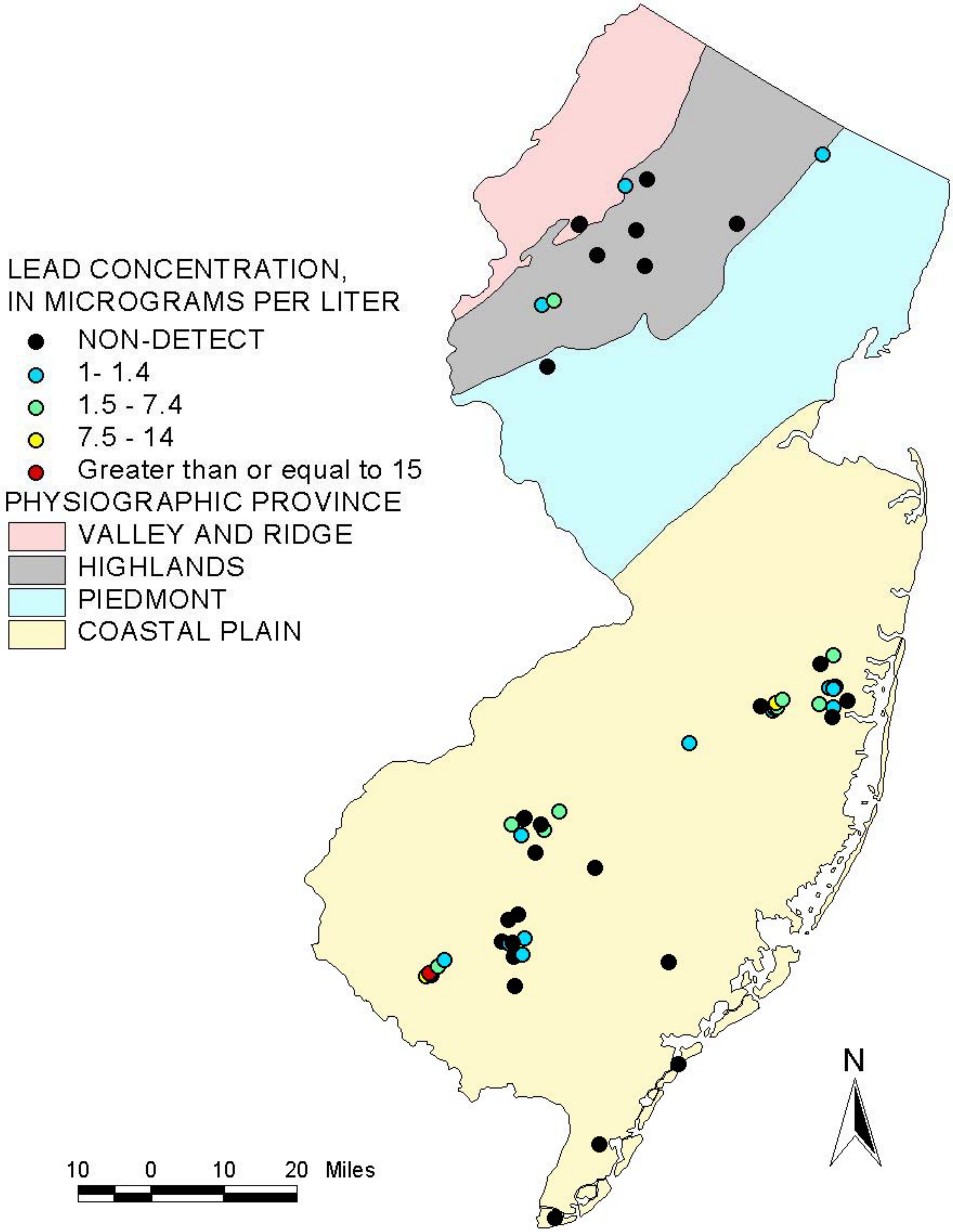

Figure 16. Concentrations of lead in 53 community water-supply wells used for development of the lead model.

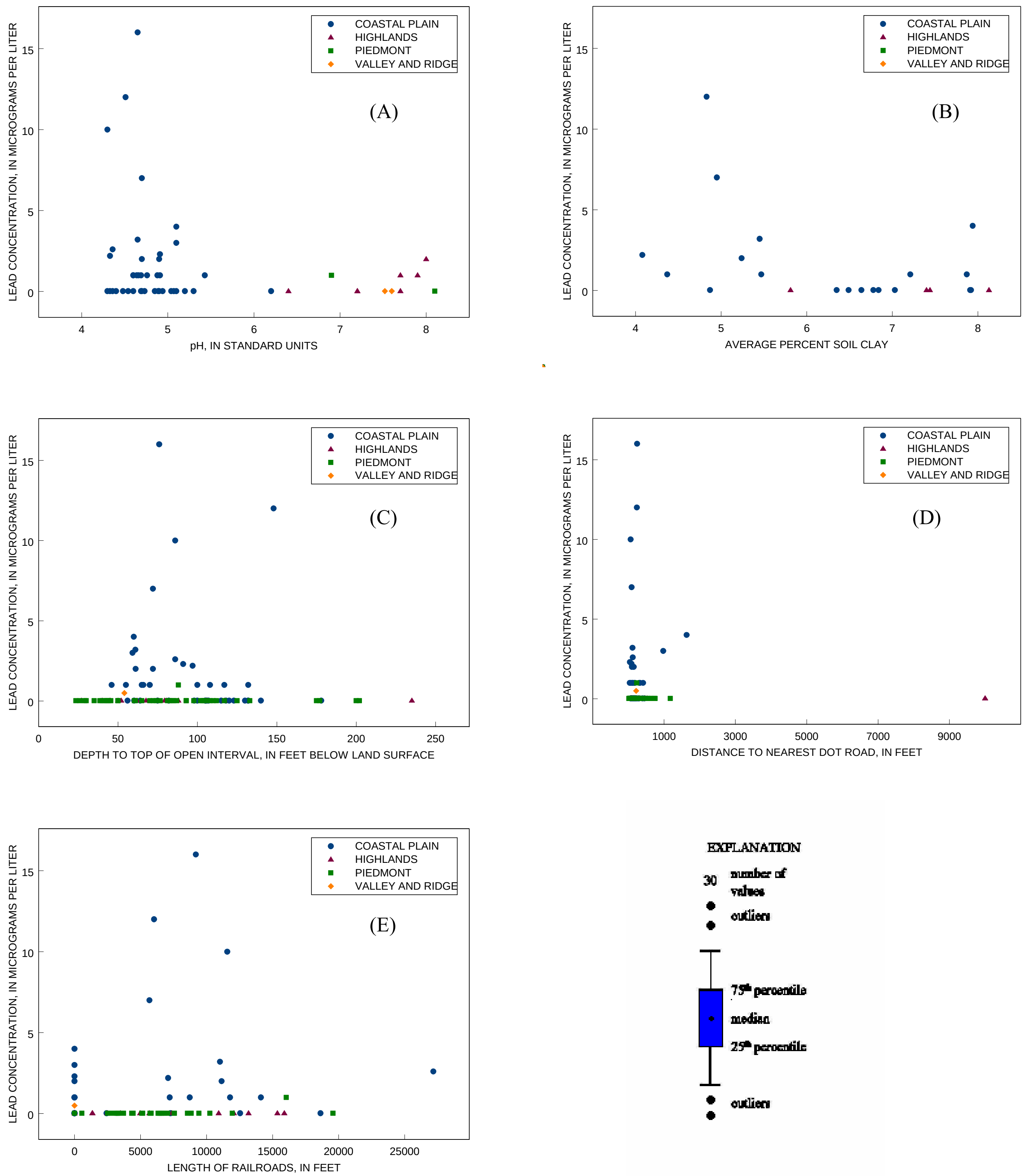

Figure 17. Relation of lead concentration to (A) pH, (B) average percent soil clay, (C) depth to top of open interval, (D) distance to nearest DOT road, and (E) length of railroads, by physiographic province, for 104 community water-supply wells in New Jersey.

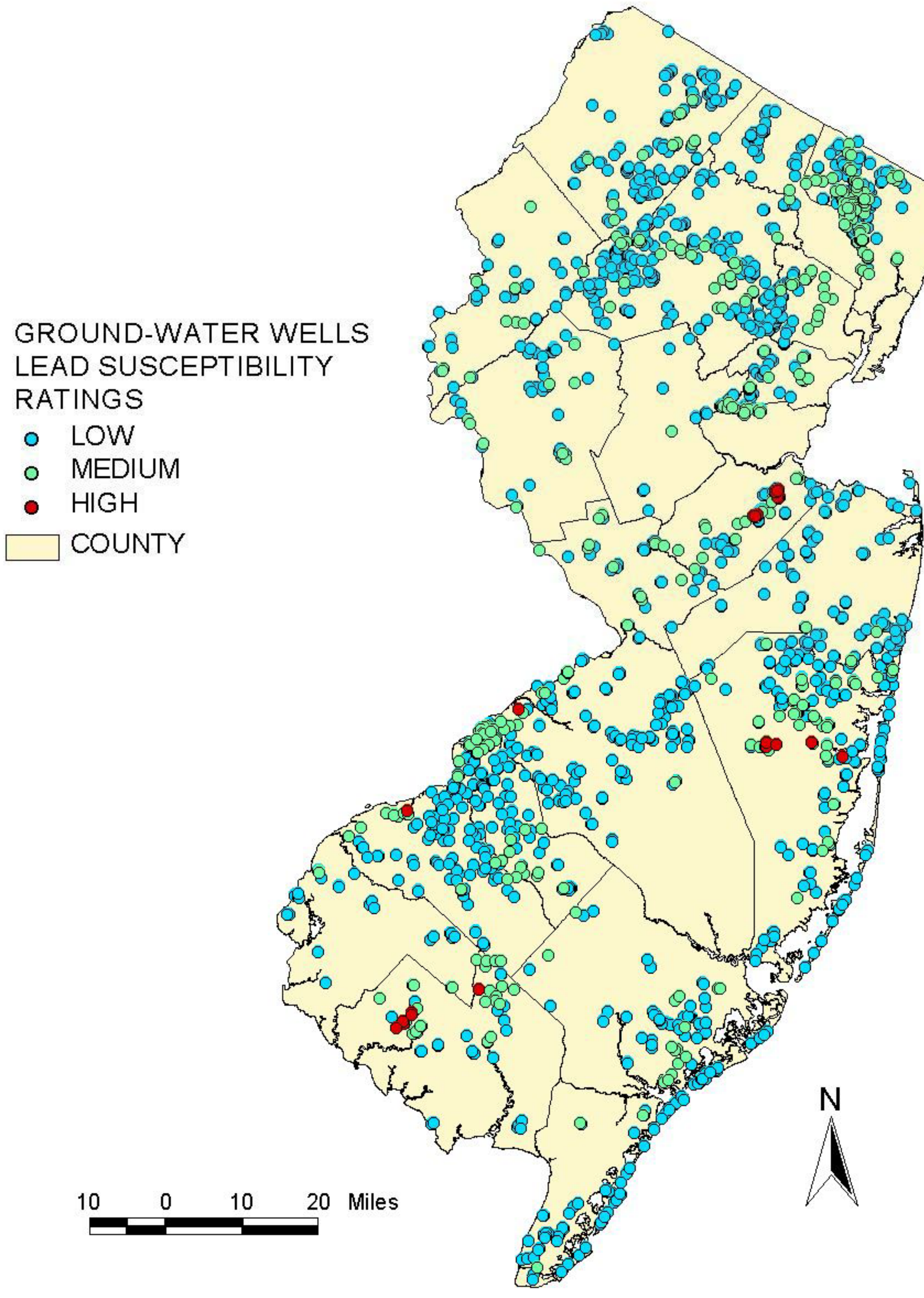

Figure 18. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by lead.

Mercury

Mercury was detected (9 of 33 sites) in water from the CWS wells used for model development (fig. 19). Mercury in water from natural sources is rare; detections of mercury in water samples are more likely the result of human activities. Elevated concentrations of mercury may result from either point or nonpoint sources. Natural degassing of the Earth's crust releases tons of mercury to the atmosphere every year. Mercury is also released to the environment by smelting and the combustion of fossil fuels. Organomercuric compounds were widely used as pesticides until they were banned in the 1960s. About 50 percent of the mercury produced is used in electrical products such as dry-cell batteries, fluorescent light bulbs, and switches. Other uses of mercury include electrolytic preparation of chlorine and caustic soda, paint manufacture, and dental preparations (http://www.epa.gov/safewater/dwh/t-ioc.html). The USEPA maximum contaminant level for mercury currently is 2 μg/L.

Mercury is volatile and tends to disperse widely in the environment (Hem, 1985). Mercury can accumulate in organic and clay-rich soil horizons (fig. 9B) (in undisturbed areas/forest soils). In water typical of aquifers in the Coastal Plain of New Jersey that is acidic, well oxygenated, and rich in chloride, the solubility of mercury increases (Barringer and others, 1997). Mercury also can accumulate in the tissue of many freshwater and marine plants and animals that live in mildly contaminated environments. Average percent soil clay and average percent soil organic matter are conceptual variables that were used to improve the results of the model by representing the tendency of mercury released at land surface to adsorb to particles in the soil.

Population density was used as a variable to improve the results of the model because mercury is widely used in industry and previously in agriculture, and releases to the environment are common. Population density, like urban land use, represents a surrogate for specific activities which can release mercury to the environment, but for which specific variables were not available for statistical testing.

Mercury was detected more frequently, and at higher concentrations in unconfined Coastal Plain wells (fig. 20A), however, few CWS wells in Northern New Jersey have results of analyses for mercury. The most recent samples from all wells in NWIS database in Northern New Jersey showed no detections of mercury. No wells in confined aquifers had results of analyses for mercury, and consequently the susceptibility of wells in confined aquifers and wells in Northern New Jersey could not be determined.

The unconfined CWS wells subset contained insufficient data to develop the mercury model; consequently, data from all unconfined CWS wells were used. In this data set, mercury was equal to or exceeded the MCL of 2 μg/L in a sample from 1 of 33 wells with analyses, and was equal to or exceeded one-tenth of MCL in samples from 6 of 33 wells. Variables selected to represent hydrogeologic sensitivity for mercury were Physiographic Province, average percent soil clay (conceptual), and average percent soil organic matter (conceptual). Variables selected to represent potential contaminant-use intensity for mercury were population density. Of the 1,246 CWS wells in the New Jersey Coastal Plain, 857 were rated as having low susceptibility, 204 were rated as having medium susceptibility, and 185 were rated as having high susceptibility (fig. 21).

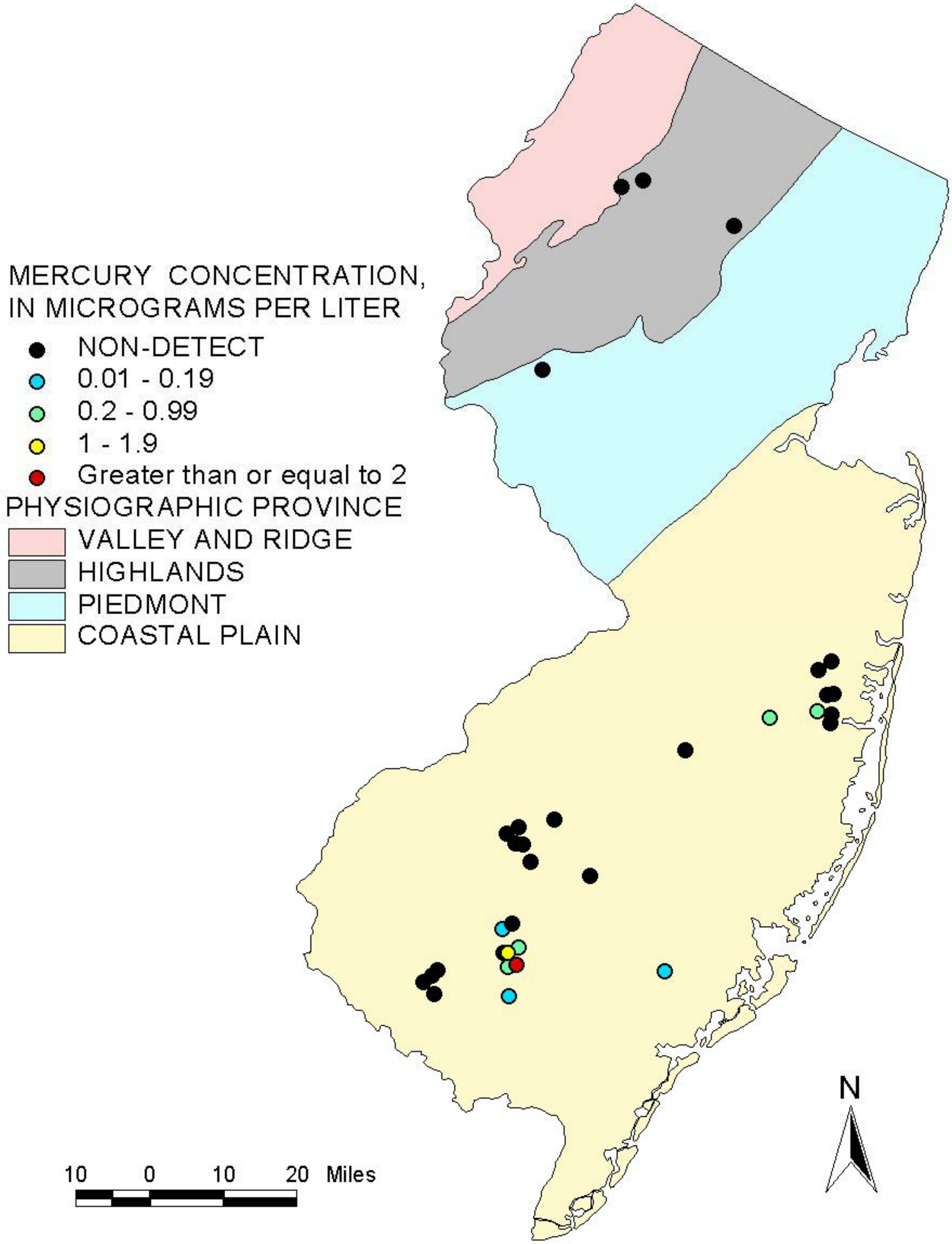

Figure 19. Concentrations of mercury in 33 community water-supply wells used for development of the mercury model.

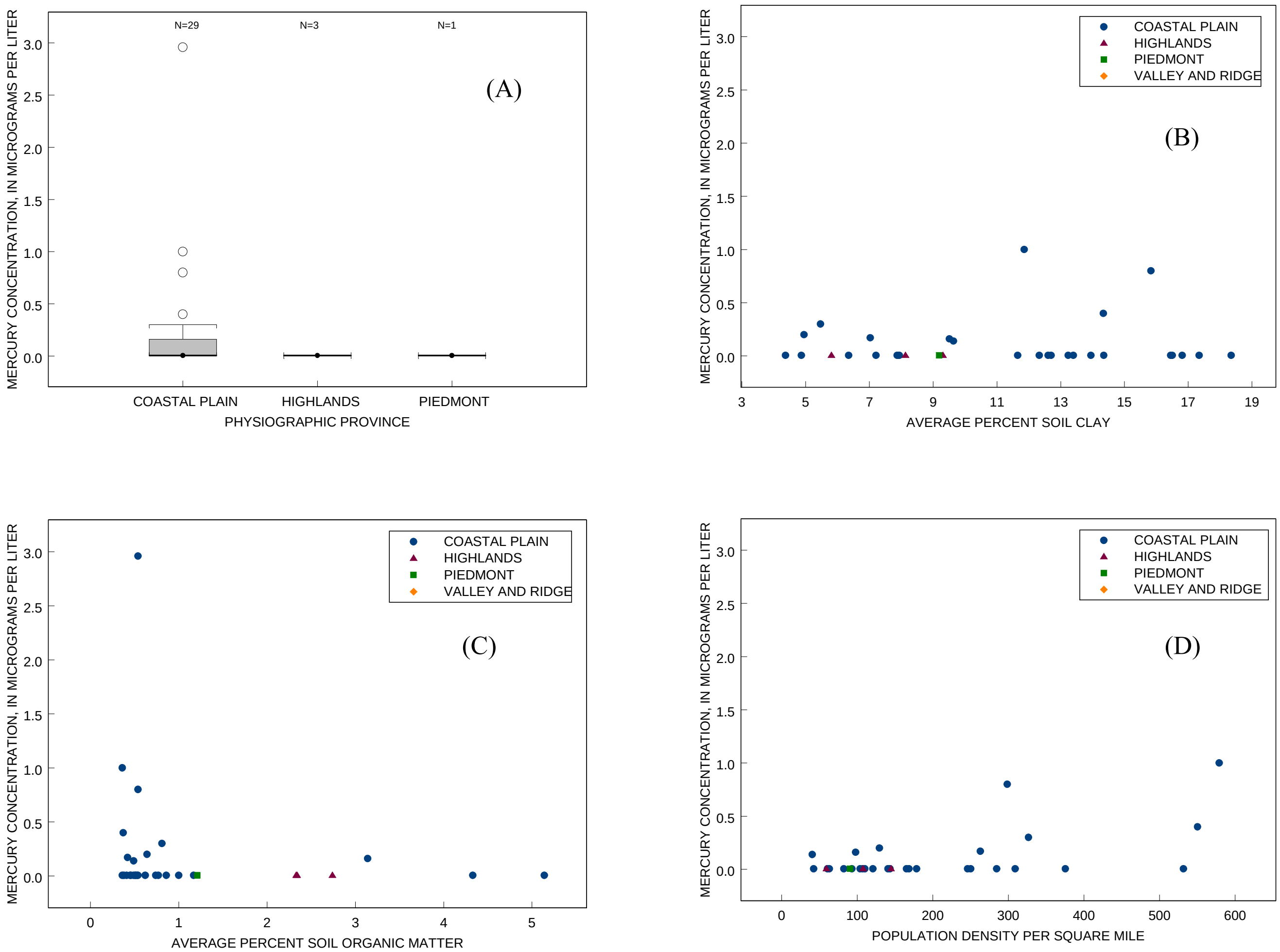

Figure 20. (A) Distribution of mercury concentration by physiographic province, and relation of mercury concentration to (B) average percent soil clay, (C) average percent soil organic matter, and (D) population density per square mile, by physiographic province, for 33 community water-supply wells in New Jersey.

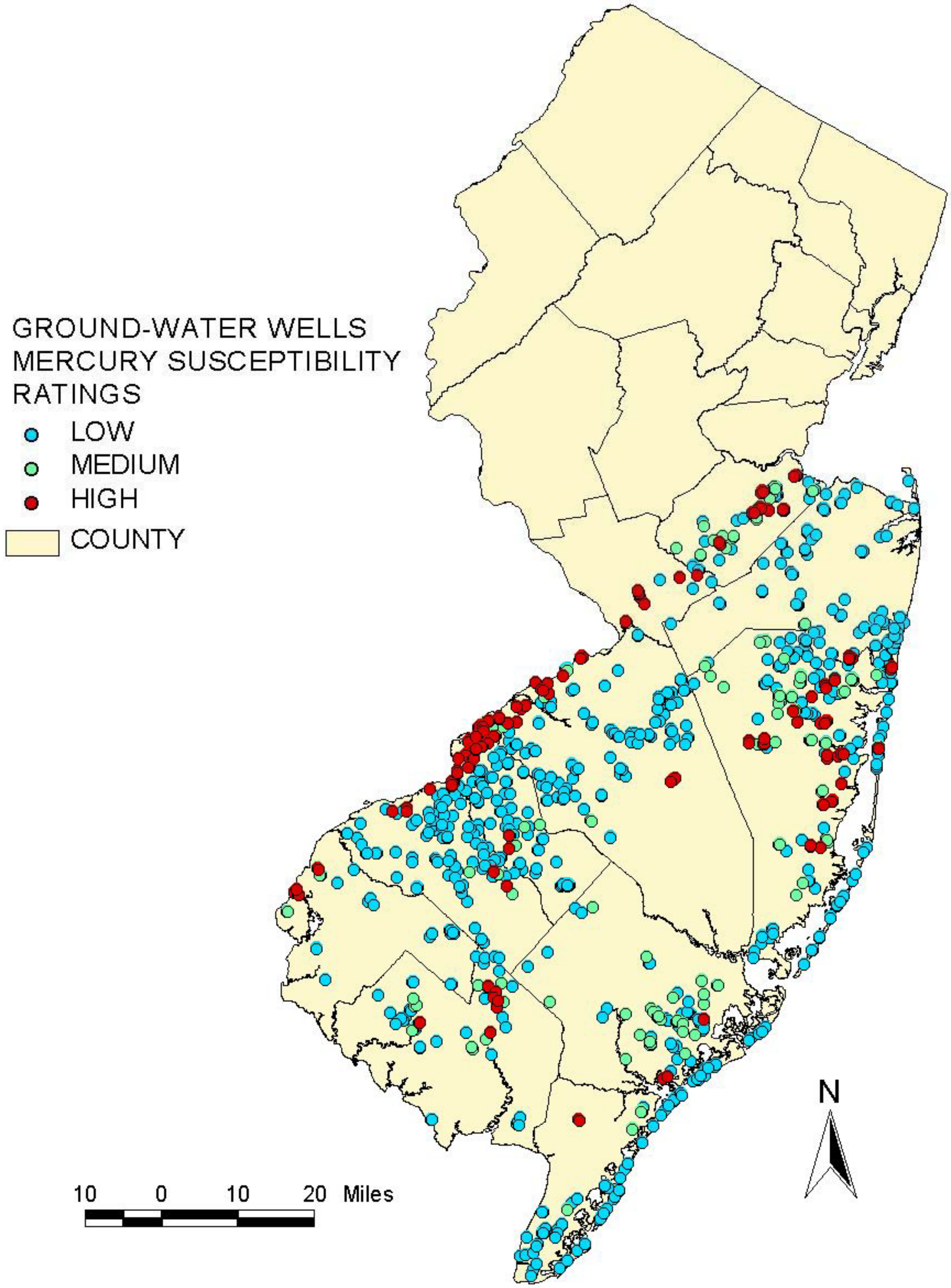

Figure 21. Susceptibility of 1,246 community water-supply wells in the New Jersey Coastal Plain to contamination by mercury.

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. 22). 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 to which the models were applied, the susceptibility to contamination by inorganic constituents was low for 789, medium for 851, and high for 597. The susceptibility ratings for the inorganic constituents 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. Application of the arsenic model estimated that 262 wells are highly susceptible to contamination by arsenic. Application of the beryllium model estimated that 183 wells are highly susceptible. Application of the lead and mercury models estimated that 25 and 185 wells, respectively, are highly susceptible. No wells were highly susceptible to contamination by barium or fluoride.

Discussion

Several limitations to the susceptibility assessment models should be noted. These models should only be used as screening tools to identify potential contamination problems. The most recent sample concentrations at a well were used in the analysis, and do not take into account fluctuations in concentrations that may occur. Most of the results of analyses for wells in the NWIS database are from filtered samples. Many inorganic constituents, including lead and mercury, 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 for 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 a constituent were run on groups of data below one-tenth of the MCL versus data equal to or exceeding one-tenth of the MCL. This level is below the one-half MCL threshold of concern of the NJDEP and may not produce the same results as if statistics were run at a higher level. For most inorganic constituents with primary standards, statistics could not be run at one-half the MCL because few, if any, of the constituents were detected at this level.

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. For example, a source may be highly susceptible to contamination and have no detections in the samples if the constituent does not originate from human activities or natural sources within the contributing area.

The database, GIS coverages, statistical analyses, and susceptibility assessment models will provide guidance to scientists and managers as they determine impacts of hydrogeology and land use on the quality of water of public supplies. The relations between water quality and susceptibility variables shown in figures, graphs, and tables will be useful in determining monitoring requirements for water purveyors to ensure public health.

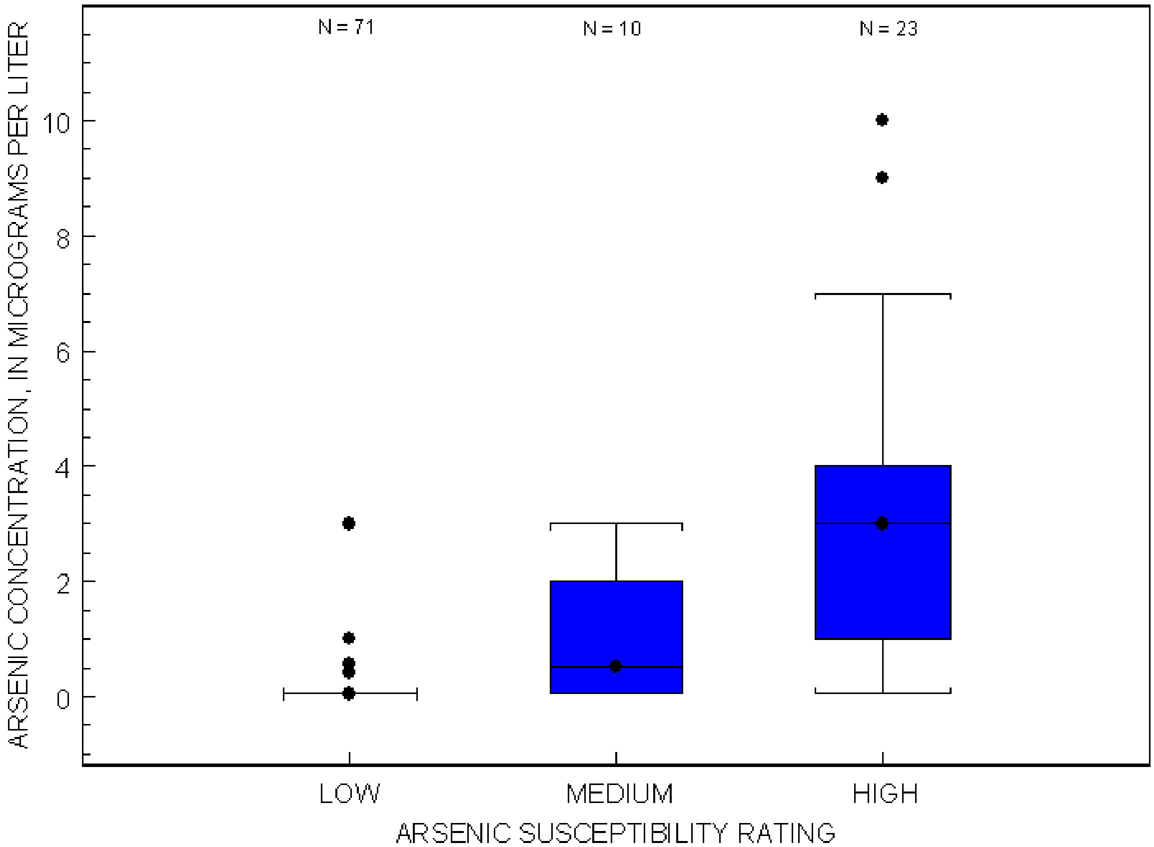

Figure 22A. Results of the arsenic susceptibility assessment model for 104 community water-supply wells in New Jersey showing distribution of arsenic concentration by susceptibility rating.

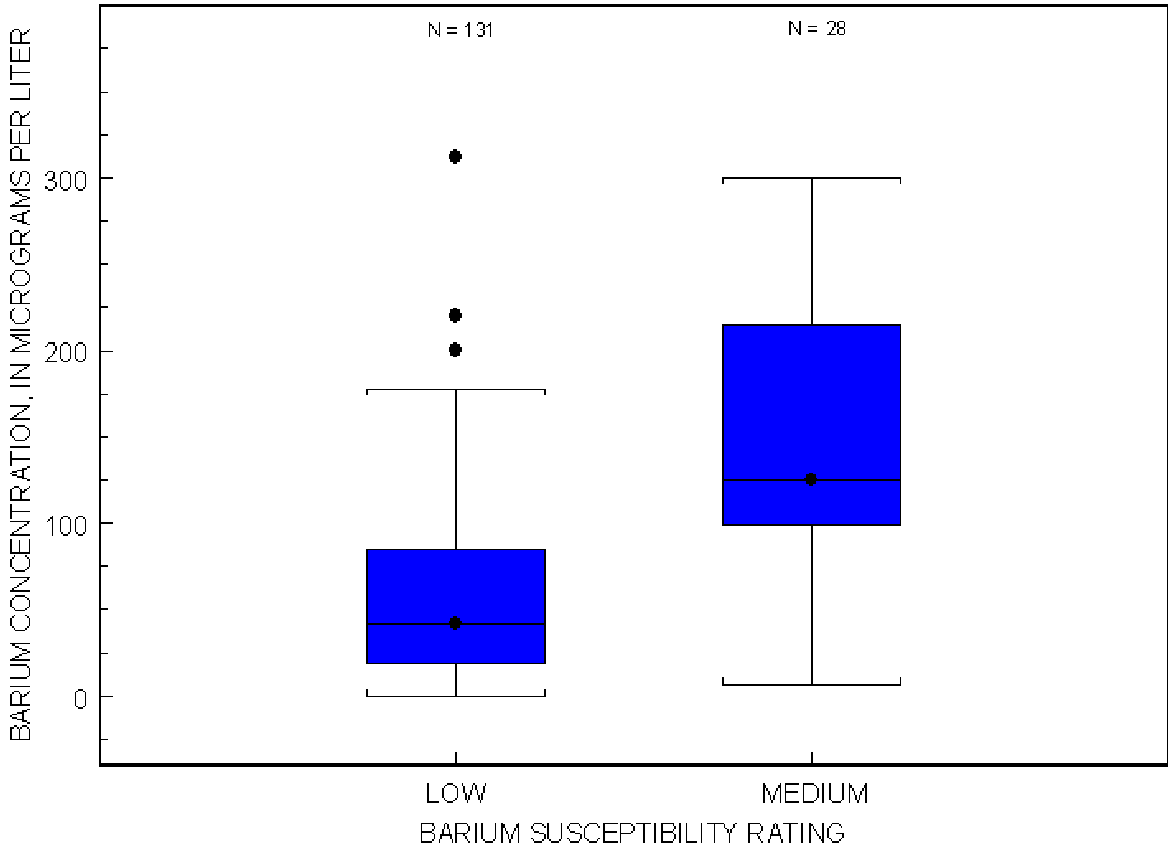

Figure 22B. Results of the barium susceptibility assessment model for 159 community water-supply wells in New Jersey showing distribution of barium concentration by susceptibility rating.

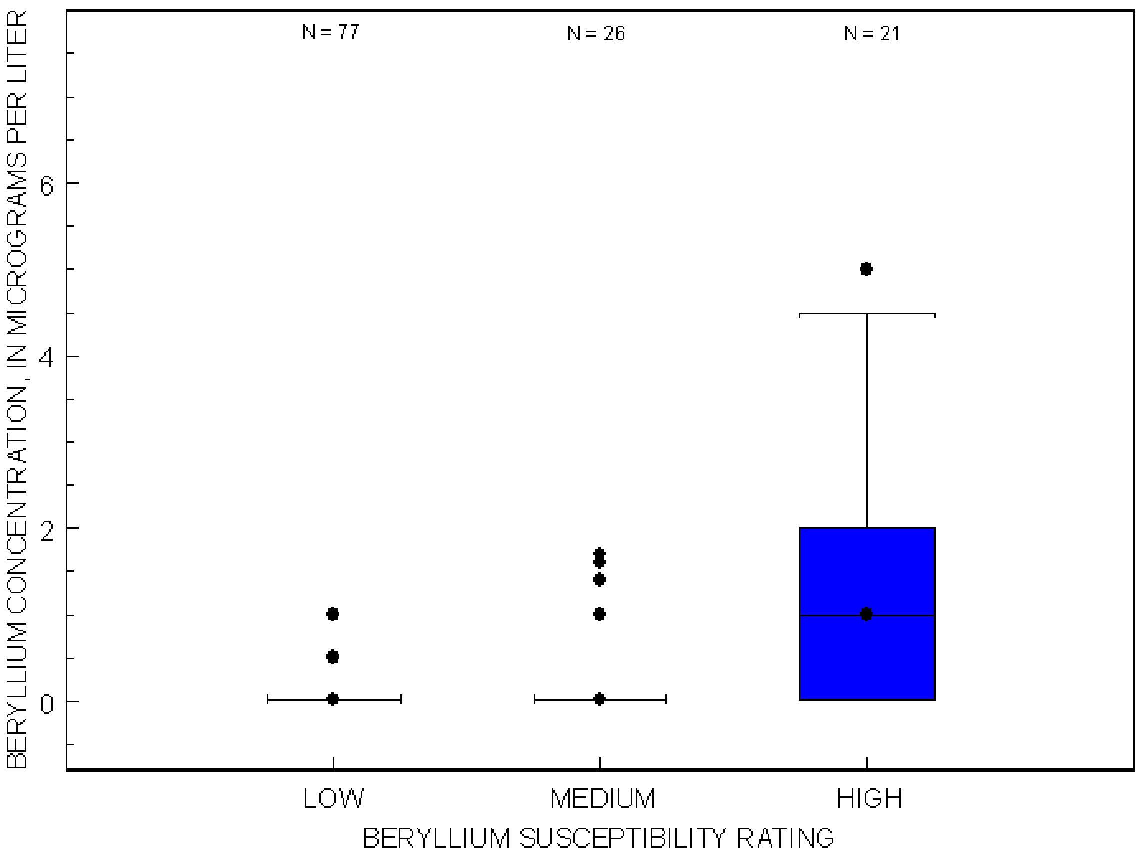

Figure 22C. Results of the beryllium susceptibility assessment model for 124 community water-supply wells in New Jersey showing distribution of beryllium concentration by susceptibility rating..

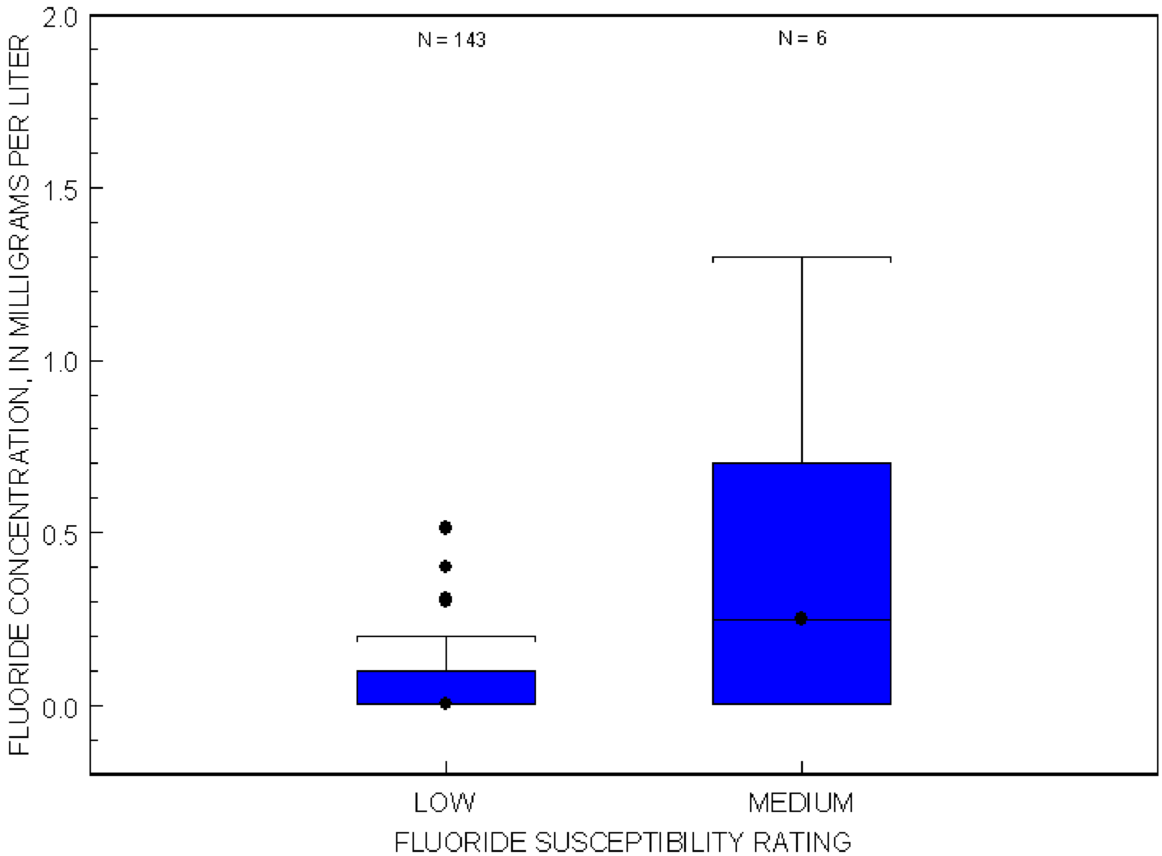

Figure 22D. Results of the fluoride susceptibility assessment model for 149 community water-supply wells in New Jersey showing distribution of fluoride concentration by susceptibility rating.

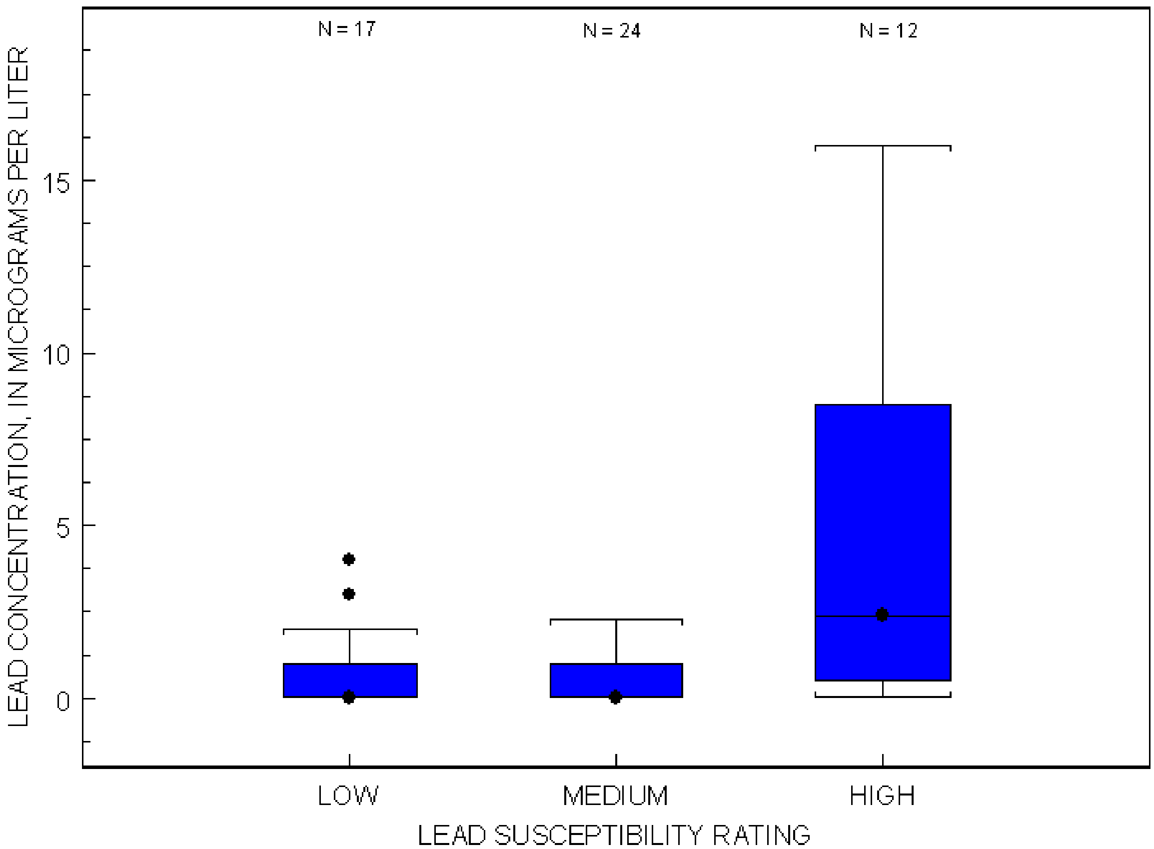

Figure 22E. Results of the lead susceptibility assessment model for 53 community water-supply wells in New Jersey showing distribution of lead concentration by susceptibility rating.

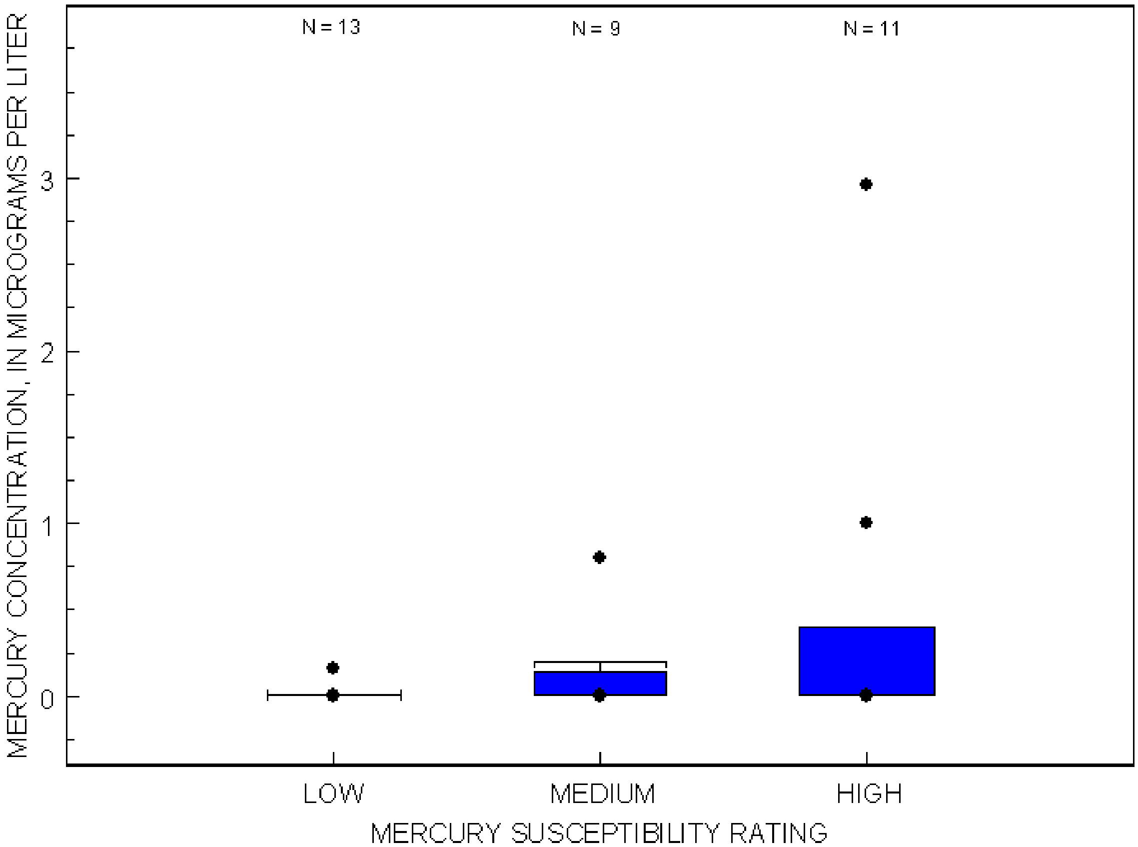

Figure 22F. Results of the mercury susceptibility assessment model for 33 community water-supply wells in New Jersey showing distribution of mercury concentration by susceptibility rating.

References

Anderson and others, 1976, A land use and land cover classification system for use with remote sensor data; U.S. Geological Survey Professional Paper 964.

Barringer, J.L., MacLeod, C.L., and Gallagher, R.A., 1997, Mercury in ground water, soils, and sediments of the Kirkwood-Cohansey aquifer system in the New Jersey Coastal Plain: U.S. Geological Survey Open File Report 95-475, 260 p.

Barringer, J.L., and MacLeod, C.L., 2001, Relation of mercury to other chemical constituents in ground water in the Kirkwood-Cohansey aquifer system, New Jersey Coastal Plain, and mechanisms for mobilization of mercury from sediments to ground water: U.S. Geological Survey Water-Resources Investigations Report 00-4230, 162 p.

Barringer, J.L., Szabo, Zoltan, and Barringer, T.H., 1998, Arsenic and metals in soils in the vicinity of the Imperial Oil Company Superfund site, Marlboro Township, Monmouth County, New Jersey: U.S. Geological Survey Water-Resources Investigations Report 98-4016, 268 p.

Helsel, D.R. and Hirsch, R.M., 2002, Statistical methods in water resources, U.S. Geological Survey Techniques of Water Resources Investigations, Book 4, Hydrologic analysis and interpretation, Chapter A3, 510 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural waters: U.S. Geological Survey Water-Supply Paper 1473, 3d edition, 263 p.

Kozinski, Jane, Szabo, Zoltan, Zapecza, O.S. and Barringer, T.H., 1995, Natural radioactivity in, and inorganic chemistry of ground water in the Kirkwood-Cohansey aquifer system, southern New Jersey, 1983-89: U.S. Geological Survey Water-Resources Investigations Report 92-4144, 130 p.

New Jersey Department of Environmental Protection, 1998, Guidance for well head protection area delineations in New Jersey, New Jersey Geological Survey Draft Technical Guidance Document, 29 p. http://www.state.nj.us/dep/dsr/delineation.PDF

New Jersey Department of Environmental Protection SWAP manual http://www.state.nj.us/dep/watersupply/swap2.htm

Serfes, M.E., Spayd, S.E., Herman, G.C., Monteverde, D.E., 2000, Arsenic Occurrence, Source and Possible Mobilization Mechanisms in Ground Water of the Piedmont Physiographic Province in New Jersey: Abstract, in EOS, Transactions of the American Geophysical Union Fall Meeting, v. 81, no. 48, November 28, 2000, p. F525-H210-08.

Smedley, P.L. and Kinniburgh, D.G., 2002, A review of the source, behavior, and distribution of arsenic in natural water: Applied Geochemistry, v. 17, p, 517-568.