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

Summary

A susceptibility assessment model was developed to predict the susceptibility of source water to community water-supply (CWS) wells in New Jersey to contamination by pathogens. Susceptibility is defined by variables describing hydrogeologic sensitivity and potential contaminant-use intensity within the area contributing water to a well. The model was developed by using water-quality data from ground-water samples collected and analyzed by the U.S. Geological Survey. The model was calibrated using results of analyses at 24 sites for coliform bacteria. Wells in or near agricultural areas were more likely to have coliform bacteria present than wells in other areas. The presence and concentration of coliform bacteria in samples likely are also related to density of septic systems within the area contributing water to wells. Variables used to estimate susceptibility to contamination by pathogens are average soil available water capacity (conceptual), depth to top of open interval, distance to agricultural land, septic density per square mile (conceptual), GWUDI designation (conceptual), and presence of surface water within tier 1 (conceptual). Of the 2,237 community water-supply wells, the susceptibility to contamination by pathogens was low for 1,251 (56 percent), medium for 892 (40 percent), and high for 94 (4 percent) (figs. 1 and 2). Susceptibility ratings for pathogens were highest in the Highlands and the Valley and Ridge Physiographic Province.

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 pathogens, (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 wells in New Jersey.

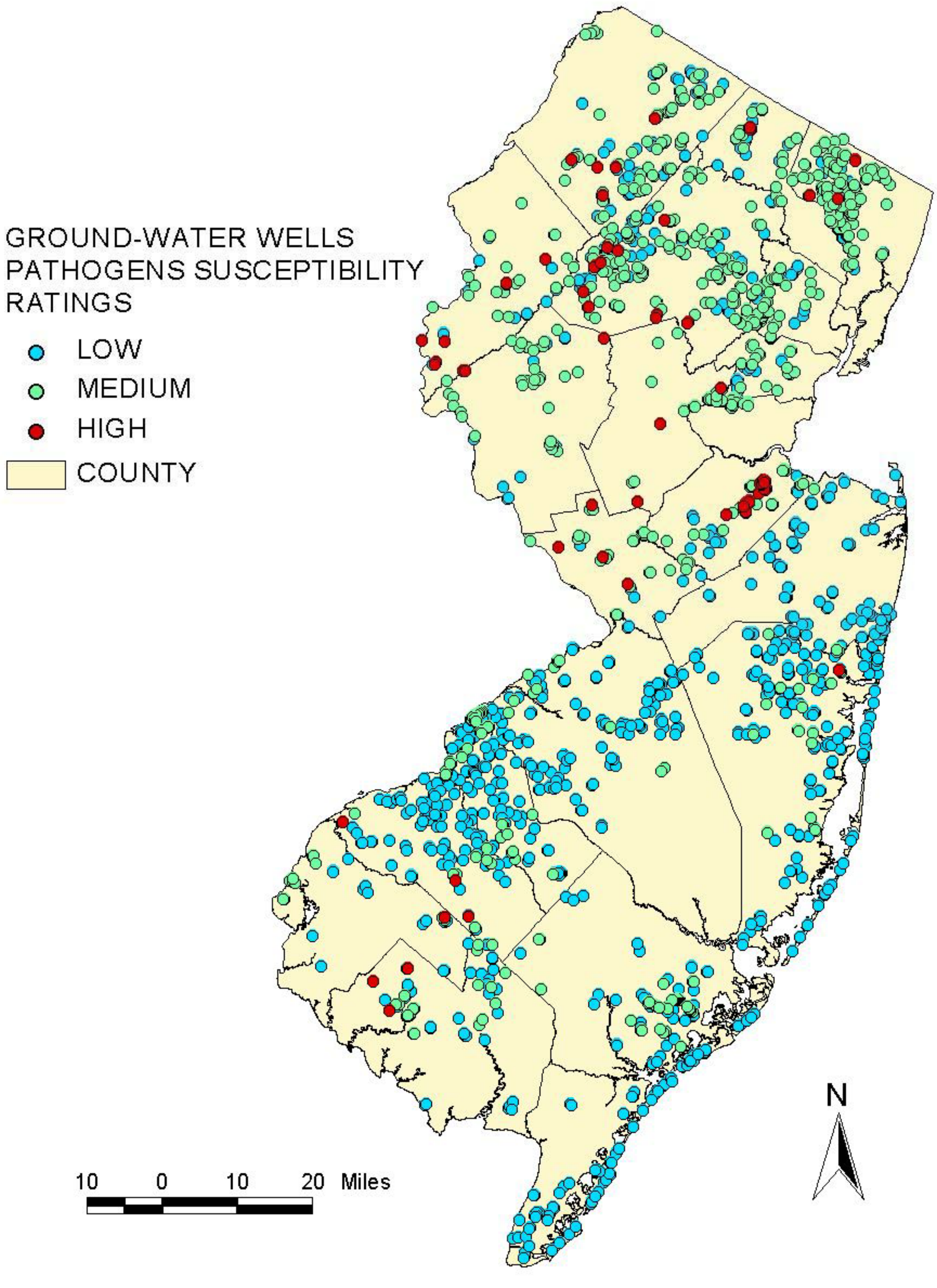

Figure 1. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by pathogens.

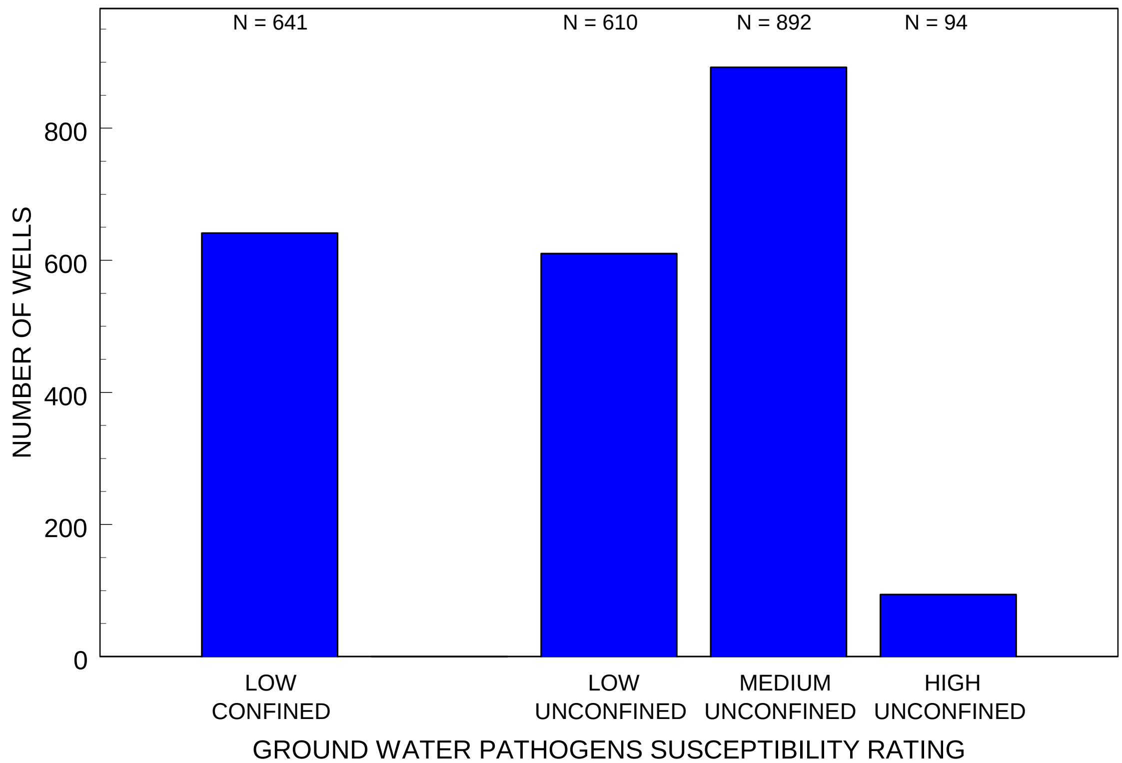

Figure 2. Number of community water-supply wells in New Jersey having low, medium, and high susceptibility to contamination by pathogens.

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. In the case of pathogens, contaminant intensity does not represent actual use of these contaminants, but instead represents potential sources of pathogens such as the application of manure on agricultural land, septic system discharge in rural areas without sewage treatment facilities, and discharge to surface water from sewage treatment facilities.

Susceptibility = Hydrogeologic Sensitivity + 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 pathogens or pathogen indicators are not likely to be detected, and the medium- and high- susceptibility categories includes wells for which pathogens or pathogen indicators are more likely to be detected. The susceptibility ratings for the pathogens constituent group are based on the presence or absence of coliform bacteria in water samples, which was used to represent pathogens with Maximum Contaminant Levels (MCL's). Results of analyses of water samples for pathogen indicators are reported in colonies per 100 mL; however, these values were used only for mapping purposes and Spearman's rho statistical tests.

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 model; and (5) assessment of relations of the constituents to model variables. An independent data set was not available to verify the model. Multiple lines of evidence were used to select the final variables used in the model.

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. Results of analyses for pathogen indicators were not available for any community or noncommunity water-supply wells; consequently, these source water assessment areas could not be used to develop the pathogens model.

Areas contributing water to 1,861 domestic, irrigation, and other types of wells in New Jersey were generated by using a GIS to determine a 500-meter buffer around each well (R.J. Baker, U.S. Geological Survey, written commun., 2003). Results of analyses for pathogen indicators were available for only 24 of these wells. The pathogens model was developed by using source water assessment areas and water-quality data from these wells.

Figure 3. Example of delineated 500-meter buffer surrounding a well showing land use, potential contaminant sources, and roads.

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. For CWS wells, the variables were calculated for each of the three ground-water tiers and for the entire source water assessment area for wells open to unconfined aquifers. The variables were calculated for the entire source water assessment area for wells open to confined aquifers. For other wells, variables were calculated only for the entire source water assessment area for wells open to unconfined 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 1995-97; lengths of roads, railways, and streams; the number of potential contaminant sources; septic-tank, population, and contaminant-site densities; and minimum distances of the well to the various land uses and to potential contaminant sources.

Water-Quality Data

Ground-water-quality data from June 1980 through October 2002 were obtained from the USGS National Water Inventory System (NWIS) database. Data were imported into a relational database and a statistical software package used for exploratory data analysis, statistical testing, and plotting. All water-quality data are from water samples collected 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 pathogen indicators 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. For other constituent groups for which models were developed, 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. However, for the pathogens constituent group, the maximum value determined at a site was used instead of the value from the most recent sample. Concentrations of coliform bacteria vary with season. Typically, concentrations are higher in the summer and lower in the winter.

Results of analyses for at least one fecal indicator organism were available for 24 ground-water wells. None of the 24 wells is a CWS well. Data for sites that had at least one of three measures of coliform bacteria were combined to develop a variable to use for statistical testing (fig. 4). Data were available for total coliform, fecal coliform, and *Escherichia coli* (*E. coli*), in colonies per 100 milliliters. All wells in the NWIS database were considered for this constituent group because insufficient data were available for wells in the subset of unconfined CWS well or all CWS well subset. The number of wells with data for pathogen indicators is shown in table 1.

Table 1. Number of sites at which pathogen indicators were detected in samples from wells in the NWIS database and frequencies of detection

Constituent	Number of sites for which data are available[1]	Number of sites at which constituent was detected	Frequency of detection[2]
Escherichia coli, colonies/100mL	12	0	0
Fecal coliform, colonies/100mL	12	3	0.25
Total coliform, colonies/100mL	12	3	0.25

[1] Number of sites represents all wells in the NWIS database for constituents with primary standards and may be different than the number of sites used to develop the model.
[2] 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 pathogen indicators within the distribution system of community water supplies. For the purpose of modeling, NJDEP determined that the presence of coliform bacteria in samples from wells is considered to be an indication of an emerging problem. The model was developed to determine the variables that best describe the presence or absence of pathogens in source waters.

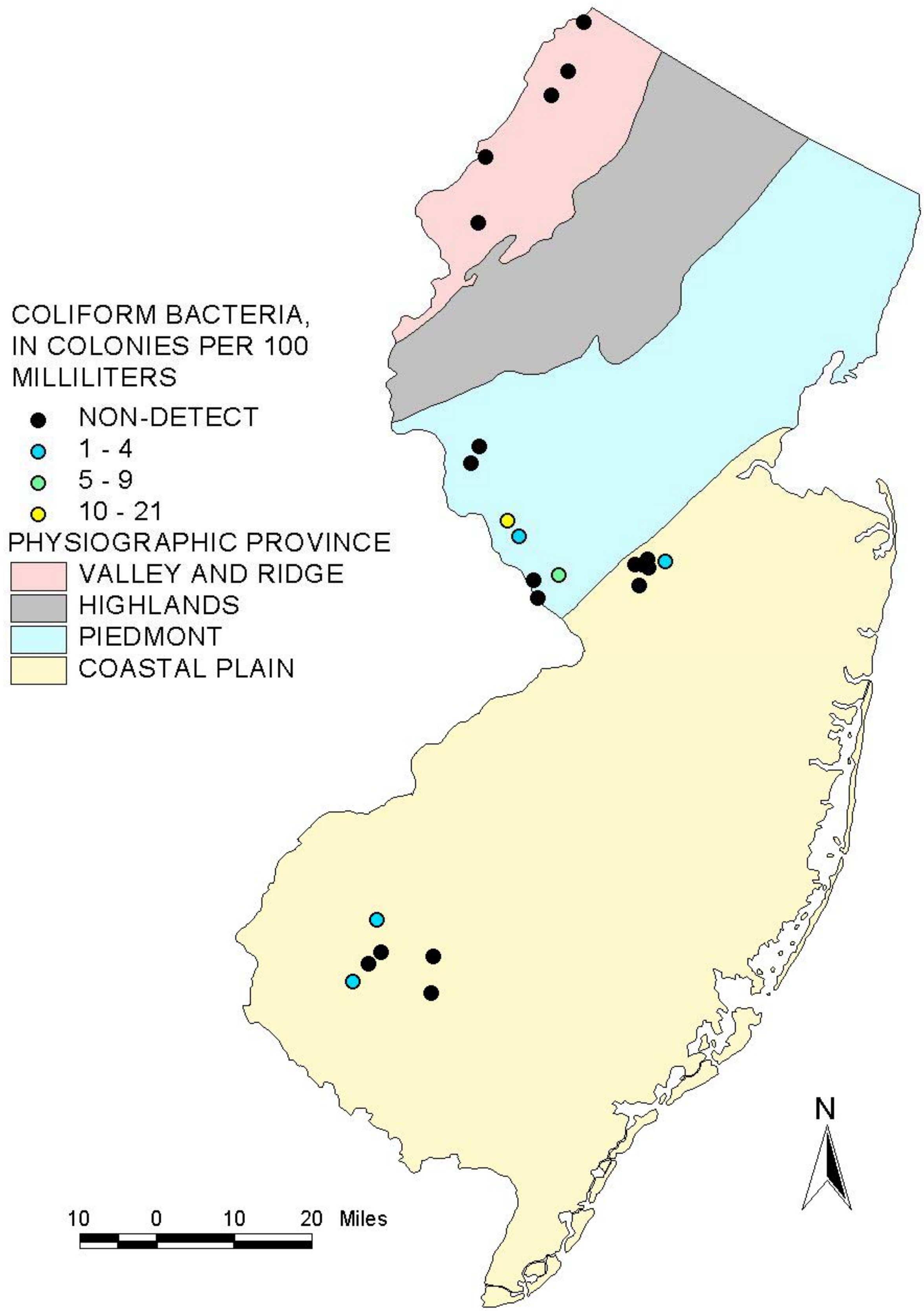

Figure 4. Concentration of coliform bacteria in 24 wells used for development of the pathogens model.

Statistical tests and graphical procedures were used to evaluate the relation between pathogen indicators and sensitivity and intensity variables. Univariate statistical tests were run on all variables. Variables included sensitivity, intensity, water quality, and site-related characteristics such as physiographic province. Univariate tests included the Kruskal-Wallis test and Spearman's rho rank correlation. Differences between median values of grouped data also were compared (Table 2).

Table 2. Results of univariate statistical tests for explanatory variables used in the pathogens model

Variable	Kruskal-Wallis rank test		Spearman's rank correlation		Conceptual variable
	Kruskal-Wallis score	p-value	Spearman's rho	p-value	
Depth to top of open interval	5.77	0.016	-0.577	0.012	No
Distance to agricultural land	4.11	0.043	-0.398	0.062	No
Average soil available water capacity[1]	1.96	0.161	0.285	0.182	Yes
Septic density per square mile[1]	1.42	0.234	-0.185	0.384	Yes
GWUDI designation[2]					Yes
Surface water within tier 1[2]					Yes

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

[2] Statistical test could not be used because variable was unavailable for the data set used to develop the model.

The Kruskal-Wallis test was used to determine whether distributions of hydrogeologic sensitivity or intensity variables differed between constituent groups in which bacteria were present in samples or were not present in samples. The sizes of the Kruskal-Wallis test statistic and corresponding p-value are used as a measure of the strength of differences between the groups. Spearman's rho, the nonparametric equivalent of a correlation coefficient, was used to evaluate linear trends between ranked explanatory and response variables because environmental variables rarely are normally distributed (Helsel and Hirsch, 2002). Correlation coefficients were calculated between the concentration of each modeled constituent and all hydrogeologic-sensitivity and intensity variables, and many water-quality variables. Scatter plots of all variables versus the concentration of the modeled constituent were generated to confirm the results of statistical tests. Boxplots were used to compare the distributions of variables among groups.

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

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

Rating Scheme

A scoring method was developed for the pathogens model that gave a maximum of four points to each variable used in the model for unconfined wells (Table 3). In some cases, the scoring interval was based on a weighting scheme relative to the strength of the statistical relation. 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 depth to the top of the open interval was statistically related (a negative Spearman's correlation, Kruskal Wallis score of 5.77, and p-value of 0.016) to the presence of coliform bacteria and the depth to the top of the open interval of a well was shallow, a score of 4 was assigned. When the depth to the top of the open interval of a well was deep, a score of 0 was assigned. Fewer points were given to variables that were less significant statistically, that had lower correlation coefficients, that appeared graphically to be grouped, or that did not show changes over the entire range of values. Relations observed in the graphs presented in this report were used as the starting point for devising the numerical code.

Table 3. Susceptibility rating scheme for pathogens in water from community water-supply wells

Ground Water Coliform Model

Coliform Rating: 0-6.5 LOW, 7-8.5 MEDIUM, 9-14 HIGH

	Sensitivity Points-Unconfined Wells					
Variable	0	1	2	3	4	Conceptual variable
Soil available water capacity-average[1]	0-0.09	>0.09-0.11	>0.11-0.13	>0.13-0.15	>0.15	Yes
Depth to top of open interval (feet)	>60		>40-60		<=40	No

Points-Sources using ground water under the direct influence of surface water[2] 9	Yes

	Intensity Points-Unconfined Wells						
Variable	0	.5	1	1.5	2	4	
Distance to agricultural land, 1995 (feet)	>50					<=50	No
Septic density per square mile[1]	0-6	>6-12	>12-18	>18-24	>24		Yes

Points-Length of streams in Tier 1 greater than zero[2] 7	Yes

Points-Confined Wells 0

[1] This conceptual variable shows a graphical relation, improves the model, and is supported by previous scientific investigation.
[2] Statistical test could not be used because variable was unavailable for the data set used to develop the model.

Wells in confined aquifers of the New Jersey Coastal Plain were assigned a score of 0 points; however, no results of analyses were available for these wells. Contamination of water in confined aquifers as a result of human activities or other sources at the land surface is unlikely, except in cases where the well casing has been breached and contaminants move along the annulus of the well.

Relation of Pathogen Indicators in Ground Water to Susceptibility Variables

Relations between concentrations of pathogen indicators 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 pathogens. The model was calibrated using results of analyses for coliform bacteria from 24 wells. Coliform bacteria were present in samples from 6 of the 24 wells used to develop the model.

Microorganisms are common in soil and water and include bacteria, protozoa, viruses, and other organisms. Some of them, pathogens, can cause disease in humans. Pathogens typically are found in higher concentrations in surface water than in ground water. Water systems that use surface water or ground water under the direct influence of surface water are required to reduce concentrations of pathogens (http://www.epa.gov/enviro/html/icr/pathogens.html). Sources of pathogens in water include sewage treatment plants, domestic septic systems, leaky sanitary sewer and storm water lines, storm water retention or infiltration basins, injection or agricultural drainage wells, animal feedlots and stock yards, rendering plants, animal burial sites, landfills, composting sites, land application of sludge or manure, manure storage areas and other sources of fecal matter that may be transported to water.

Total coliform bacteria are organisms that live in the digestive system of animals, but also commonly live in soil and water. Most strains of coliform bacteria are harmless. However, tests for total coliform bacteria have been shown to be reliable as indicators of water that have been contaminated by fecal waste (Atherholt and others, 2003). Fecal coliform bacteria are specific groups of bacteria, such as *E. coli*, that may be present in contaminated water. *E. coli* live in the digestive systems of humans and animals. Most strains of *E. coli* are harmless; however, some can cause severe illness (http://www.epa.gov/safewater/ecoli.html), primarily gastrointestinal. A few strains do produce toxins that might cause fatalities among infected populations. Total coliform bacteria are used as a general indicator of water quality and how likely the water is to be contaminated with potentially disease causing pathogens from fecal matter or other sources (http://www.epa.gov/enviro/html/icr/gloss_path.html).

The highest concentrations and greatest frequency of detection of coliform bacteria were found in agricultural areas. Wells in or near agricultural areas (50 feet or less) were more likely to contain coliform bacteria than wells in other areas (fig. 5). The concentrations and types of microorganisms that are found in natural water depend largely on the availability of nutrients, environmental conditions, other organisms present, and physical factors (Frobisher and others, 1974). In the Piedmont Physiographic Province, where detection was most frequent, the highest concentrations of coliform bacteria were found in areas with mixed agricultural, residential, and forested land.

The presence and concentration of coliform bacteria likely is related to density of septic systems. Septic systems can have extremely large populations of coliform bacteria, often exceeding one million colonies per 100 mL (Weisekel and others, 1996; Szabo, oral commun., 2003). Leaking septic systems, leach fields, and the location of wells near or downgradient from domestic systems may result in contamination of wells (fig. 6). Organic matter and other substances useful as food (nutrients) for microorganisms, present in septic system effluent, tend to adsorb to moist surfaces of soil particles, such as silt or sand. These surfaces provide extensive areas where microorganisms can flourish in warm weather (Frobisher and others, 1974). Septic density, a conceptual variable, was used in the model to represent the likelihood that a well may be affected by effluent from septic systems.

Typically, the shallower the open interval of a well and the smaller the length of casing used in the construction of the well, the more likely it is that contaminants will be transported from sources at land surface to the well (fig. 7). The depth of the top of the open interval of a well is a measure of the minimum distance a contaminant would have to travel from sources of the contaminant at land surface to reach the well. Most microorganisms in soil live in the upper few feet of the soil, and concentrations decrease with depth, depending partly on the availability of moisture and nutrients (Frobisher and others, 1974). Land-applied manure, septic system leachate, and other sources introduce microorganisms at land surface or to shallow soil; thus, shallow wells are simply closer to the sources of microorganisms than are deeper wells.

All life forms, including pathogens, require an adequate supply of water to survive. Available water capacity, a conceptual variable, is a measure of the amount of water available for plant growth. Bacteria can survive through brief periods without water during certain parts of their life cycle. However, to actively expand their population, moisture must be present (Frobisher and others, 1974). Soils that have low moisture content or that frequently dry out generally have smaller populations of microorganisms (fig. 8).

Pathogens may be present in drinking-water supplies as a result of a variety of factors, including the presence of active colonies or oocysts in source water, and entry of, and development of stable reproducing colonies of bacteria in storage and distribution systems. Inadequate disinfection during the treatment process may allow colonies to grow and flourish. Most suppliers add the lowest amount of disinfectant necessary to assure safety in order to minimize the formation of disinfection by-products, which also may pose a health risk.

The variables selected to represent hydrogeologic sensitivity of ground water to contamination by pathogens were average soil available water capacity (conceptual) and depth to top of open interval. Variables selected to represent potential contaminant-use intensity to contamination of ground water by pathogens were distance to agricultural land and septic density per square mile (conceptual). Of the 24 ground-water sites used for model development, 11 were rated as having low susceptibility, 6 were rated as having medium susceptibility, and 7 were rated as having high susceptibility (figs. 9 and 10).

Two conceptual variables (GWUDI designation and surface water within tier 1) were added to the pathogens susceptibility model used to determine the susceptibility ratings of all CWS wells. These variables were added to the model because the wells used to the development model did not include any CWS well. CWS wells typically draw water from a larger area than do domestic or other types of wells. Consequently, the model data set could not adequately determine whether a relation between pathogen indicators and variables that define surface water within the contributing area was significant. These variables include measures such as distance to stream, percent water, and length of streams within the contributing area.

All wells designated by NJDEP as sources using ground water under the direct influence of surface water (GWUDI) were given a high susceptibility rating. Part of the water withdrawn from these wells is believed to come directly from surface water bodies. All wells that have surface water within the tier 1 boundary (2-year travel time) were given a medium susceptibility rating, unless a high rating was determined by using other variables. All surface water has been designated by NJDEP as highly susceptible to contamination by pathogens. Wells are designated as GWUDI based on well construction characteristics, results of raw water-quality samples, and the proximity of the well to surface-water bodies and sources of microbial contamination which may involve a ground water discharge, as described in N.J.A.C. 7:10-9.3. These variables were included in the model when applying the model to CWS wells, but were not included when the model was applied to the model development data set.

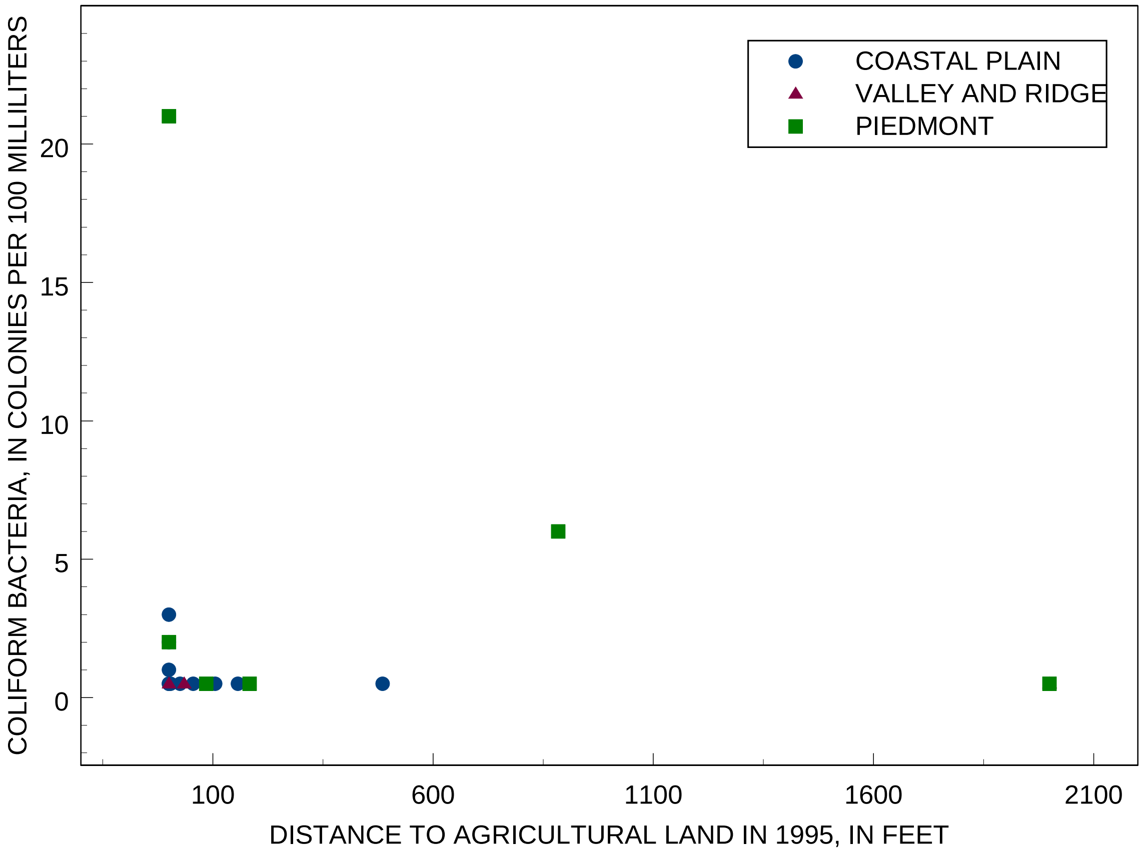

Figure 5. Relation of coliform bacteria to distance to agricultural land in 1995, by physiographic province, for 24 wells in New Jersey.

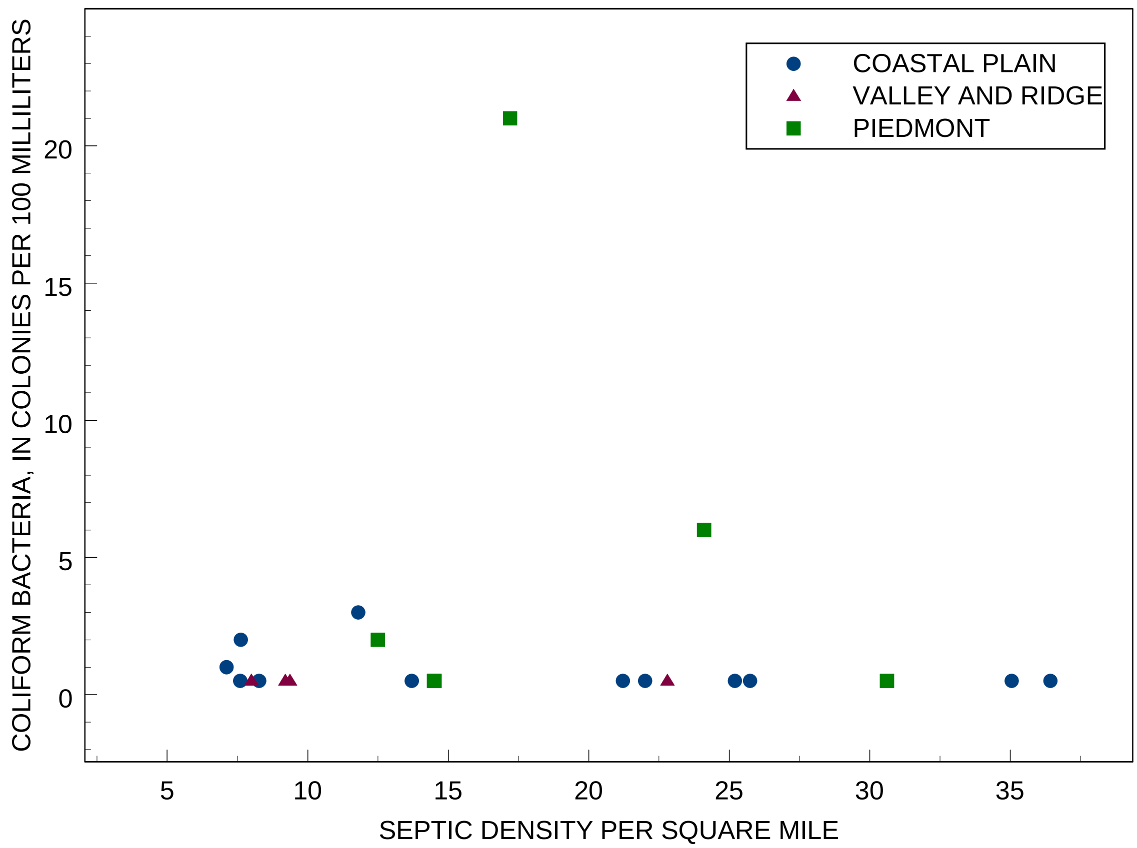

Figure 6. Relation of coliform bacteria to septic density, by physiographic province, for 24 wells in New Jersey.

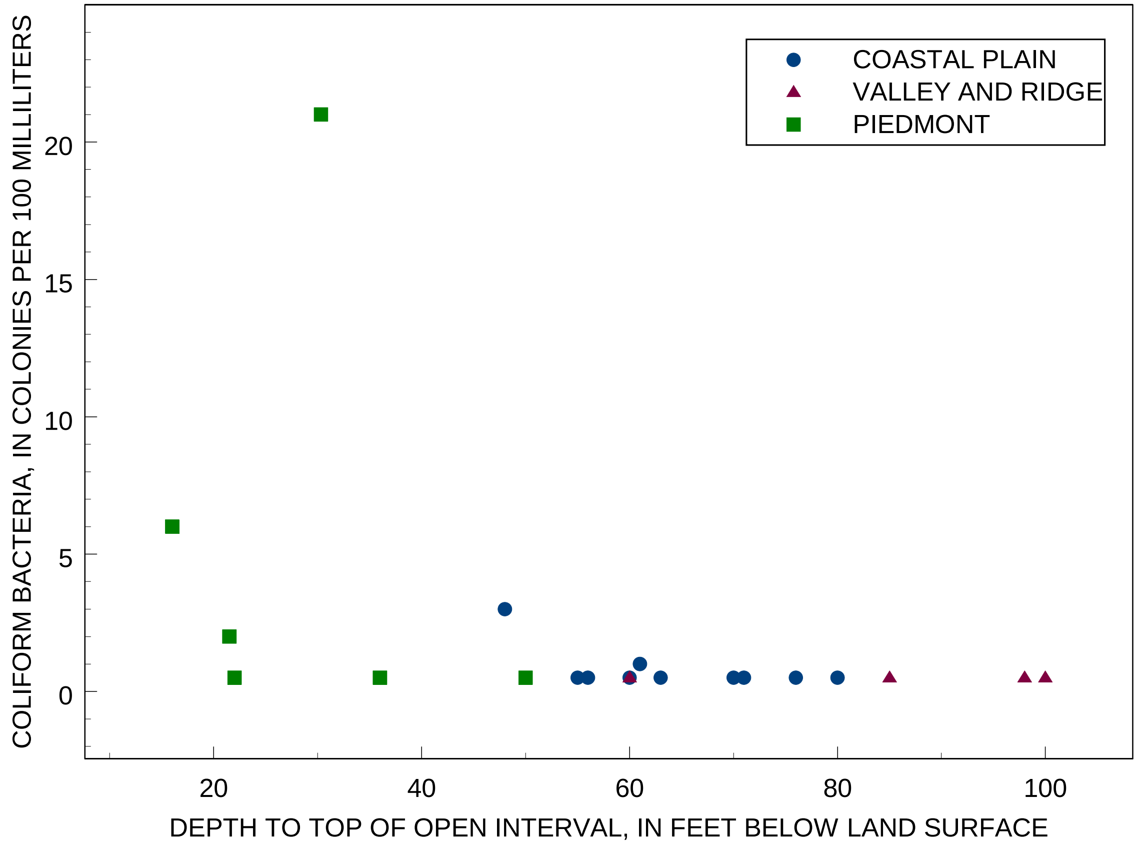

Figure 7. Relation of coliform bacteria to depth to top of open interval, by physiographic province, for 24 wells in New Jersey.

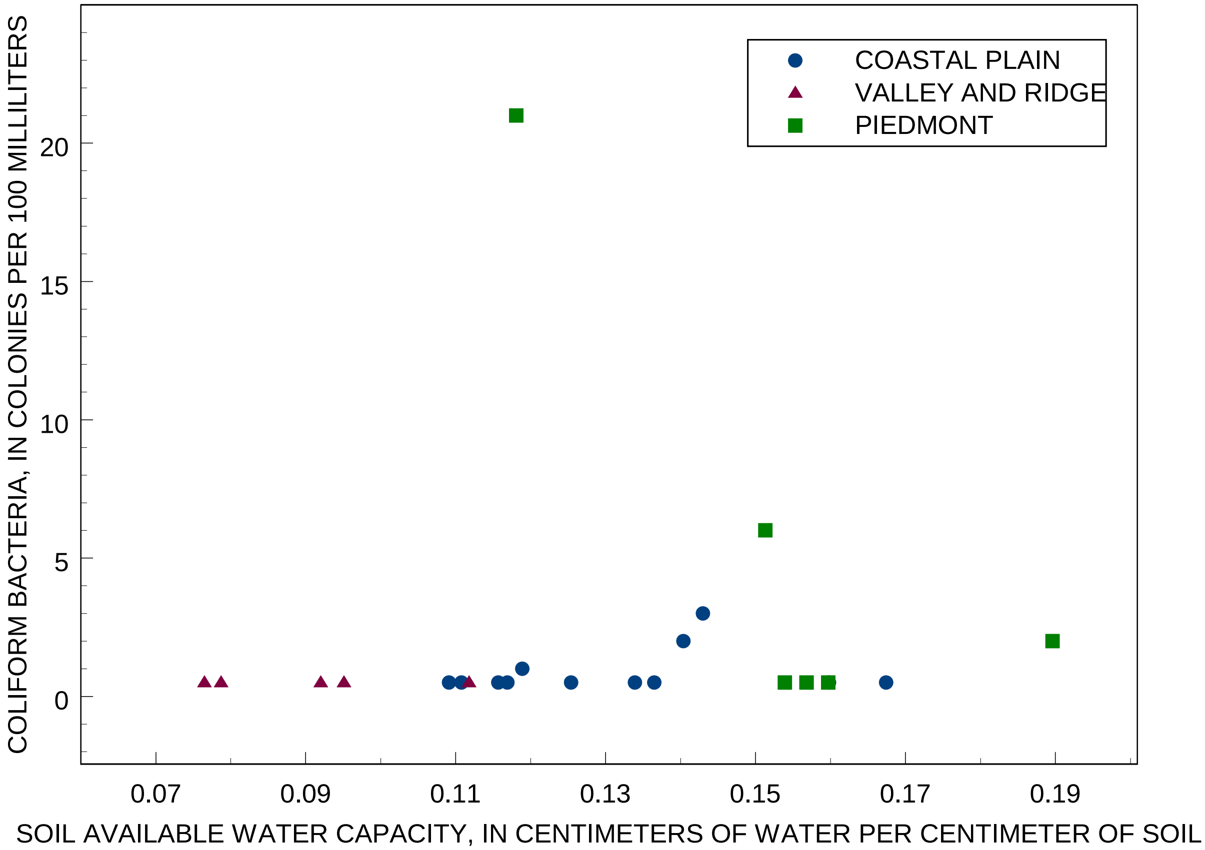

Figure 8. Relation of coliform bacteria to soil available water capacity, by physiographic province, for 24 wells in New Jersey.

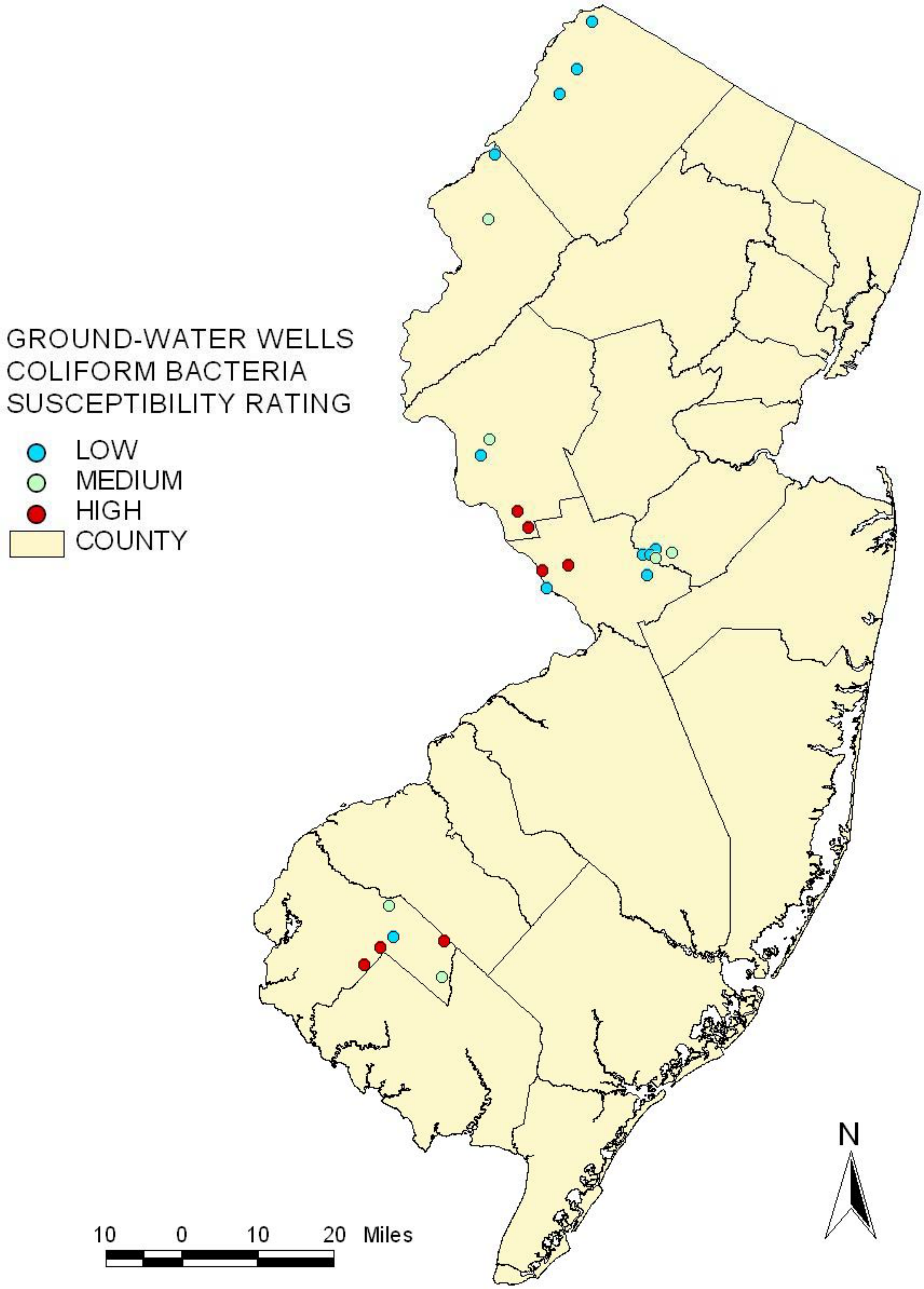

Figure 9. Susceptibility of 24 ground-water wells in New Jersey used for model development to contamination by coliform bacteria.

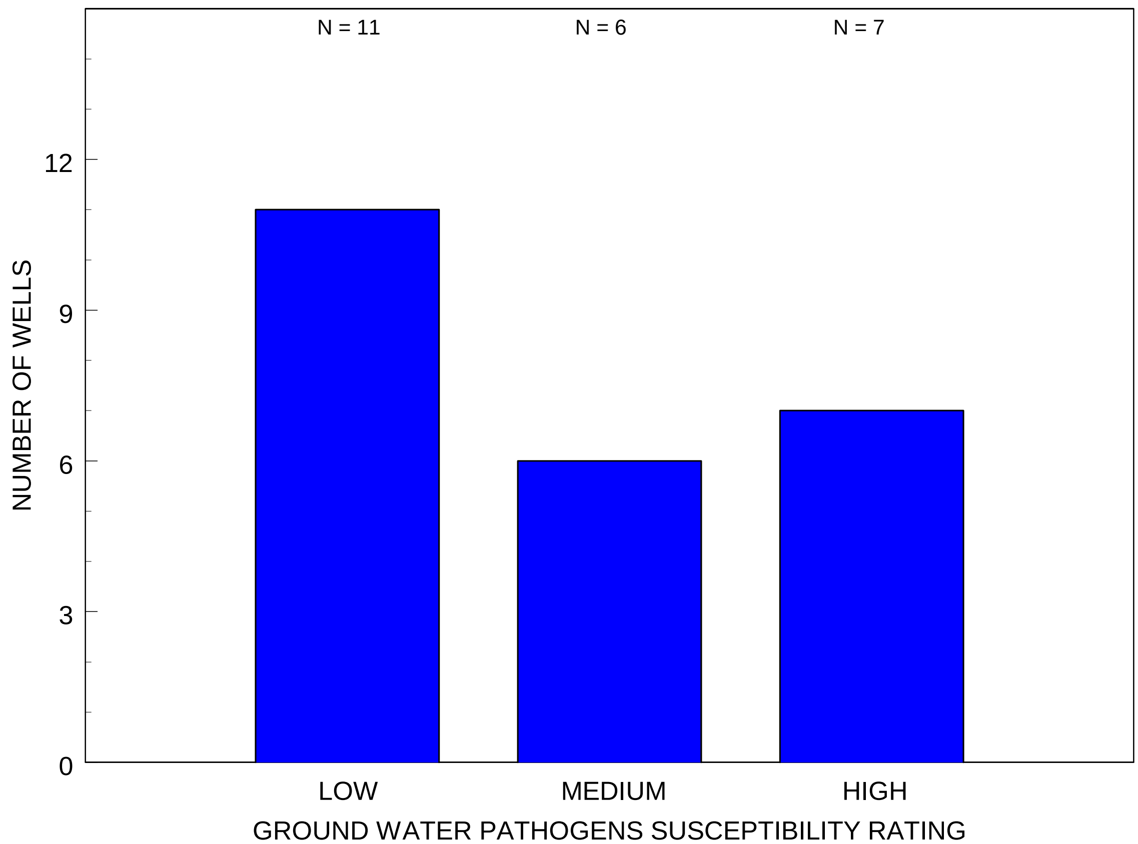

Figure 10. Number of ground-water wells in New Jersey used for model development having low, medium, and high susceptibility to contamination by pathogens.

Susceptibility of Ground-Water Sources

The results of the susceptibility assessment models indicate that as sensitivity and intensity increase, the concentrations of the coliform bacteria increase (fig. 11). The numerical rating scheme created during model development was applied to the sensitivity and intensity variables of each CWS well. Of the 2,237 CWS wells to which the model was applied, the susceptibility to contamination by pathogens was low for 1,251, medium for 892, and high for 94.

Discussion

Several limitations of the susceptibility assessment model should be noted. The model should be used only as a screening tool to identify potential contamination problems. The maximum sample concentrations for each well 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 for the susceptibility assessment model. The method used to determine source water assessment areas produces only estimates of the actual contributing area.

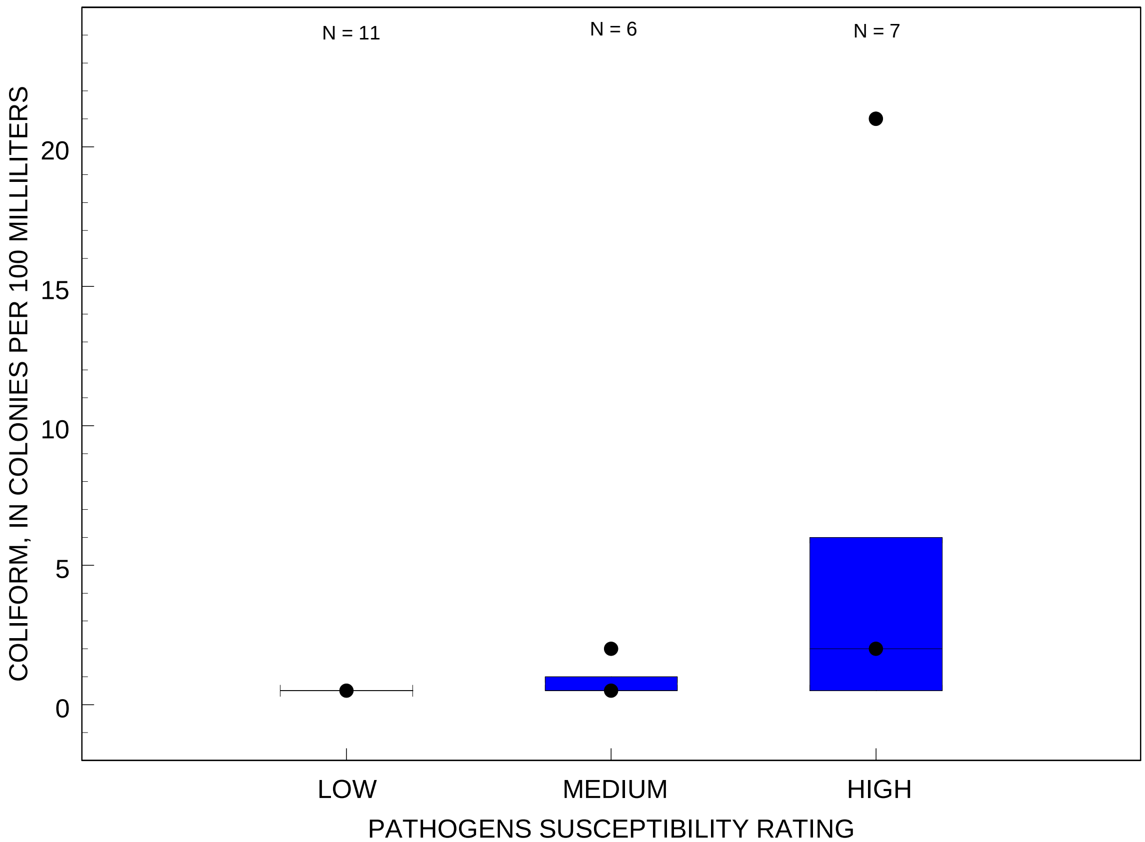

Figure 11. Results of the pathogens susceptibility assessment model for 24 wells in New Jersey showing distribution of coliform bacteria by susceptibility rating.

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, although a well may be highly susceptible to contamination, a given constituent will not be detected in the samples from that well if the constituent does not originate from human activities or natural sources within the contributing area. Furthermore, in the case of pathogens, their transport through the ground-water system is not well understood and is an ongoing area of research. As such, it is not clear what levels in soil, manure, or septic systems may result in well water contamination, even though pathogens are definitely present in all three media.

The pathogens susceptibility model was developed by using only non-CWS well data, and variables selected may not represent factors that affect the quality of water from CWS wells. The data set used to develop the model included results of analyses from a study that was designed to determine the effect of agriculture on ground-water quality and may have introduced bias into the results of the model.

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

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