SUSCEPTIBILITY OF SOURCE WATER TO COMMUNITY AND NONCOMMUNITY SURFACE-WATER SUPPLIES AND RELATED WELLS IN NEW JERSEY TO CONTAMINATION BY INORGANIC CONSTITUENTS

Summary

Susceptibility assessment models were developed to predict the susceptibility of source water to 49 surface-water-supply intakes and 11 ground-water sources under the direct influence (GWUDI) of surface water in New Jersey to contamination by inorganic constituents. In this report, inorganic constituents are metals and major constituents with primary standards. A separate report and model is available for nitrate. Susceptibility is defined by the variables that describe hydrogeologic sensitivity and potential contaminant-use intensity within the area contributing water to a surface-water source. The models were developed using water-quality data from surface-water samples collected and analyzed by the U.S. Geological Survey (USGS). Models were developed for 3 of 14 constituents with primary maximum contaminant levels: arsenic, lead, and fluoride. The maximum susceptibility of the three individual models is the overall inorganic susceptibility assessment rating at each of the 60 sources (figs. 1 and 2). Overall, the individual constituent models had low to medium susceptibility ratings at most of the surface-water sources. Susceptibility to inorganic constituents for the 11 GWUDI was medium for 5 and high for 6.

Of the 49 surface-water-supply intakes, the susceptibility to inorganic constituents was medium for 9 and high for 40. Susceptibility ratings for arsenic were highest in the Piedmont Physiographic Province. This is possibly associated with geologic sources. Most of the surface-water sources with high susceptibility for lead are located in the northwest area of the Coastal Plain and other areas associated with greater urban land use. The surface-water sources rated with a medium susceptibility for fluoride have greater than 46 percent of their contributing area as developed land, which is urban and agricultural land combined.

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 surface 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 source 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 used for public drinking water; (2) inventory the potential contaminant sources within the source water assessment area; (3)

determine the public water system's susceptibility to contaminants; and (4) incorporate public participation and education **(www.state.nj.us/dep/swap)**.

Susceptibility assessment models were developed to rate each public surface-water source as 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 water-supply intakes and ground water sources under the direct influence of surface water to these constituents, and (3) documents the distribution of these constituents in surface water in New Jersey. The models are intended to be screening tools to guide monitoring of public water supplies in New Jersey.

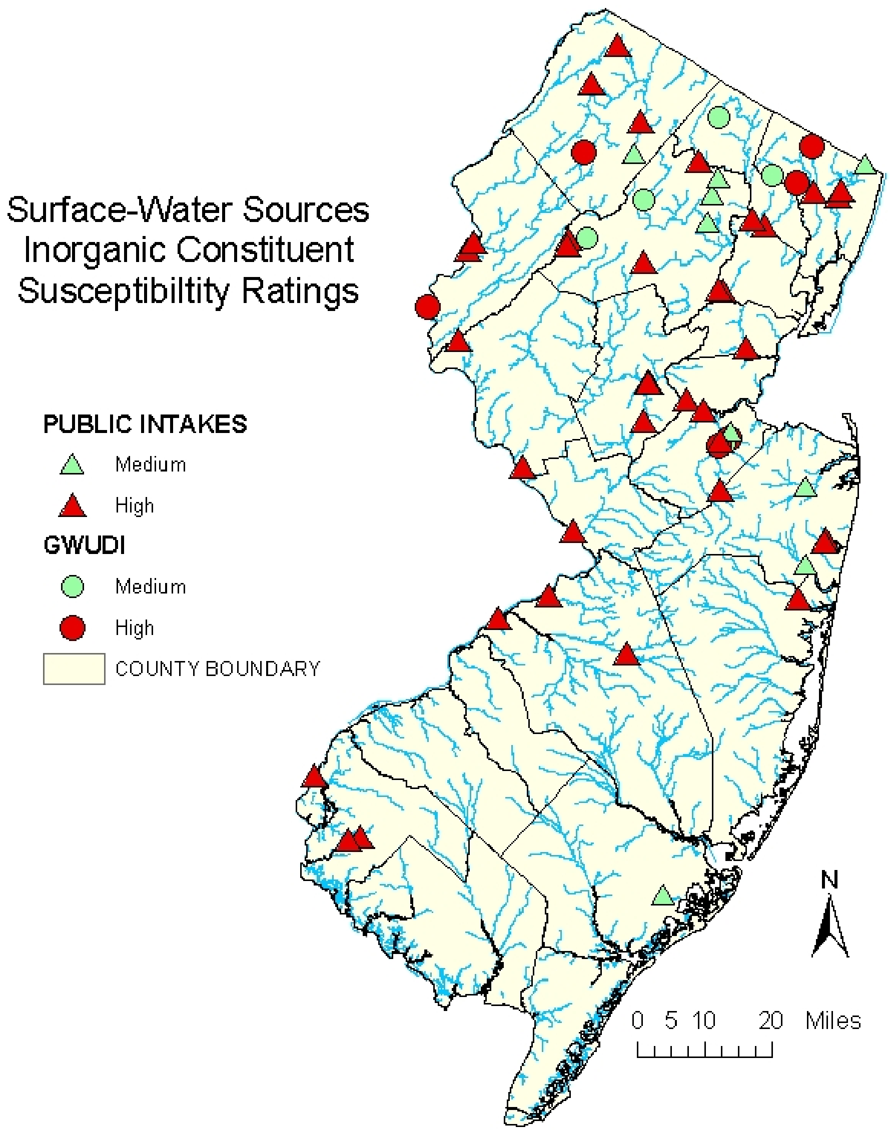


Figure 1. Susceptibility of 60 surface-water sources in New Jersey to contamination by inorganic constituents.

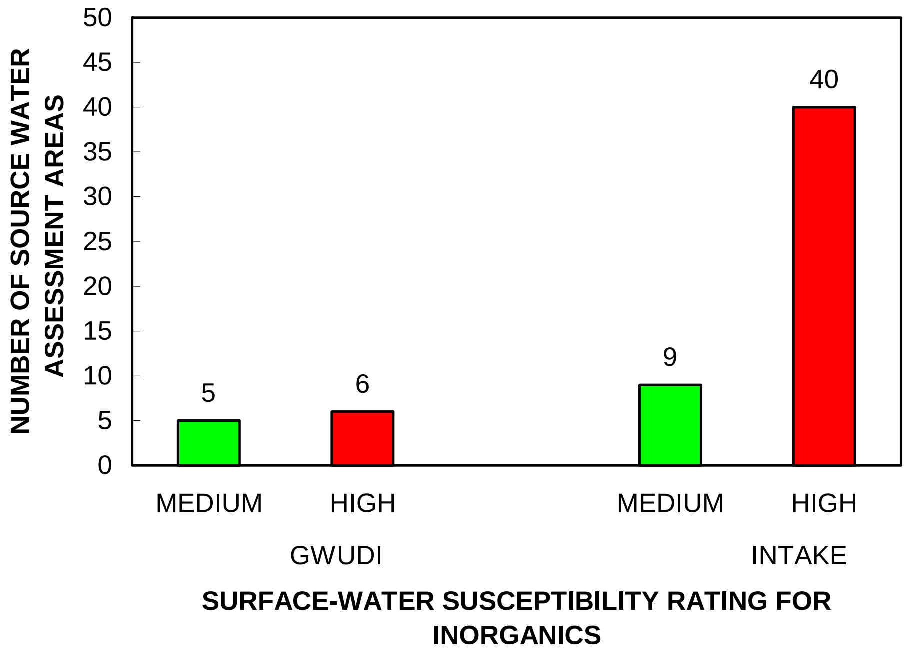


Figure 2. Number of water-supply intakes and related wells in New Jersey having medium and high susceptibility to contamination by inorganic constituents.

Definition of Susceptibility

The susceptibility of a public water supply to contamination by various 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 based on the 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 surface-water source.

Susceptibility = Hydrogeologic Sensitivity + Potential Contaminant-use Intensity

The 1999 NJDEP SWAP Plan postulated that all surface-water sources would be considered highly sensitive, but that premise has been redefined for some constituents through modeling. In some cases, documented research from existing studies and statistical methods of this study show that a sensitivity variable has a significant relation to contaminant concentrations.

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 community and noncommunity water supplies as low, medium, or high susceptibility to contamination for the groups of constituents using, as guidance, the thresholds developed by NJDEP for the use in the models. In general, the low-susceptibility category includes surface-water sources for which constituent values are not likely to equal or exceed one-tenth of the New Jersey's drinking water maximum contaminant level (MCL). The medium-susceptibility category includes surface-water sources for which constituent values are not likely to equal or exceed one-half of the MCL, and the high-susceptibility category includes surface-water sources for which constituent values equal or exceed one-half of the MCL. The susceptibility assessment rating for the inorganic constituent group is based on the results of three individual constituent susceptibility assessment models. The highest of the three susceptibility ratings for the individual constituents is selected as the susceptibility rating at an intake or a ground-water source under the direct influence of surface water for the inorganic constituent group.

Susceptibility Model Development

The development of the susceptibility assessment models involved several steps (J.A. Hopple and others, U.S. Geological Survey, written commun., 2003): (1) development of source water assessment areas to community and noncommunity 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 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. Some of the components of the analysis were subjective, especially the coding scheme of the model ratings. 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.

Development of Source Water Assessment Areas

NJDEP estimated 60 areas contributing water to surface-water sources used for drinking water in New Jersey (fig. 3); 49 are associated with surface-water intakes, and 11 are associated with sources using ground water under the direct influence of surface water. For most surface-water sources, the source water assessment area includes the entire drainage area that contributes to the water that flows past the intake or source. These source water assessment areas include the headwaters and tributaries and are based on the USGS 14-digit hydrologic unit code (HUC 14) (Ellis and Price, 1995) (http://www.state.nj.us/dep/swap). For intakes or sources with extremely large contributing areas, the source water assessment area is based on the time of travel to the intake or source.

NJDEP has classified approximately 55 wells as sources using ground water under the direct influence of surface water (GWUDI). Water from wells that are classified as GWUDI wells must meet specific water-quality criteria and is treated in a manner similar to water from surface-water intakes. To determine the susceptibility rating for these wells, NJDEP performed an integrated delineation combining the ground-water assessment area with the surface-water assessment area.

The ground-water assessment area was delineated using the Combined Model/Calculated Fixed Radius Method (www.state.nj.us/dep/dsr/whpadel.pdf). The surface-water assessment area was delineated as the entire drainage area that contributes water to the well, with the 2-year time-of-travel demarcation of the ground-water assessment area determining the downstream boundary. A few GWUDI wells do not have an associated surface-water assessment area because no surface-water body is present within the 2-year ground-water time-of-travel area. In these instances, only the ground-water assessment area was used. Both the ground- and surface-water models were applied to these areas, and the higher of the two ratings was selected as the susceptibility rating for that well.

The USGS estimated areas contributing water to 388 surface-water-quality sites in New Jersey for model development and verification. Drainage areas contributing water to a surface-water-quality site were delineated using a GIS macro language program that determines basin area from a digital elevation model (DEM) based on a 1:24,000 scale and 30-meter resolution to contour intervals (L.J. Kauffman, U.S. Geological Survey, written commun., 2002).

Figure 3. Example of delineated contributing area to a surface-water-supply intake.

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 could affect surface-water quality within areas contributing water to surface-water sources. The variables were calculated for the entire source water assessment area. Sensitivity variables used in the statistical analysis include average soil properties and predominant watershed, hydrologic unit, and physiographic province. Intensity variables include land use from coverages for 1995-97; lengths of roads, railways, and streams; the number of potential contaminant point sources; septic-tank and contaminant-site densities; and minimum distances of the surface-water source to various land uses and potential contaminant sources.

Water-Quality Data

Surface-water-quality data from June 1980 through October 2002 were obtained from the USGS NWIS database. Data for 801 surface-water-quality sites were retrieved. Analyses that were determined by older, less accurate, or less precise methods and those with high reporting levels were excluded. All water-quality data are from water samples collected by the USGS prior to treatment, unless otherwise noted. Analyses of water from sites with known contamination problems also were not used. Sites in northern New Jersey with more than 20 percent of the contributing area in New York State were eliminated because comparable sensitivity and intensity variables were unavailable. A statewide network of 388 USGS surface-water-quality sites was selected for the modeling process. Many of these sites are part of the systematic data-collection program in the USGS New Jersey District. Some are sites in the USGS National Water Quality Assessment program, and others are part of regional and local investigations. All water-quality data were read into a relational database and a statistical software package to be used for exploratory data analysis, statistical testing, and plotting.

Of the 388 surface-water-quality sites delineated for the modeling process 346 had analyses for one or more of the following constituents: arsenic at 256 sites, lead at 213 sites, and fluoride at 338 sites (table 1). The maximum concentration measured at a surface-water-quality site was used because surface water is more variable than ground water, higher concentrations are of greater risk to human health, and selecting one sample per site avoided problems of averaging samples with Maximum Reporting Levels that may have changed over time.

Table 1. Number of sites at which selected constituents in samples from surface-water-quality sites met or exceeded selected criteria related to the MCL.

Constituent	Standard - MCL unless otherwise noted	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
Asbestos	7 million fibers per liter	0	-	-	-	-
Cyanide	200 ug/L (0.2 mg/L)	18	0	0	0	0
Fluoride	4000 ug/L (4.0 mg/L)	338	248	43	0	0
Selenium	50 ug/L	292	56	2	0	0
Antimony	6 ug/L	0	-	-	-	-
Arsenic	10 ug/L	256	212	189	13	6
Barium	2000 ug/L	159	133	4	0	0
Beryllium	4 ug/L	193	67	0	0	45
Cadmium	5 ug/L	208	58	1	1	0
Chromium	100 ug/L	213	90	4	0	0
Copper	1300 ug/L (Action Level)	213	176	0	0	0
Lead	15 ug/L (Action Level)	213	109	76	6	6
Mercury	2 ug/L	186	18	5	0	0
Thallium	2 ug/L	0	-	-	-	-

[1] Number of sites represents 388 surface-water-quality sites with estimated contributing areas in the NWIS database for constituents with primary standards and may be different than the number of sites used to develop an individual model.
[2] Criterion 1: Concentration is at least equal to 10 percent of the standard, but is less than 50 percent of the standard
[3] Criterion 2: Concentration is at least equal to 50 percent of the standard, but is less than the standard

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 above one-tenth of the MCL are considered in this report as an indication of an emerging problem, but health effects at this level are of less concern. The inorganic 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 (table 1). The Kruskal-Wallis test is a nonparametric statistical method and is calculated by performing a one-way analysis of variance on the ranks of a data set (Iman and Conover, 1983). 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, potential contaminant-use intensity, and many water-quality variables. Scatter plots of each variable in relation to 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 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. 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 was not supported by scientific investigations, (3) the variable did not show a graphical relation to the constituent (4) the variable was found to have a similar relation to the constituent as another variable.

Table 2A. Results of univariate statistical tests for explanatory variables used in the arsenic model.			
Variable	**Kruskal-Wallis Score**	**P-value**	**Conceptual Variable**
pH of water-quality sample	19.5223	0.0000	No
Physiographic Province		[1]	Yes[2]
New Jersey Water Region	19.0654	0.0008	No
Distance to agricultural land, 1995		[1]	Yes[2]

[1] Not significant at the alpha < 0.05 level.
[2] This conceptual variable improves the model, shows a graphical relation, and is supported by previous scientific investigations.

Table 2B. Results of univariate statistical tests for explanatory variables used in the lead model.			
Variable	**Kruskal-Wallis Score**	**P-value**	**Conceptual Variable**
Average percent soil organic matter		[1]	Yes[2]
Physiographic Province		[1]	Yes[2]
Percent urban land, 1995	12.5576	0.0004	No
Density of KCSL, SWL, NJPDES GW, SWRRF, SWTF200011, Class B, DPCC, UST[3]	14.5238	0.0001	No

[1] Not significant at the alpha < 0.05 level.
[2] This conceptual variable improves the model, shows a graphical relation, and is supported by previous scientific investigations.
[3] Known Contaminated Sites (KCSL), Solid Waste Landfills (SWL), NJPDES Ground Water Permits (NJPDES GW), Resource Recover Facilities (SWRRF), Transfer Facilities (SWTF200011), Class B Recycling Facilities (Class B), Discharge Prevention Containment and Countermeasures Facilities (DPCC), Underground Storage Tanks (UST)

Table 2C. Results of univariate statistical tests for explanatory variables used in the fluoride model.			
Variable	**Kruskal-Wallis Score**	**P-value**	**Conceptual Variable**
Average percent soil organic matter		[1]	Yes[2]
Percent developed land, 1995		[1]	Yes[2]
Percent commercial-industrial land, 1995		[1]	Yes[2]
Density of NJPDES SW/Storm[3], Compost Facilities	16.7065	0.0000	No

[1] Not significant at the alpha < 0.05 level.
[2] This conceptual variable improves the model, shows a graphical relation, and is supported by previous scientific investigations.
[3] NJPDES Surface Water Permits (NJPDES SW), NJPDES Storm Water Permits (NJPDES Storm)

Rating Scheme

A scoring method was developed for each model that assigned points to each conceptual and statistically significant variable used in the model. Relations observed in scatter plots or boxplots of the variable versus the maximum constituent concentration were used to explore the distribution of the data considering the MCL or action level as the starting point for devising the code.

As an example, the rating of pH of the water-quality sample for the arsenic model had a sensitivity point scheme of 1, 3, and 5 (table 3a). The scatter plot of the data show that at a pH of $\leq$ 5 concentrations of arsenic are generally below 2 µg/L (fig. 4a). A score of 1 is given for pH concentrations $\leq$ 5. The concentrations of arsenic increase from >5 to 7, but do not exceed one half of the MCL. A score of 3 is given for this range of pH. At a pH of >7 to 14, some values of pH exceed the 10 µg/L MCL, so a score of 5 is given. A site located in the Lower Delaware Water Region of the Coastal Plain Physiographic Province is assigned a score of 3 in addition to the score of one assigned for Coastal Plain Physiographic Province (figures 4b and 4c). Physiographic Province is a conceptual variable. This method is used because sites located in the Lower Delaware Water Region have a greater potential of contamination from arsenic. The sites with Atlantic Coastal drainage have a lower potential of contamination from arsenic. It is necessary to calculate the score in this manner because this concept combines variables from two GIS coverages whose data are maintained separately in the project database. Intensity scoring for distance to agricultural land (1995) was determined by exploring the distribution of the scatter plot with consideration of the data ranges at one-tenth and one-half of the MCL, and above the MCL for arsenic (fig. 4d).

Scoring of the lead model includes the sensitivity variables, which are also conceptual variables, of average percent soil organic matter and physiographic province, and the intensity variables of percent urban land (1995) and the density of known contaminated sites (KCSL), solid waste landfills (SWL), NJPDES ground water permits (NJPDES GW), resource recover facilities (SWRRF), transfer facilities (SWTF200011), class B recycling facilities (Class B), discharge prevention containment and countermeasures facilities (DPCC), and underground storage tanks (UST) (table 3b). Scatter plots and a boxplot were examined to determine the scoring for each variable. Guidelines included looking at data ranges for one-tenth and one-half of the 15µg/L action level, and data that exceeded the action level.

Scoring of the fluoride model has average percent soil organic matter as the sensitivity variable and it is a conceptual variable. Intensity variables that are conceptual variables are percent commercial-industrial land (1995) and percent developed land (1995). The density of NJPDES surface water permits (NJPDES SW), NJPDES storm water permits (NJPDES Storm), and composting facilities is also an intensity variable (table 3c). Scatter plots of the variables were examined using one-tenth and one-half of the MCL, and the 4 mg/L MCL to determine the scoring.

Table 3A. Susceptibility rating scheme for arsenic in water from surface-water-quality sites. Arsenic Rating: 0-4 Low, 5-11 Medium, 12-14 High

	Sensitivity Points					Conceptual Variable
Variable	1	2	3	4	5	
pH of water-quality sample	≤5		>5 - ≤7		>7	No
Physiographic Province	Coastal Plain	Valley & Ridge	Highlands	Piedmont		Yes[1]
New Jersey Water Region			Lower Delaware			No
	Intensity Points					Conceptual Variable
Variable	1	2	3	4	5	
Distance to Agricultural Land, 1995	>20,000		>5,000 - ≤20,000		≤5,000	Yes[1]

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

Table 3B. Susceptibility rating scheme for lead in water from surface-water-quality sites. Lead Rating; 0-7 Low, 7-13 Medium, 14-17 High

	Sensitivity Points						Conceptual Variable
Variable		1	2	3	4	5	
Average percent soil organic matter		>5		>2 - ≤5		≤2	Yes[1]
Physiographic Province		Valley & Ridge	Piedmont	Coastal Plain	Highland s		Yes[1]
	Intensity Points						Conceptual Variable
Variable	0	1	2	3	4	5	
Percent Urban Land, 1995	0	>0 - ≤5		>5 - ≤75	-	>75	No
Density of KCSL, SWL, NJPDES GW, SWRRF, SWTF200011, Class B, DPCC, UST[2]	0	>0 - ≤2.5		>2.5 - ≤50		>50	No

[1] This conceptual variable improves the model, shows a graphical relation, and is supported by previous scientific investigations.
[2] Known Contaminated Sites (KCSL), Solid Waste Landfills (SWL), NJPDES Ground Water Permits (NJPDES GW), Resource Recover Facilities (SWRRF), Transfer Facilities (SWTF200011), Class B Recycling Facilities (Class B), Discharge Prevention Containment and Countermeasures Facilities (DPCC), Underground Storage Tanks (UST)

Table 3C. Susceptibility rating scheme for fluoride in water from surface-water-quality sites. Fluoride Rating: 0-14 Low, 15-17 Medium, (no High)

	Sensitivity Points						Conceptual Variables
Variable		1	2	3	4	5	
Average percent soil organic matter		>8		>4 - ≤8		≤4	Yes[1]
	Intensity Points						**Conceptual Variables**
Variable	0	1	2	3	4	5	
Percent developed land, 1995	0	>0 - ≤20		>20 - ≤45		>45	Yes[1]
Percent commercial-industrial land, 1995	0	>0 - ≤5		>5 - ≤30		>30	Yes[1]
Density of NJPDES SW/Storm[2], Compost Facilities	0	>0 - ≤0.1	>0.1				No

[1] This conceptual variable improves the model, shows a graphical relation, and is supported by previous scientific investigations.
[2] NJPDES Surface Water Permits (NJPDES SW), NJPDES Storm Water Permits (NJPDES Storm)

Relation of Inorganic Constituents in Surface Water to Susceptibility Variables

Models were developed to investigate relations between concentrations of arsenic, lead, and fluoride from USGS surface-water-quality sites and various hydrogeologic sensitivity and potential contaminant-use intensity variables. These three constituents had sufficient data to develop meaningful statistical models (table 1). Asbestos, antimony, and thallium did not have sufficient data for model development. Cyanide data are highly censored (no reported detections) and cyanide is considered to have low susceptibility for all surface-water intakes in New Jersey. The susceptibility is low for contamination from copper because the data do not exceed one-tenth of the MCL. Data for selenium, barium, cadmium, chromium, and mercury include concentration values exceeding one tenth of the MCL at one or more sites, but in each case insufficient data are available for meaningful statistical modeling. Beryllium has sufficient data for statistical modeling, but much of it is not useable because the method reporting levels used prior to 1990 were greater than 10 percent of the MCL (written comm., Jacob Gibs, U.S. Geological Survey, 2003)

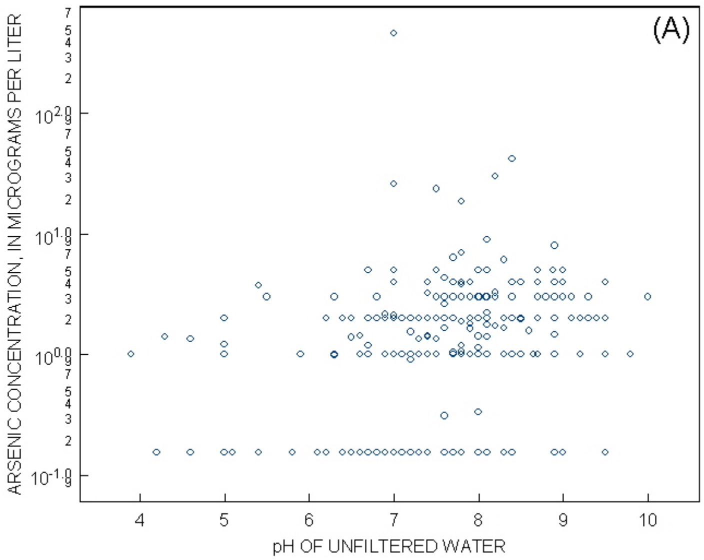
Arsenic

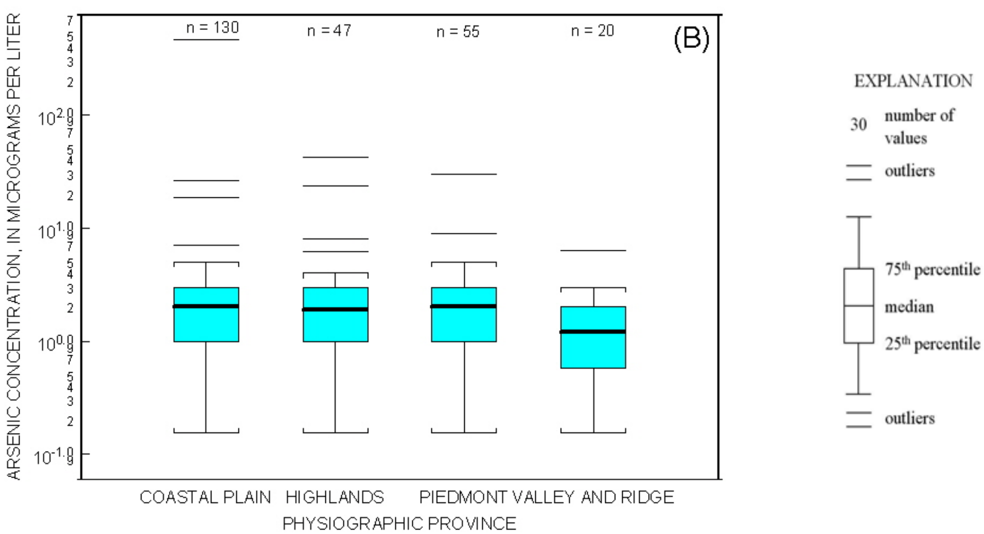
Arsenic can occur naturally in surface water at low concentrations from the weathering of rock and soils. Arsenic is also present from human activities, such as structures built of preserved wood and the application of arsenic-based herbicides, insecticides, and rodenticides. Historically, arsenic-based herbicides were used extensively in New Jersey from 1900 to 1980 (Murphy and Aucott, 1998). Results of streambed sediments collected and analyzed for arsenic during a cooperative study by the USGS and NJDEP showed that the presence of arsenic is related to agricultural land use (O'Brien, 1997).

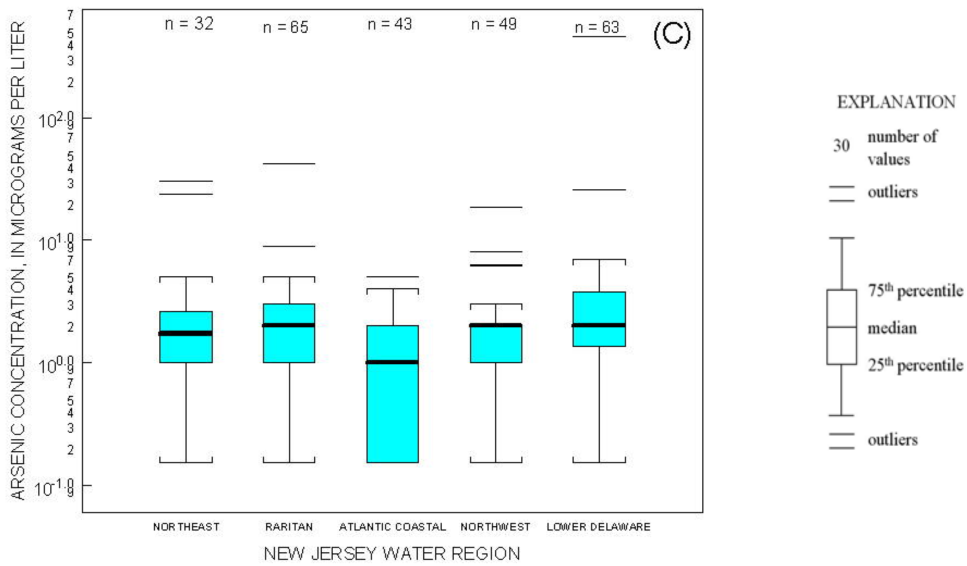
Arsenic occurs primarily as inorganic oxyanions (negatively charged ions that include oxygen) in the environment and is more likely to be in solution at alkaline pHs (Smedley and Kinniburgh, 2002). Ground-water studies conducted in New Jersey have shown that the highest arsenic concentrations are in the Piedmont Physiographic Provinces and are associated with sources in the bedrock material (Serfes, 2000). Ground water discharges to streams. In most cases, during periods of base flow, the streamflow is mainly composed of ground water.

The distribution of maximum arsenic concentrations measured at 256 surface-water-quality sites in New Jersey is shown in figure 5. Six sites exceed the federal MCL of 10 µg/L, which will be effective January 2006 (http://www.epa.gov/safewater/ars/implement.html) (table 1). This MCL was used for model development. Two of these sites are located on the Maurice River in southern New Jersey near a known contamination site that manufactured arsenic-based herbicides from 1950 to 1994 (http://www.epa.gov/region02/superfund/npl/0200209c.pdf). In all, 208 of 256 sites exceed one-tenth of the MCL (table 1).

Results of Kruskal-Wallis univariate statistics for the variables used in the arsenic model are shown in table 2a. Variables with significant Kruskal-Wallis values (a p-value ≤ 0.05) were pH of the water-quality sample and New Jersey Water Region. Arsenic concentrations tend to increase with increasing pH. Figure 4a shows that for water-quality samples with arsenic concentrations greater than 10 µg/L, the pH of the water-quality sample is greater than or equal to 7. New Jersey Water Region is strongly related to arsenic concentration (table 2a). The water regions are based on topographic divides, which are not representative of the geology. Physiographic province was used as a conceptual variable because it represents the variation in geology (figure 6). The boxplot of New Jersey Water Regions shows that arsenic concentrations in water from the Atlantic Coastal and Lower Delaware Water Regions that comprise the Coastal Plain Physiographic Province are statistically different (fig. 4b and 4c). Medians of maximum arsenic concentration at the surface-water-quality sites show that the Lower Delaware Region had higher concentrations than the Atlantic Coastal Region, so the model takes into account that there is a greater potential for elevated arsenic concentrations in the Lower Delaware Region (figure 6). Greensands and clays in the Lower Delaware region are known to contain higher arsenic concentrations (J.L. Barringer, U.S. Geological Survey, written comm., 2002). Distance to nearest agricultural land (1995) is a conceptual variable that is included because of historic use of arsenic-based herbicides. Figure 4d shows that as distance to nearest agricultural land (1995) increases, maximum arsenic concentration decreases. The conceptual variables, physiographic province and distance to agricultural land (1995), are supported by previous scientific investigations and graphs 4b and 4d, respectively. The final arsenic model included the following intensity variable; distance to agricultural land (1995), which is a conceptual variable, and the following sensitivity variables; pH of the water-quality sample, the conceptual variable physiographic province with the Lower Delaware drainage area of the Coastal Plain rated separate from the Atlantic Coastal drainage. The arsenic model was applied to 252 of the 256 surface-water-quality sites with arsenic data; four sites did not have pH data. The arsenic model applied to the 252 sites showed 4 sites were rated low susceptibility, 95 sites were medium susceptibility, and 153 sites were high susceptibility (figs. 6 and 7).


(A)
ARSENIC CONCENTRATION, IN MICROGRAMS PER LITER
pH OF UNFILTERED WATER


(B)
n = 130
n = 47
n = 55
n = 20
ARSENIC CONCENTRATION, IN MICROGRAMS PER LITER
COASTAL PLAIN
HIGHLANDS
PIEDMONT
VALLEY AND RIDGE
PHYSIOGRAPHIC PROVINCE
EXPLANATION
30 number of values
outliers
75th percentile
median
25th percentile
outliers



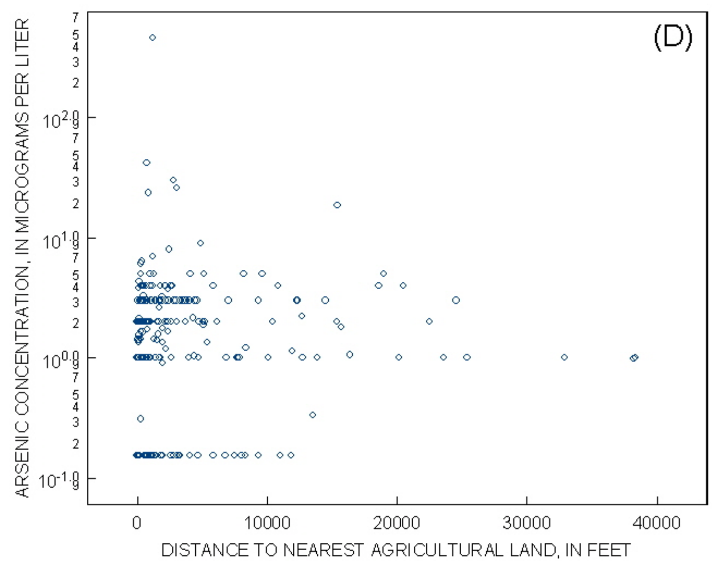


Figure 4. (A) Relation of arsenic concentration to pH of unfiltered water, (B) distribution of arsenic concentration by physiographic province, and (C) New Jersey water region, (D) relation of arsenic concentration to distance to agricultural land for 256 USGS surface-water-quality sites in New Jersey.

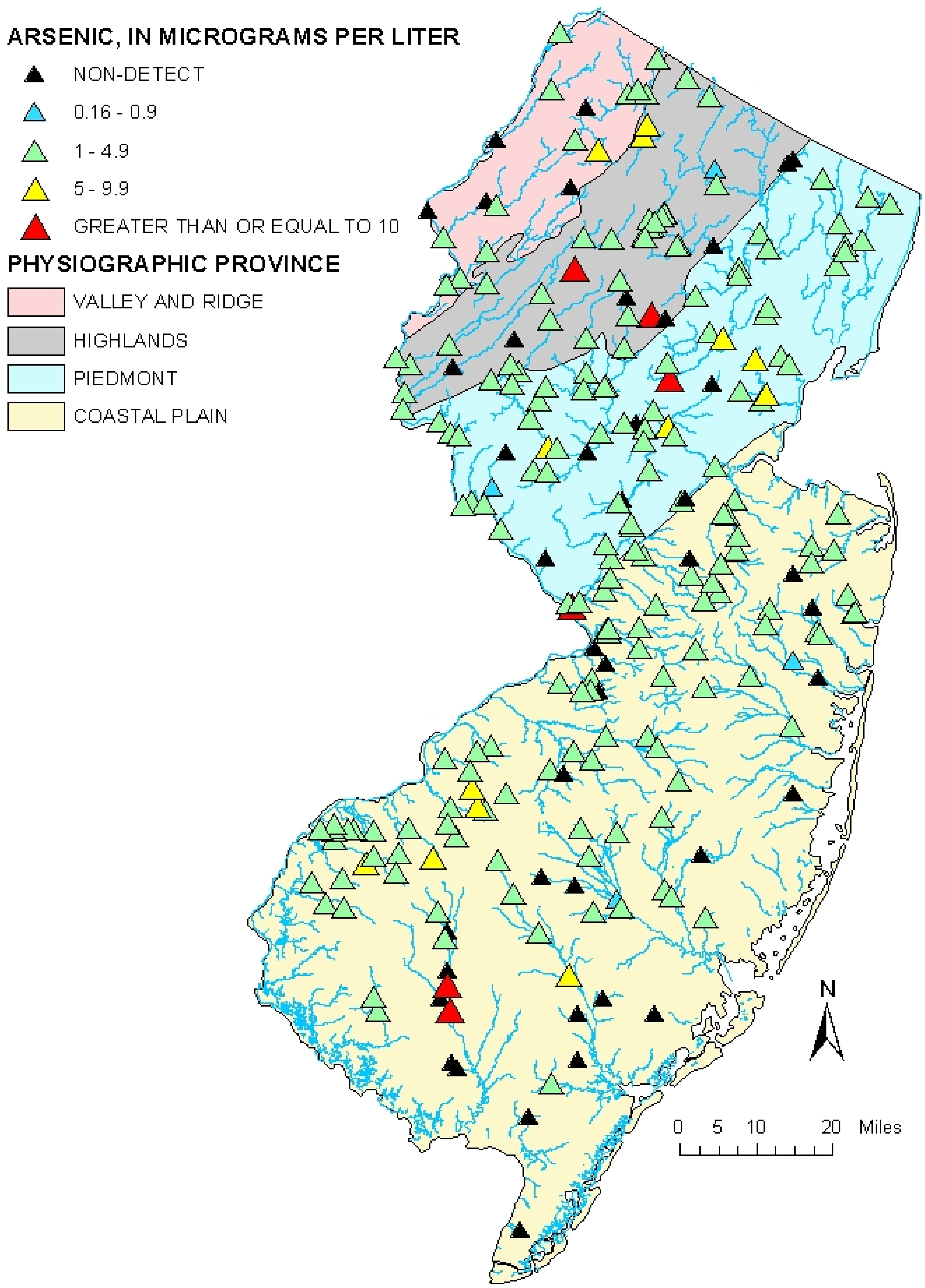


Figure 5. Concentration of arsenic at 256 USGS surface-water-quality sites in New Jersey used for development of arsenic model.

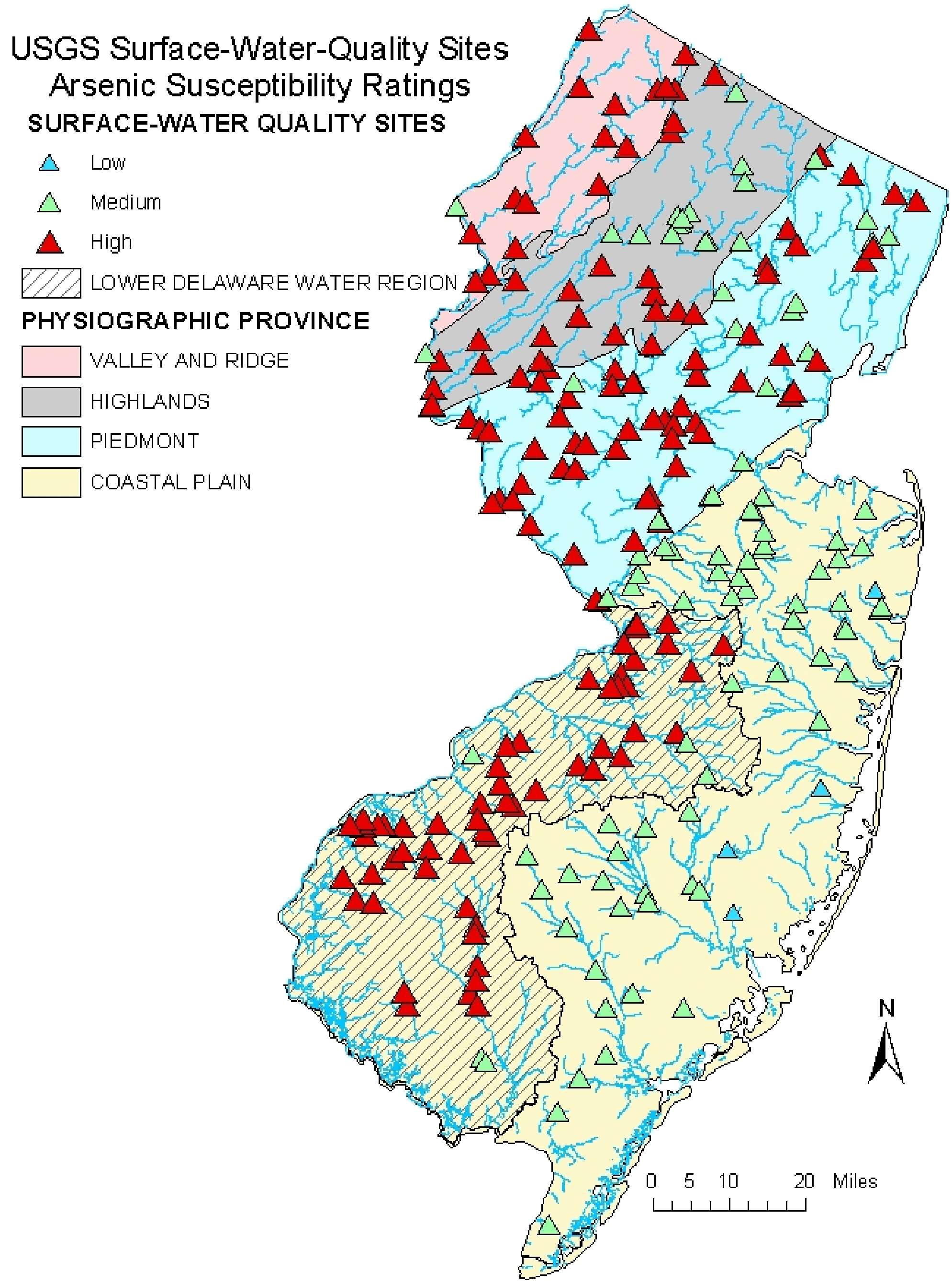


Figure 6. Susceptibility of 252 USGS surface-water-quality sites in New Jersey to contamination by arsenic.

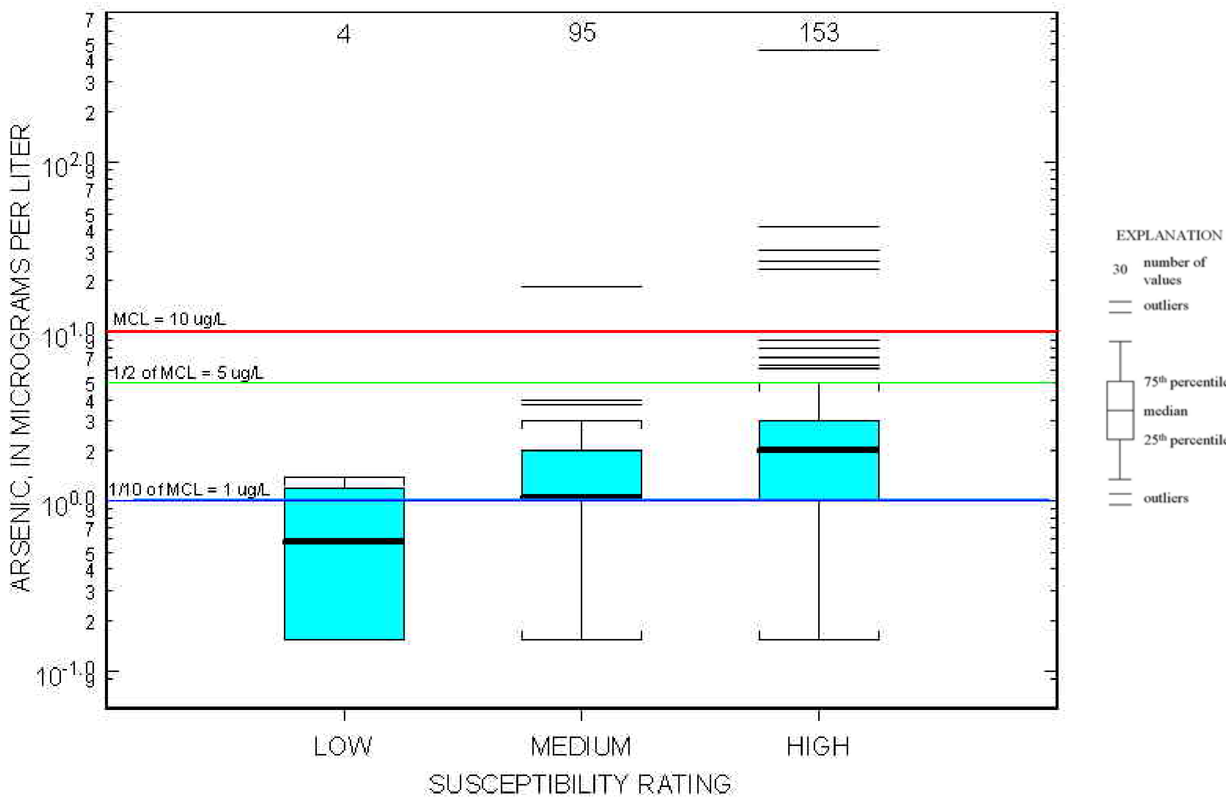


Figure 7. Results of arsenic susceptibility assessment model at 252 USGS surface-water-quality sites in New Jersey showing distribution of arsenic concentration by susceptibility rating.

Lead

Lead can occur naturally from the weathering of sedimentary rocks. Human activities such as smelters, lead-based gasoline and paint, lead pipes, and some plastics have widely dispersed lead into the environment. Results of streambed sediments collected and analyzed for lead during a cooperative study by the USGS and NJDEP show the presence of lead was highest in glaciated materials of the Highlands and Piedmont Physiographic Provinces and concluded that lead distribution was related to population density (O'Brien, 1997).

Lead has a low solubility causing its natural mobility to be low and lead can absorb onto organic and inorganic sediment surfaces. Water having a low pH can dissolve lead from the distribution system where pipes and solder may contain lead. Water with low alkalinity and pH can retain significant concentrations of lead (Hem, 1985).

Maximum lead concentrations in New Jersey are shown at 213 surface-water-quality sites in figure 8. Six sites exceed the Federal action level of 15 µg/L (table 1). These sites can be linked to areas with dense population and other lead related human activities. For lead, 76 sites exceeded one tenth of the action level (table 1).

Results of Kruskal-Wallis univariate statistics for variables used in the lead model are shown in table 2b. Intensity variables that showed a correlation with the lead data are percent urban land (1995) and the density of known contaminated sites (KCSL), solid waste landfills (SWL), NJPDES ground water permits (NJPDES GW), resource recover facilities (SWRRF), transfer facilities (SWTF200011), class B recycling facilities (Class B), discharge prevention containment and countermeasures facilities (DPCC), and underground storage tanks (UST). The scatter plot of percent urban land use versus maximum lead concentration shows lead concentrations increase as percent of urban land (1995) tends to increase (figure 9a). The scatter plot of the density of KCSL, SWL, NJPDES GW, SWRRF, SWTF200011, Class B, DPCC, and UST versus maximum lead concentration shows the lead concentration tends to increase as the number of potential contaminant sites increases (figure 9b). The two sensitivity variables, physiographic province and average percent soil organic matter, are conceptual variables that are supported by graphical and scientific investigations (figures 9c and 9d). The median concentrations of maximum lead values show variation between the four physiographic provinces and relates to differences in geology. Lead adsorbs to organic matter in soil, so as the percent organic matter in soil increases the lead in surface-water should decrease (DeVolder and others, 2003). Evidence of this effect is shown in figure 9d. The lead model applied to 213 sites showed 4 sites were rated low susceptibility, 161 sites were rated medium susceptibility, and 48 sites were rated high susceptibility (figs. 10 and 11).

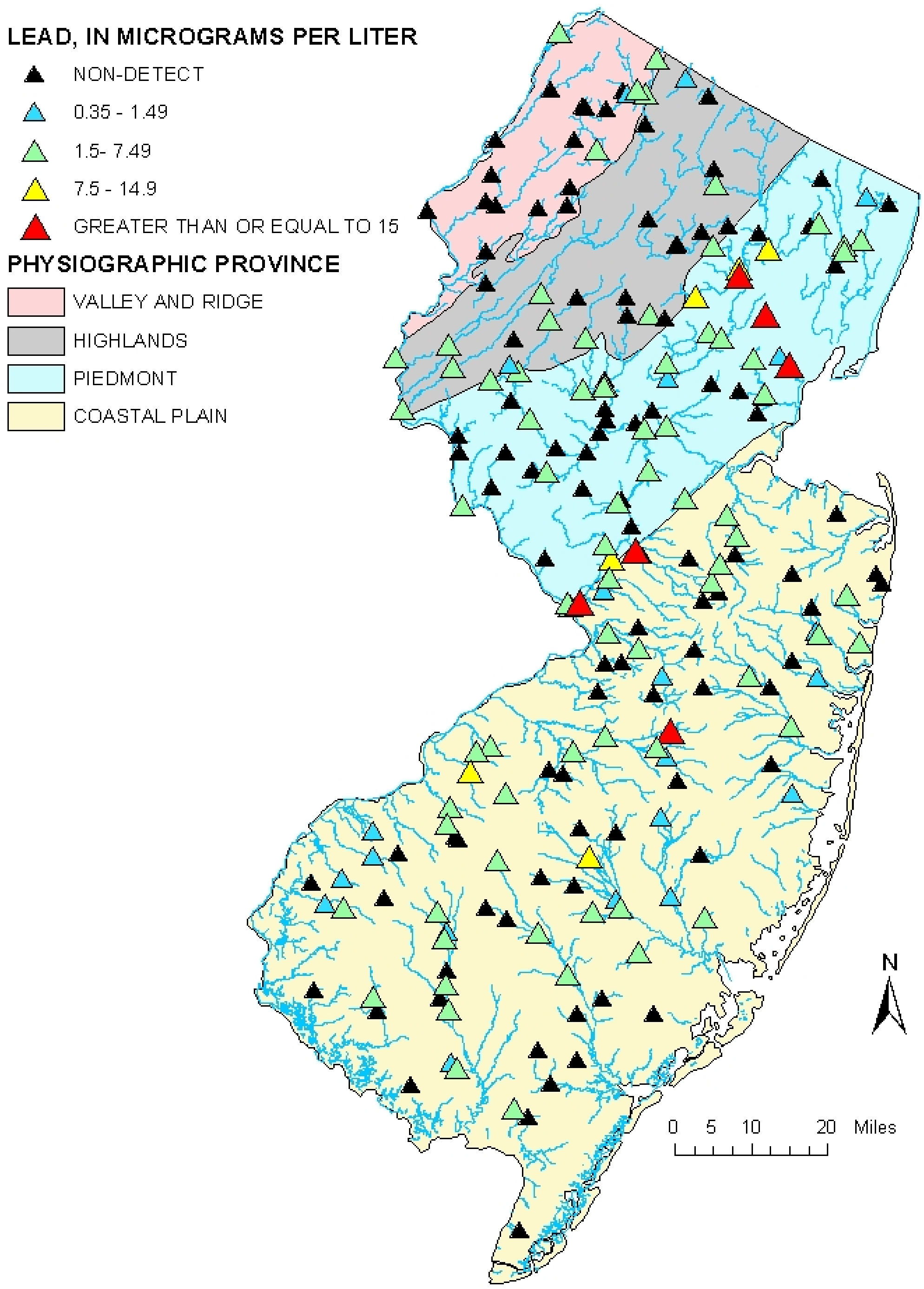
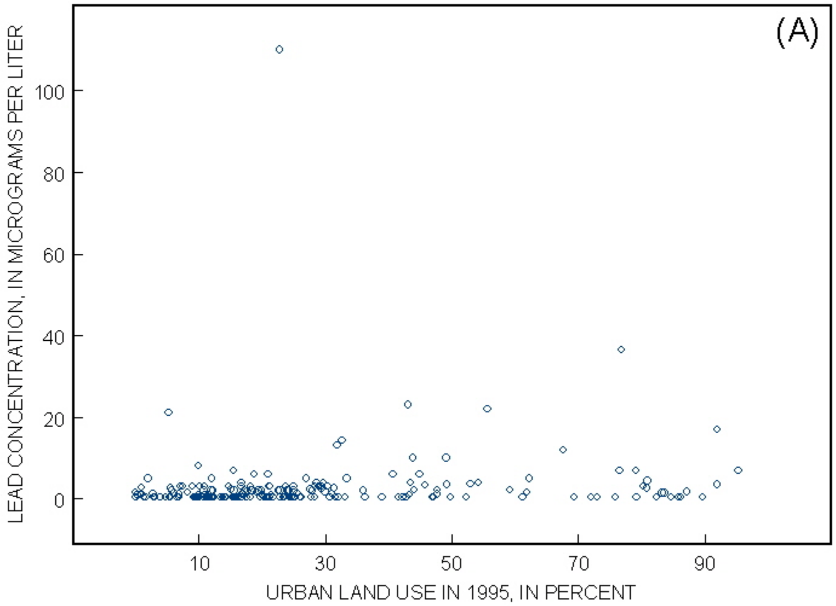
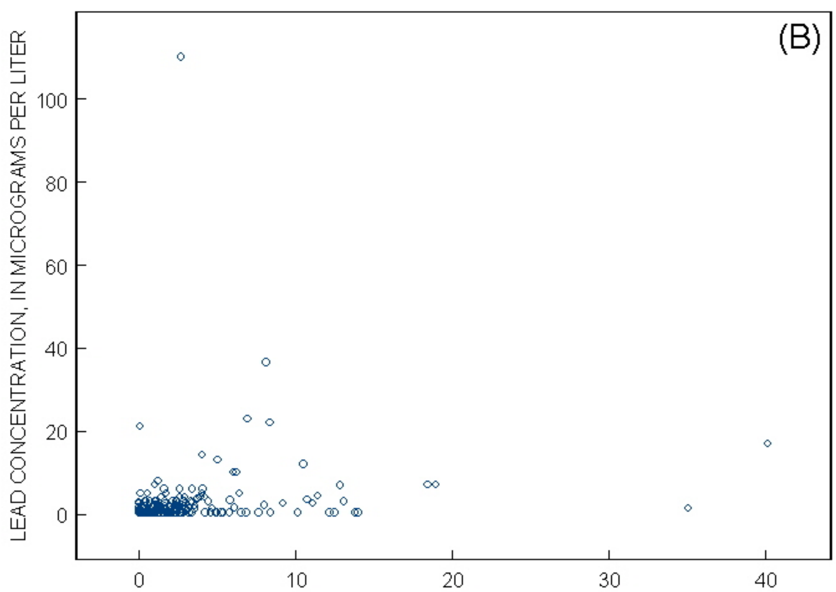
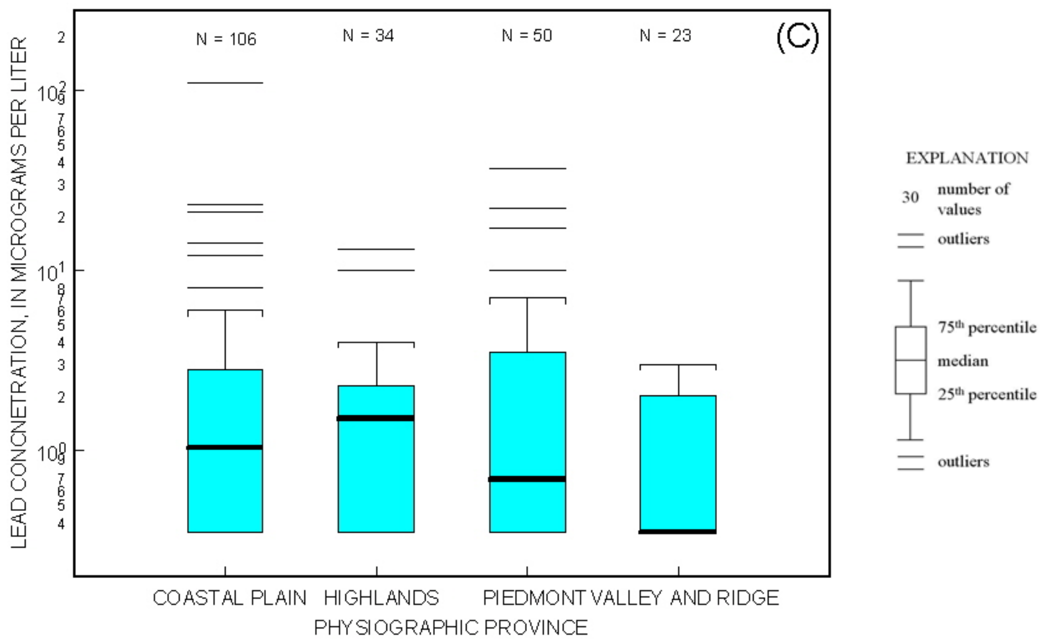


Figure 8. Concentration of lead at 213 USGS surface-water-quality sites in New Jersey used for development of lead model.


(A)
LEAD CONCENTRATION, IN MICROGRAMS PER LITER
0
20
40
60
80
100
10
30
50
70
90
URBAN LAND USE IN 1995, IN PERCENT


(B)
LEAD CONCENTRATION, IN MICROGRAMS PER LITER
0
20
40
60
80
100
0
10
20
30
40
DENSITY OF KCSL, SWL, NJPDES GW, SWRRF, SWTF200011, CLASS B, DPCC, UST PER SQUARE MILE



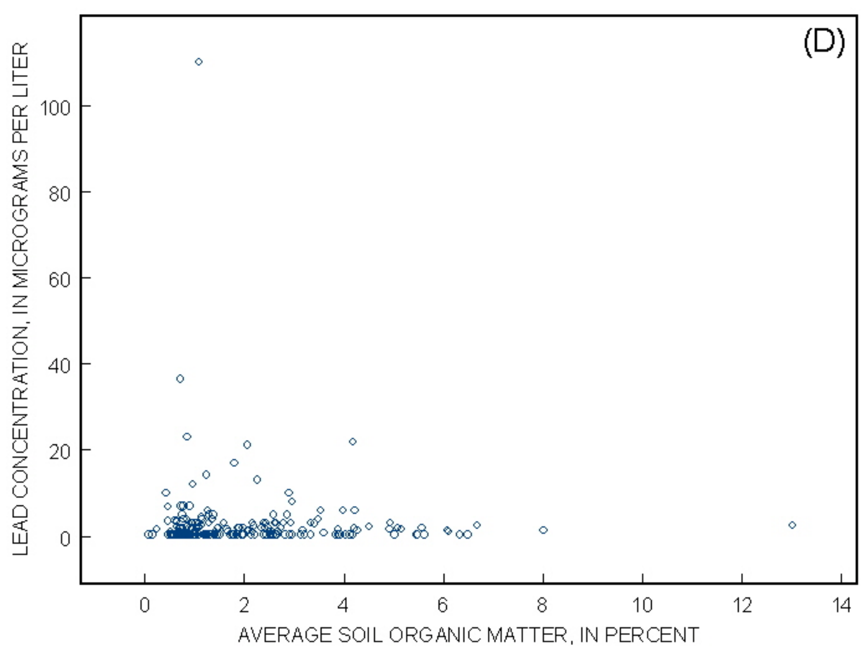


Figure 9. (A) Relation of lead concentration to percent urban land use, 1995, and (B) density of KCSL, SWL, NJPDES GW, SWRRF, SWTF200011, Class B, DPCC, and UST, (C) distribution of arsenic concentration by physiographic province, and (D) relation of lead concentration to percent average soil organic matter.

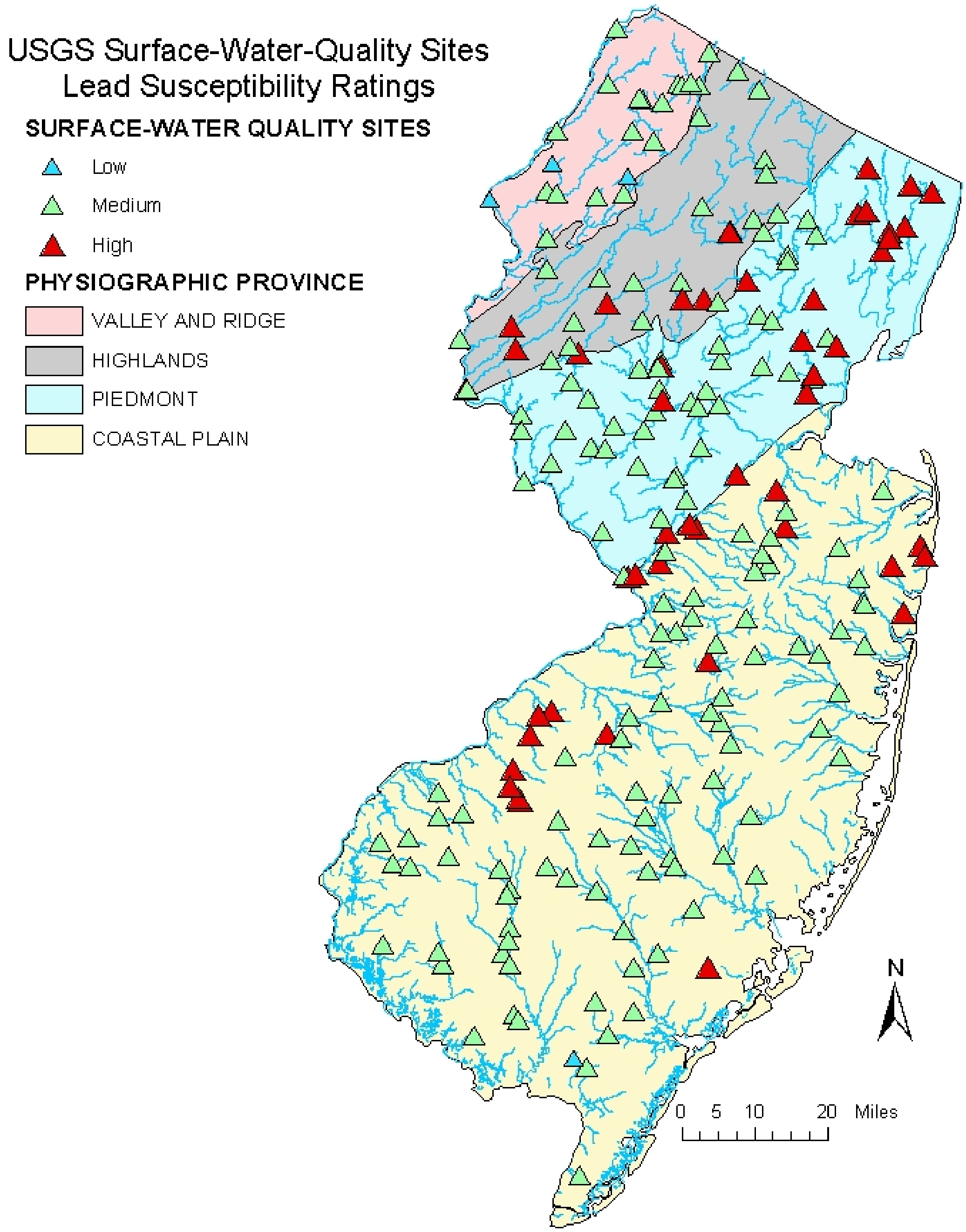


Figure 10. Susceptibility of 213 USGS surface-water-quality sites in New Jersey to contamination by lead.

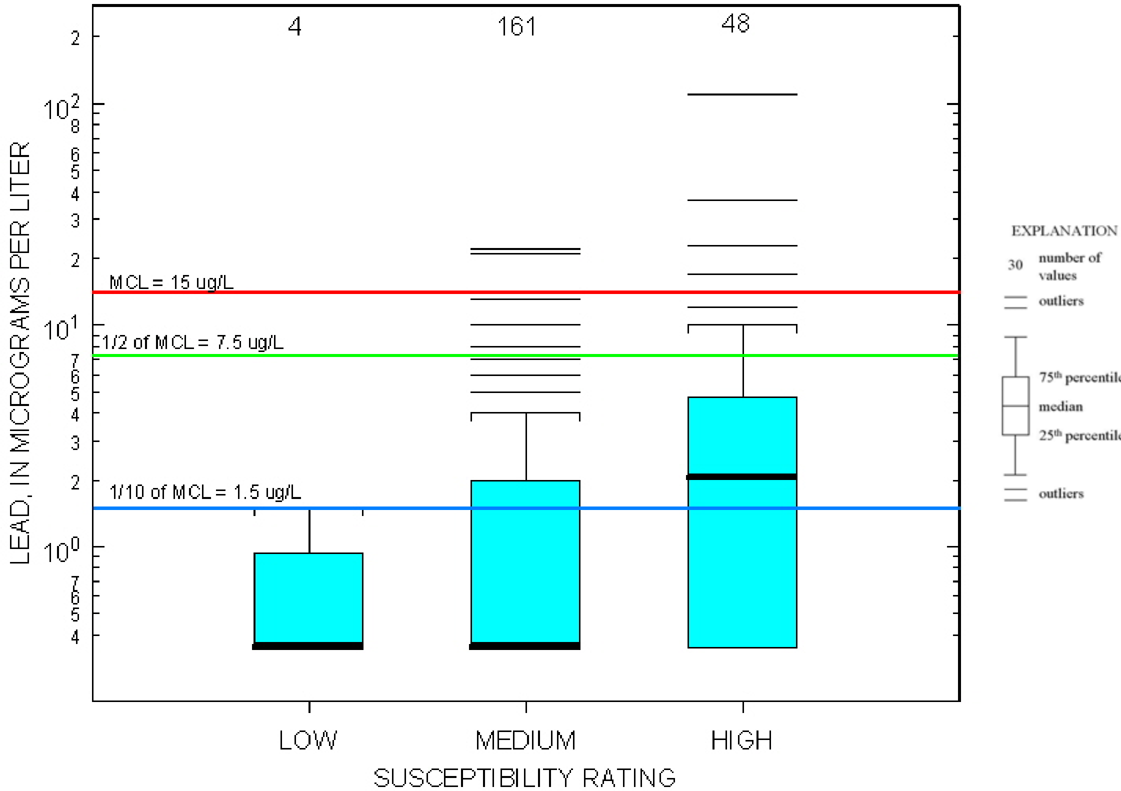


Figure 11. Results of lead susceptibility assessment model at 213 USGS surface-water-quality sites in New Jersey to contamination by lead.

Fluoride

Fluoride can be both naturally occurring and from human activities. Fluoride can be found in both igneous and sedimentary rock (Hem, 1985). Fluoride is introduced into the environment from activities such as aluminum smelting, commercial phosphate fertilizers, coal combustion, glass etching, steel manufacturing, and fluoridation of water supplies. The USEPA has effluent limit guidelines for fluoride that originates from the cleaning of the interiors of transportation containers, iron and steel manufacturing, and metal finishing facilities (USEPA, 1998, 2000, 2001).

The distribution of maximum fluoride concentration at 338 surface-water-quality sites in New Jersey is shown in figure 12. The MCL of 4 mg/L was not exceeded in any samples analyzed and only 43 sites exceed one tenth of the MCL (table 1).

Results of Kruskal-Wallis univariate statistics for variables used in the fluoride model are shown in table 2c. Graphs of fluoride concentrations in relation to model explanatory variables are shown in figure 13. Laboratory reporting of fluoride data rounds values to the nearest one-tenth of a milligram per liter and as a result the data is discretized. The percent of developed land (1995), urban and agricultural land (1995) combined, was not significant with a p-value >0.05, but the scatter plot indicates that as developed land (1995) increases, the maximum fluoride concentration also increases (figure 13a). Percent developed land (1995) is a conceptual variable that can be representative of the phosphate fertilizer, of which fluoride is an impurity, applied to agricultural land and also includes the many urban components of fluoride sources. The density of NJPDES SW, NJPDES storm, and composting facilities was statistically significant (table 2c and figure 13b). Fluoride concentrations tend to increase with increasing density of NJPDES SW, NJPDES storm, and composting facilities. The presence of sewage treatment plant discharges in NJPDES SW represents the fluoride present in water from fluoridation and various forms of human consumption. Percent commercial-industrial land (1995) was a conceptual variable that is supported graphically and is supported by previous scientific investigations. Only one model variable, density of NJPDES SW, NJPDES storm, and composting facilities, was statistically significant. Including percent commercial-industrial land (1995) as a conceptual variable helped improve the overall strength of the model. The scatter plot shows a general increase in maximum fluoride concentrations as percent commercial-industrial land (1995) increases, which may represent the manufacture of products that contain fluoride or sites with fluoride emissions (figure 13c). Fluoride tends to bind to organic matter in soils (Kaiser and Guggenberger, 2001). Results of the Kruskal-Wallis test for average percent soil organic matter shows the p-value just exceeds 0.05, it is considered a conceptual variable. The scatter plot shows as average soil organic matter increases, maximum fluoride concentration in surface-water samples decreases (figure 13d). The intensity variables in the fluoride model are the conceptual variable percent of developed land (1995), density of NJPDES SW, NJPDES storm, and composting facilities, and conceptual variable percent commercial-industrial land (1995). The sensitivity variable that is also a conceptual variable is average percent soil organic matter. The fluoride model applied to the 338 sites showed 261 sites were rated low susceptibility and 77 sites were rated medium susceptibility (figs. 14 and 15). There are no sites rated as high susceptibility because fluoride concentrations did not exceed one-half of the MCL.

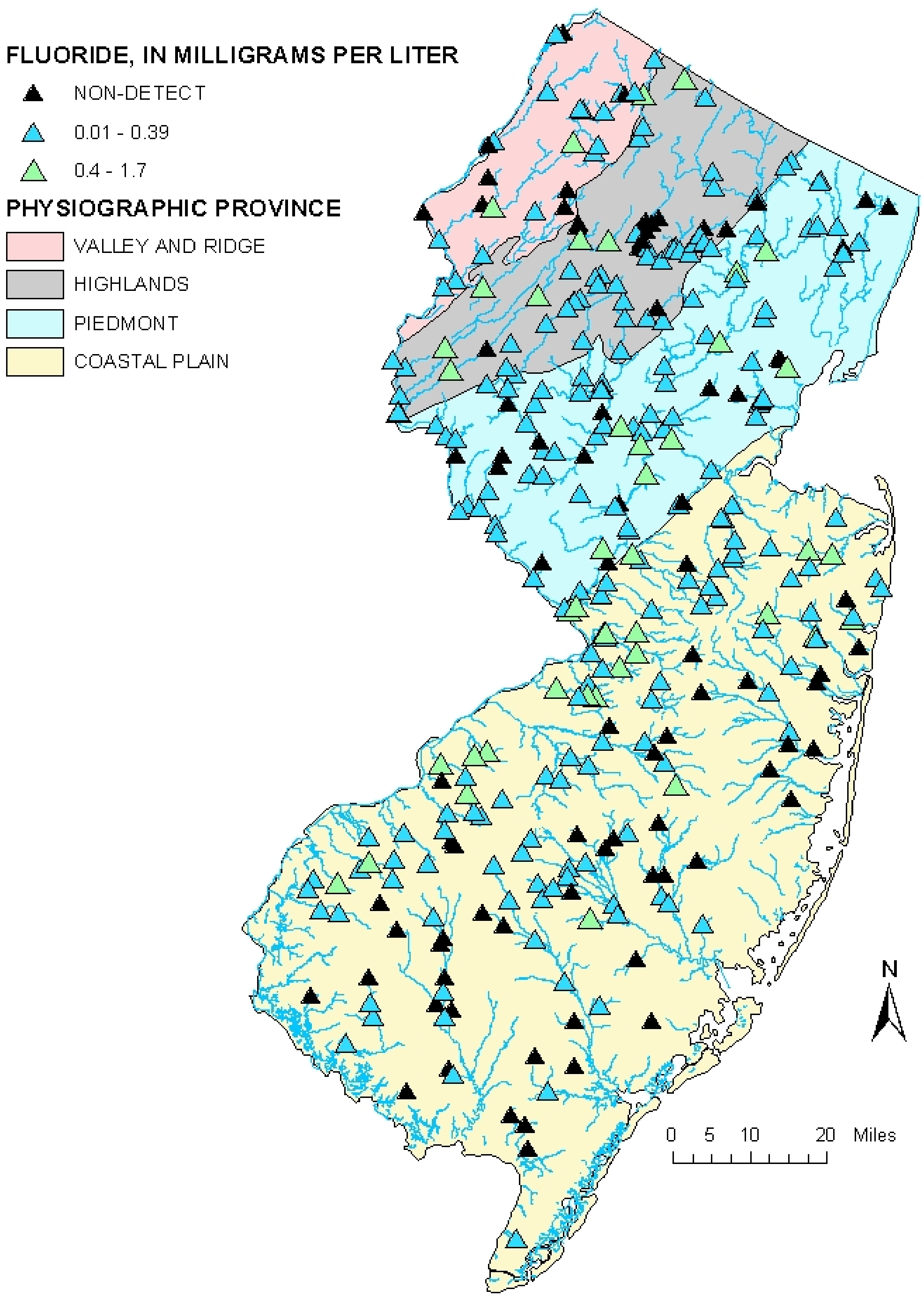
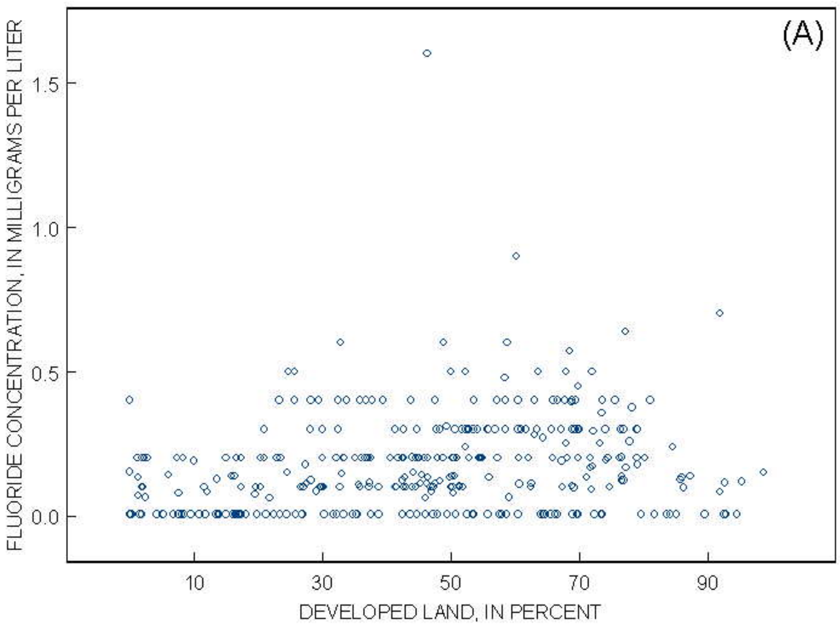
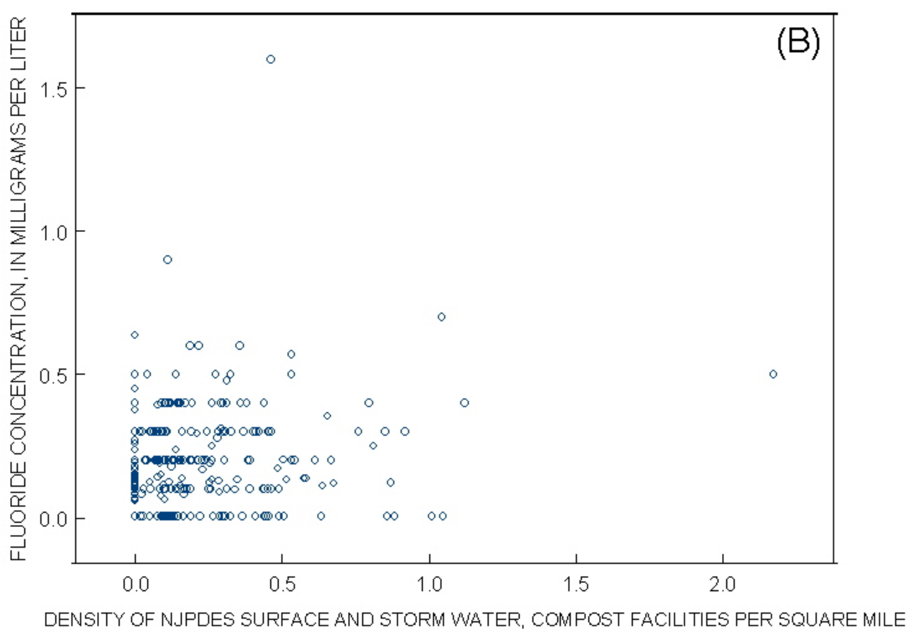
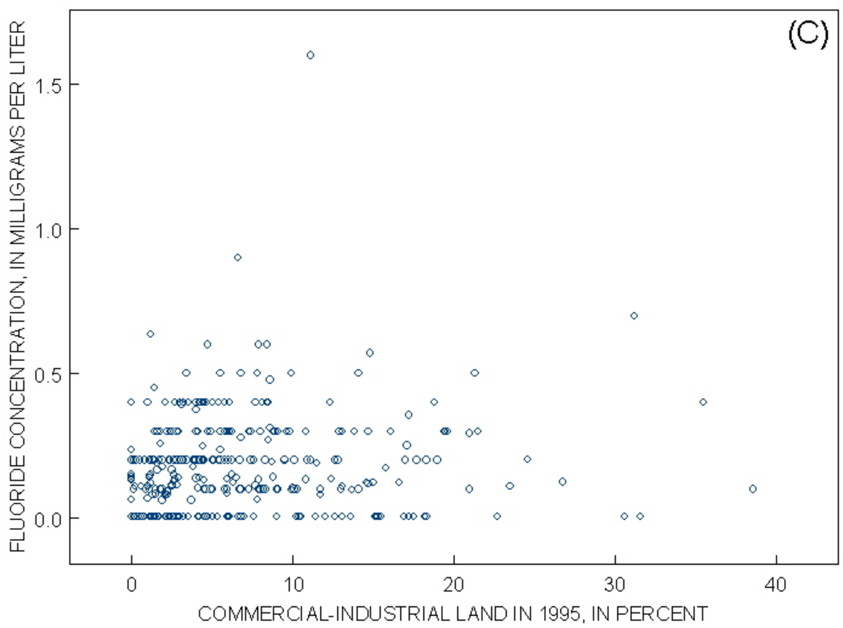


Figure 12. Concentration of fluoride at 338 USGS surface-water-quality sites in New Jersey used for development of fluoride model.


(A)
FLUORIDE CONCENTRATION, IN MILLIGRAMS PER LITER
0.0
0.5
1.0
1.5
10
30
50
70
90
DEVELOPED LAND, IN PERCENT


(B)
FLUORIDE CONCENTRATION, IN MILLIGRAMS PER LITER
0.0
0.5
1.0
1.5
0.0
0.5
1.0
1.5
2.0
DENSITY OF NJPDES SURFACE AND STORM WATER, COMPOST FACILITIES PER SQUARE MILE



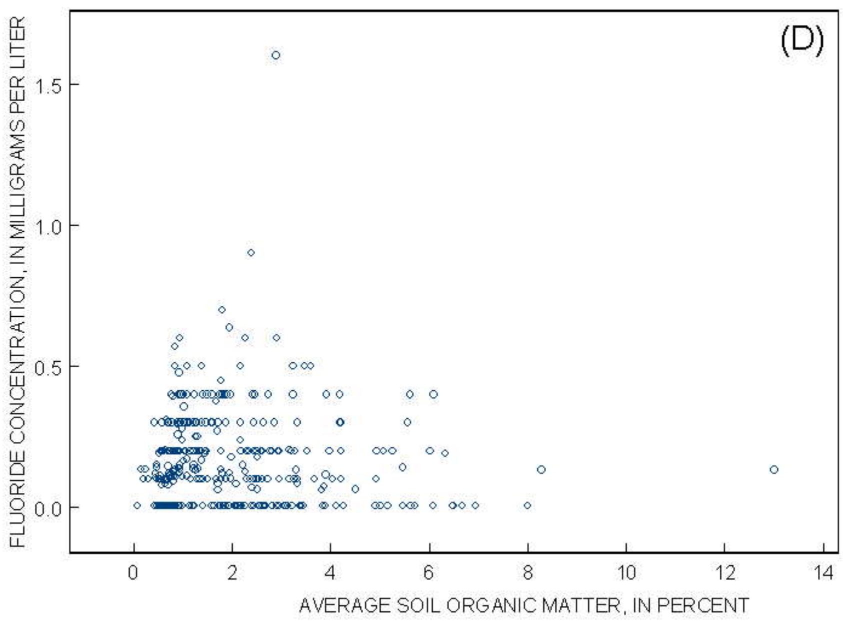


Figure 13. (A) Relation of fluoride concentration to percent developed land in 1995, (B) density of NJPDES SW, NJPDES Storm, and compost facilities, (C) percent commercial-industrial land in 1995, (D) percent average soil organic matter for 338 USGS surface-water-quality sites in New Jersey.

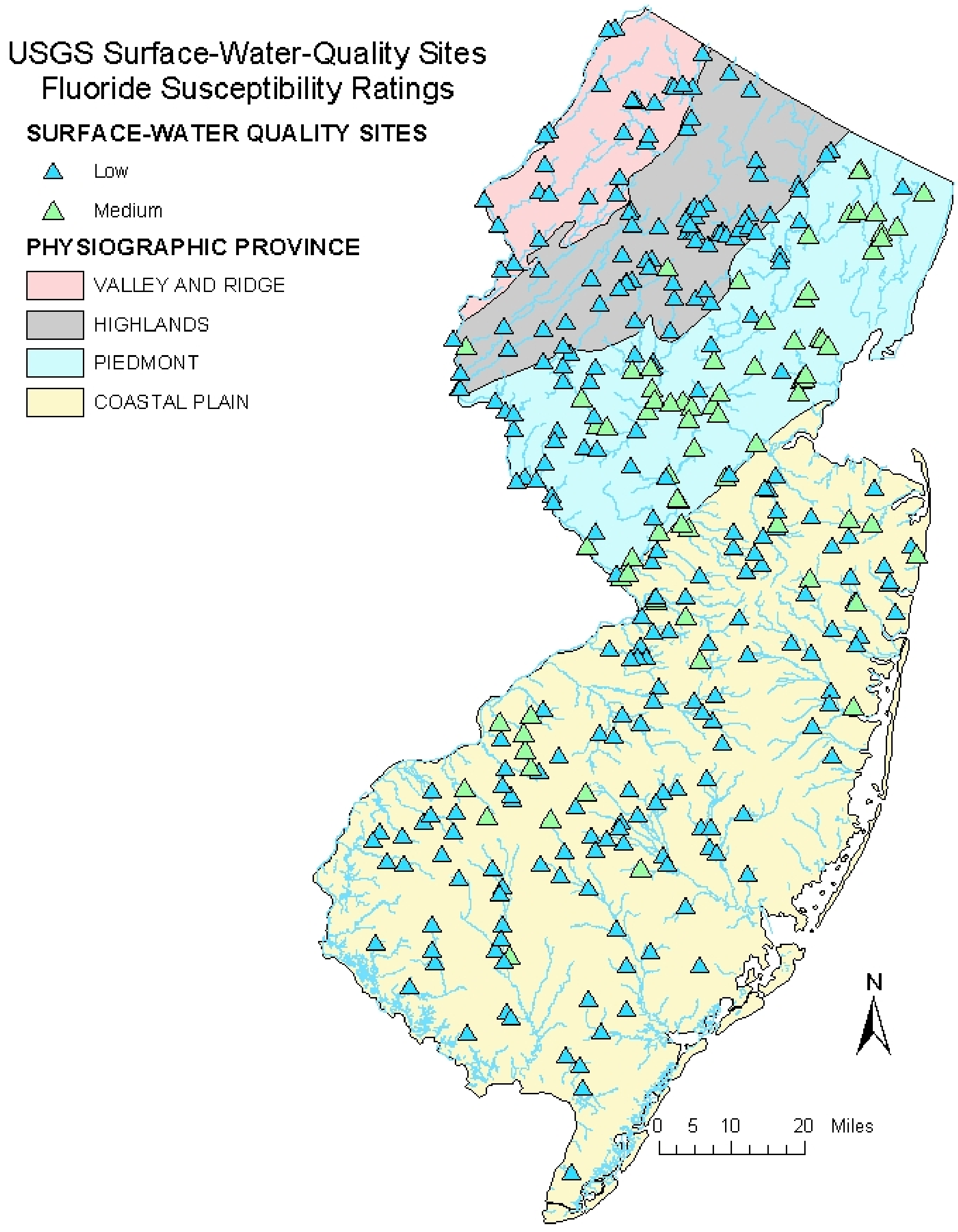


Figure 14. Susceptibility of 338 USGS surface-water-quality sites in New Jersey to contamination by fluoride.

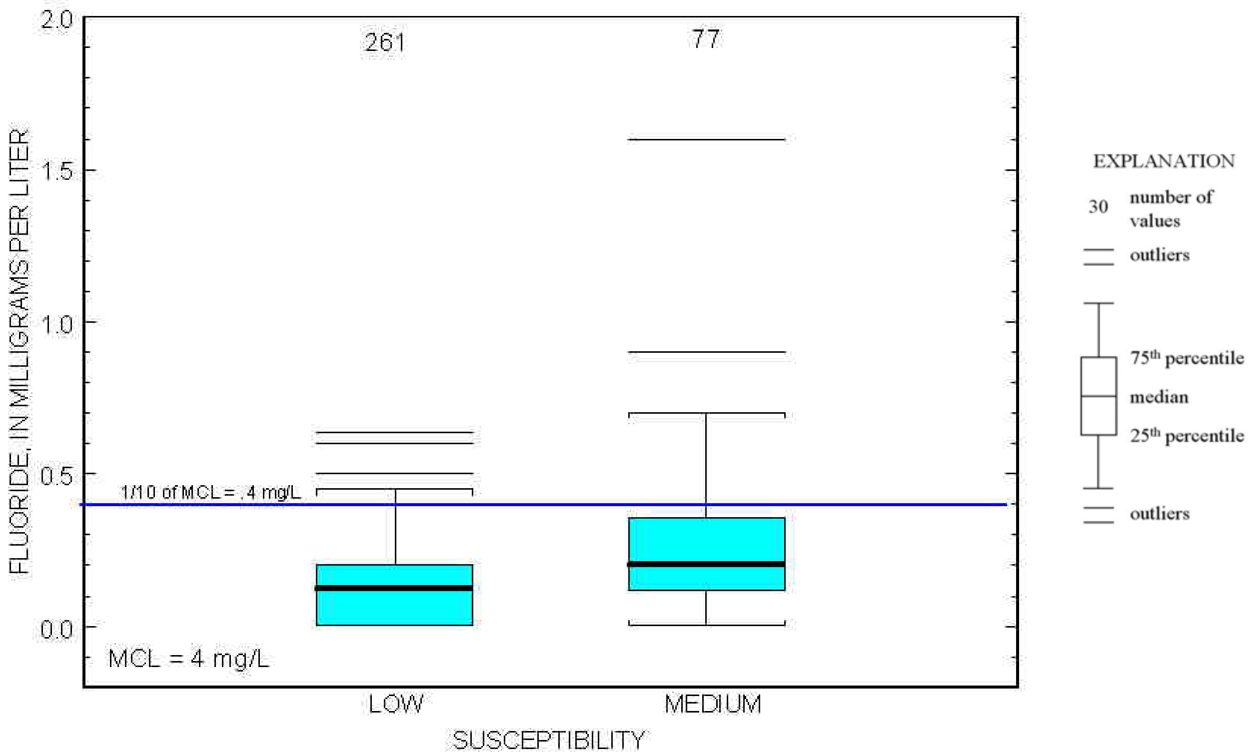


Figure 15. Results of fluoride susceptibility assessment model at 338 USGS surface-water-quality sites in New Jersey showing distribution of fluoride concentration by susceptibility rating.

Susceptibility of Surface-Water Sources

The rating schemes created during the arsenic, lead, and fluoride model development were applied to the sensitivity and intensity variables of each GWUDI and surface-water intake. The sensitivity and intensity variable scores were added to yield a susceptibility assessment rating at a source for each of the three inorganic constituents. The rating is designated as low, medium, or high susceptibility to contamination in relation to one-tenth of, one-half of, and the maximum contaminant level. The arsenic model used pH of the water-quality sample at USGS surface-water-quality sites as a sensitivity variable. This variable was not available for GWUDI and surface-water intakes. For arsenic model application, this variable was estimated by using the pH of the water-quality sample from the nearest USGS surface-water-quality site upstream from the GWUDI or surface-water intake.

Application of the arsenic model estimated 7 GWUDI as having medium susceptibility, 4 GWUDI as having high susceptibility, 17 intakes as having medium susceptibility, and 32 intakes as having high susceptibility to contamination by arsenic (figs. 16 and 17). Application of the lead model estimated 1 GWUDI as having low susceptibility, 7 GWUDI as having medium susceptibility, 3 GWUDI as having high susceptibility, 2 intakes as having low susceptibility, 36 intakes as having medium susceptibility and 11 intakes as having high susceptibility to contamination by lead (figs. 18 and 19). Application of the fluoride model estimated 9 GWUDI as having low susceptibility, 2 GWUDI as having medium susceptibility, 36 intakes as having low susceptibility, and 13 intakes as having medium susceptibility to contamination by fluoride (figs. 20 and 21).

The final susceptibility assessment rating at a surface-water source for the inorganic constituent group is the highest susceptibility assessment rating of the three individual inorganic ratings. The results of the inorganic model estimated that for 11 GWUDI, zero was in the low group, 5 were in the medium group, and 6 were in the high group. For the 49 intakes, zero was in the low group, 9 were in the medium group, and 40 were in the high group (figs. 1 and 2). The final inorganic contaminant model indicates that 5 surface-water sources in the Coastal Plain, 3 in the Piedmont, 6 in the Highlands, and zero in the Valley and Ridge Physiographic Province are in the medium susceptibility group and 13 surface-water sources in the Coastal Plain, 19 in the Piedmont, 8 in the Highlands, and 6 in the Valley and Ridge Physiographic Province are in the medium susceptibility group. There are no intakes in the low susceptibility group for the inorganic constituent model.

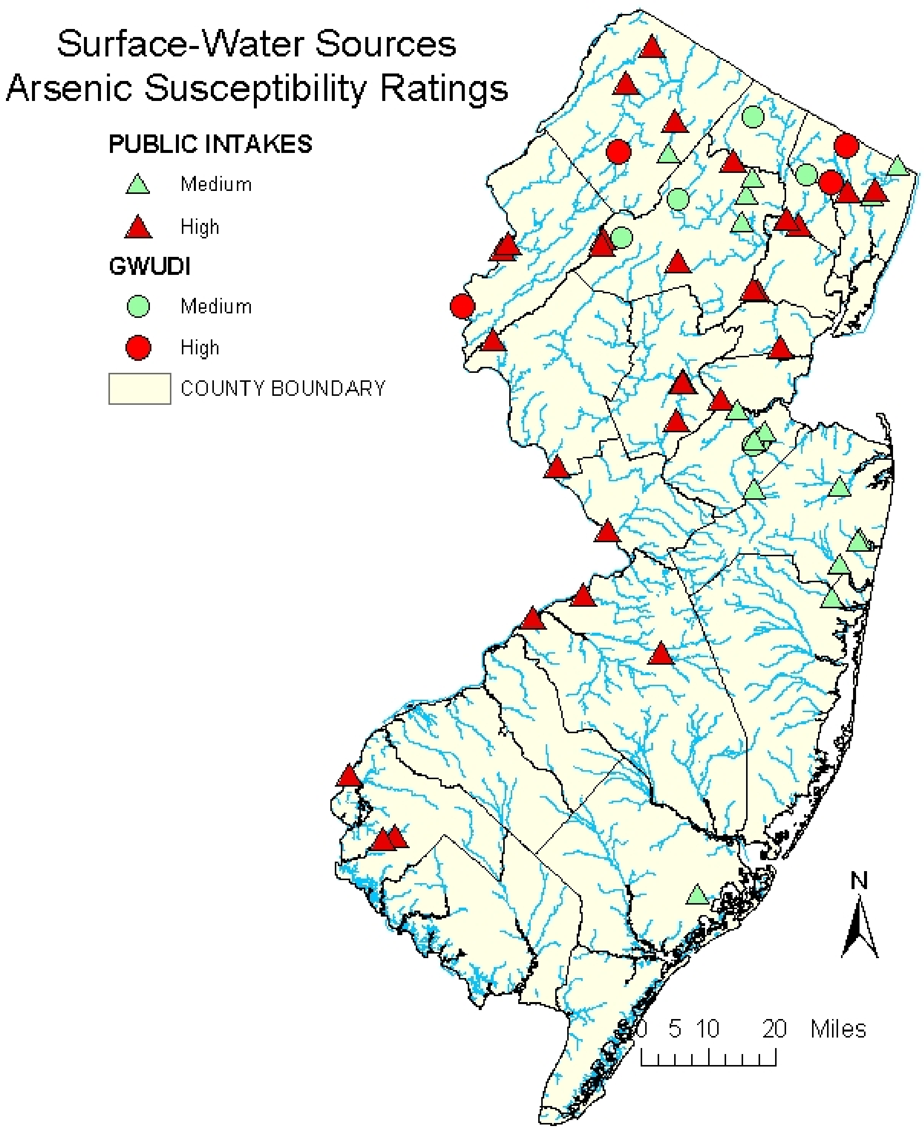


Figure 16. Susceptibility of 60 surface-water sources in New Jersey to contamination by arsenic.

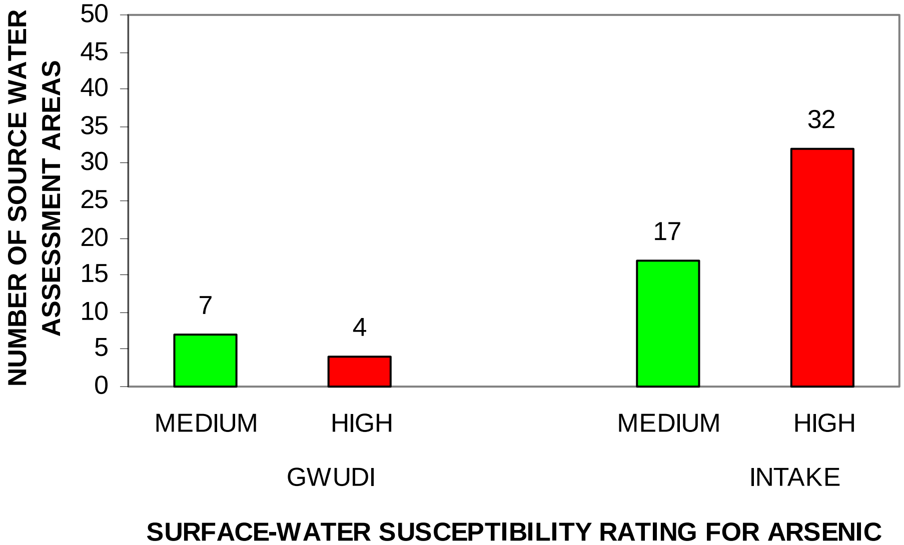


Figure 17. Number of water-supply intakes and related wells in New Jersey having medium and high susceptibility to contamination by arsenic.

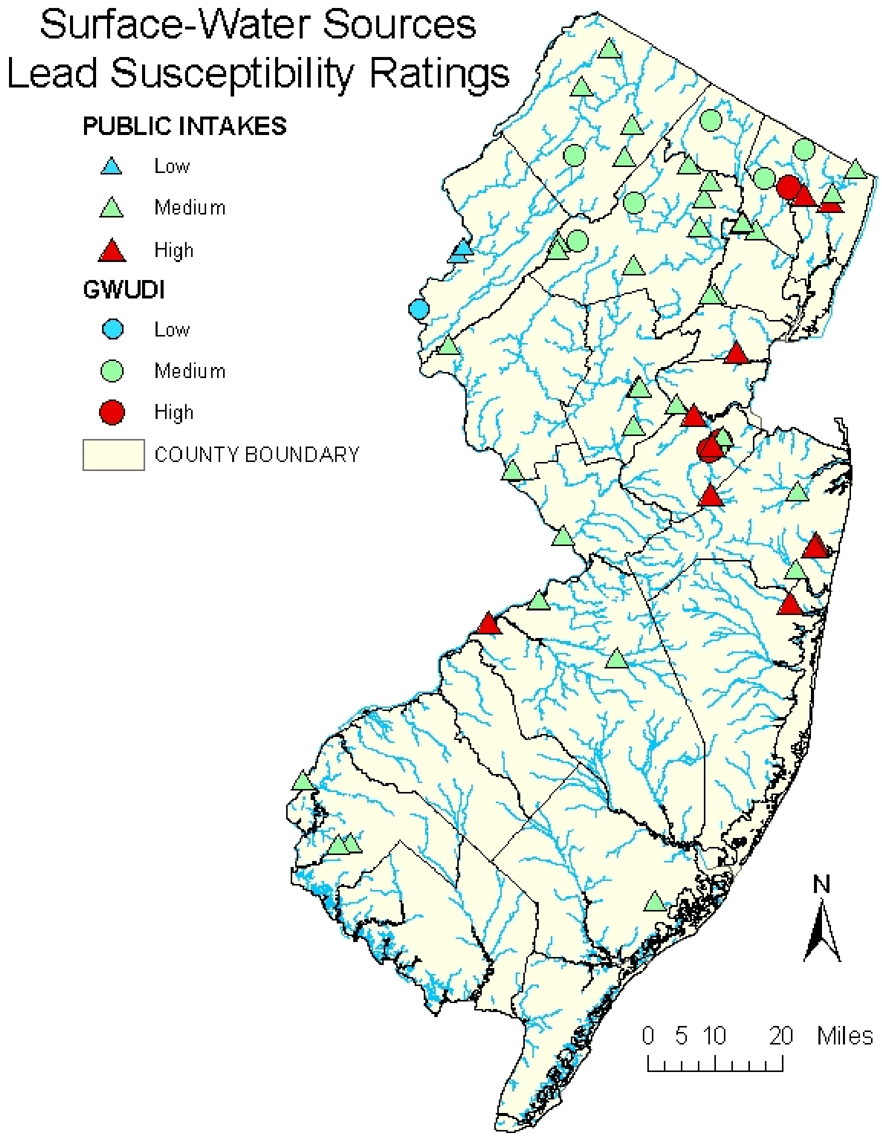


Figure 18. Susceptibility of 60 surface-water sources in New Jersey to contamination by lead.

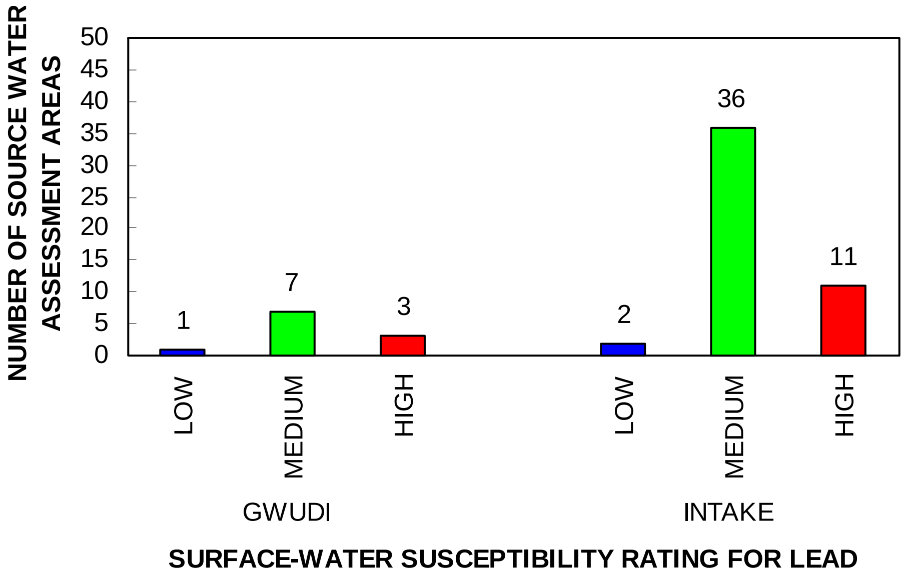


Figure 19. Number of water-supply intakes and related wells in New Jersey having low, medium, and high susceptibility to contamination by lead.

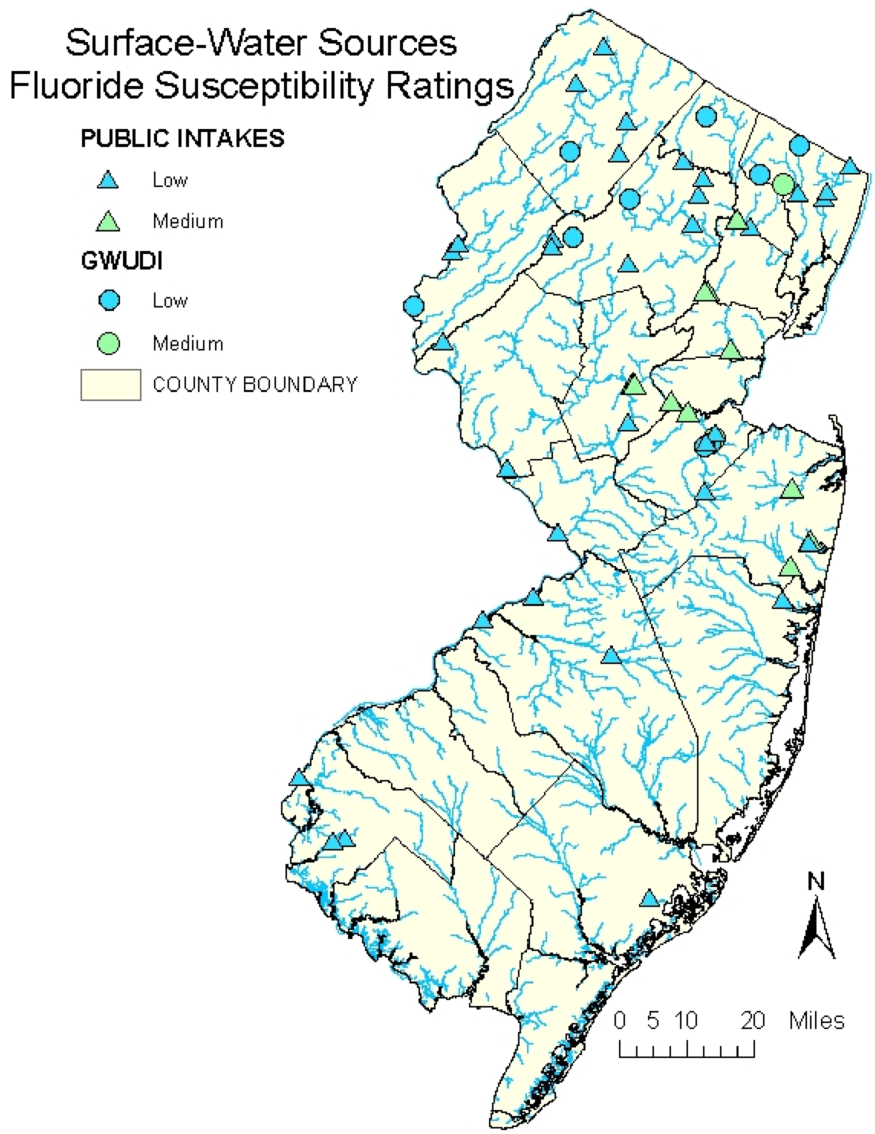


Figure 20. Susceptibility of 60 surface-water sources in New Jersey to contamination by fluoride.

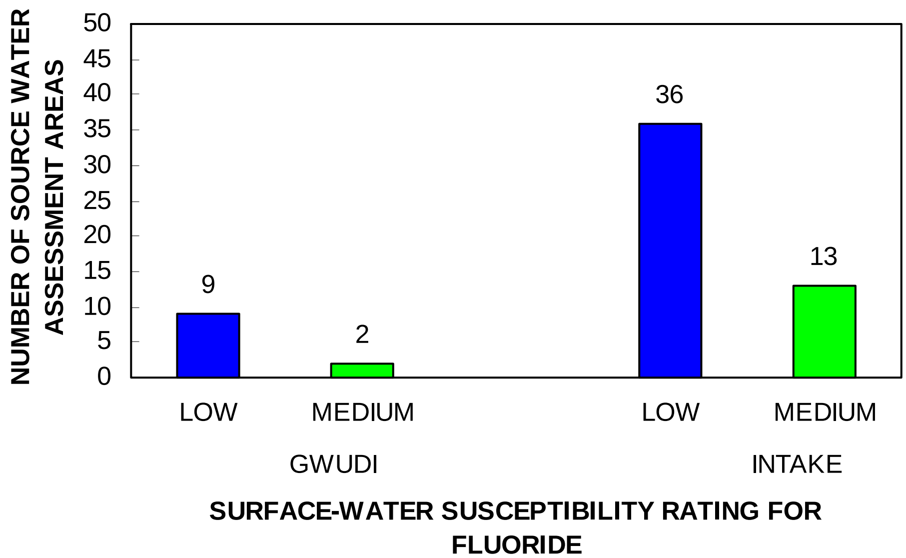


Figure 21. Number of water-supply intakes and related wells in New Jersey having low and medium susceptibility to contamination by fluoride.

Discussion

There are several limitations to the susceptibility assessment models. These models should be used only as screening tools to assess the potential susceptibility of a surface-water source to contamination from regulated constituents. The maximum concentrations in samples from a surface-water site were used in the analysis to develop models and do not take into account fluctuations in concentrations that may occur. Some of the components of the analysis were subjective, especially the coding scheme used for the susceptibility assessment model. Problems may exist in the interpretation of data at a local scale and projecting to statewide scales. Using different scales for various GIS layers could bias statistical results and land-use changes could cause spurious relations. The method used to determine source water assessment areas for intakes with large contributing areas that represent times of travel of water to the intake is inexact, and produces only estimates of the areas that may affect the water quality at the intake. Significant susceptibility factors can change with time and additional water-quality data can be used in the future to update the models.

Statistics were run on grouped constituent values and at a level below the threshold of concern of the NJDEP and may not produce the same results as statistics that were run for 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 assessment area.

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

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