SUSCEPTIBILITY OF SOURCE WATER TO COMMUNITY WATER-SUPPLY WELLS IN NEW JERSEY TO CONTAMINATION BY VOLATILE ORGANIC COMPOUNDS

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 volatile organic compounds (VOCs). Susceptibility is defined by variables that describe hydrogeologic sensitivity and potential contaminant-use intensity within the area contributing water to the wells. The models were developed using water-quality data from ground-water samples collected and analyzed by the U.S. Geological Survey (USGS). Variables were selected using two sets of wells and two groups of VOCs; only tetrachloroethylene was common between the data sets. The model was verified using concentrations of trichloroethylene in water from CWS wells in unconfined aquifers. The variable selected to represent hydrogeologic sensitivity is the average percent soil organic matter. Variables selected to represent potential contaminant-use intensity are the area of urban land in 1995, the percent impervious surface in 1995, percent of commercial and industrial land use in 1995, and the density of solid-waste landfills, underground storage tanks and sites on the Known Contaminated Site List. Wells in confined aquifers generally are not susceptible to contamination by VOCs, as indicated by a lack of detections of VOCs in water from such wells. Overall, of 2,237 CWS wells for which susceptibility was determined, the susceptibility to contamination by VOCs was low for 56 percent and high for 44 percent of CWS wells (figs. 1 and 2). There were no medium VOC susceptibility ratings assigned; the model predicted that concentrations of VOC would be either less than one-tenth the maximum contaminant level (MCL) of the respective VOC (low) or equal to or greater than one-half the MCL of the respective VOC (high).

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 contaminants, 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 volatile organic compounds, (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.

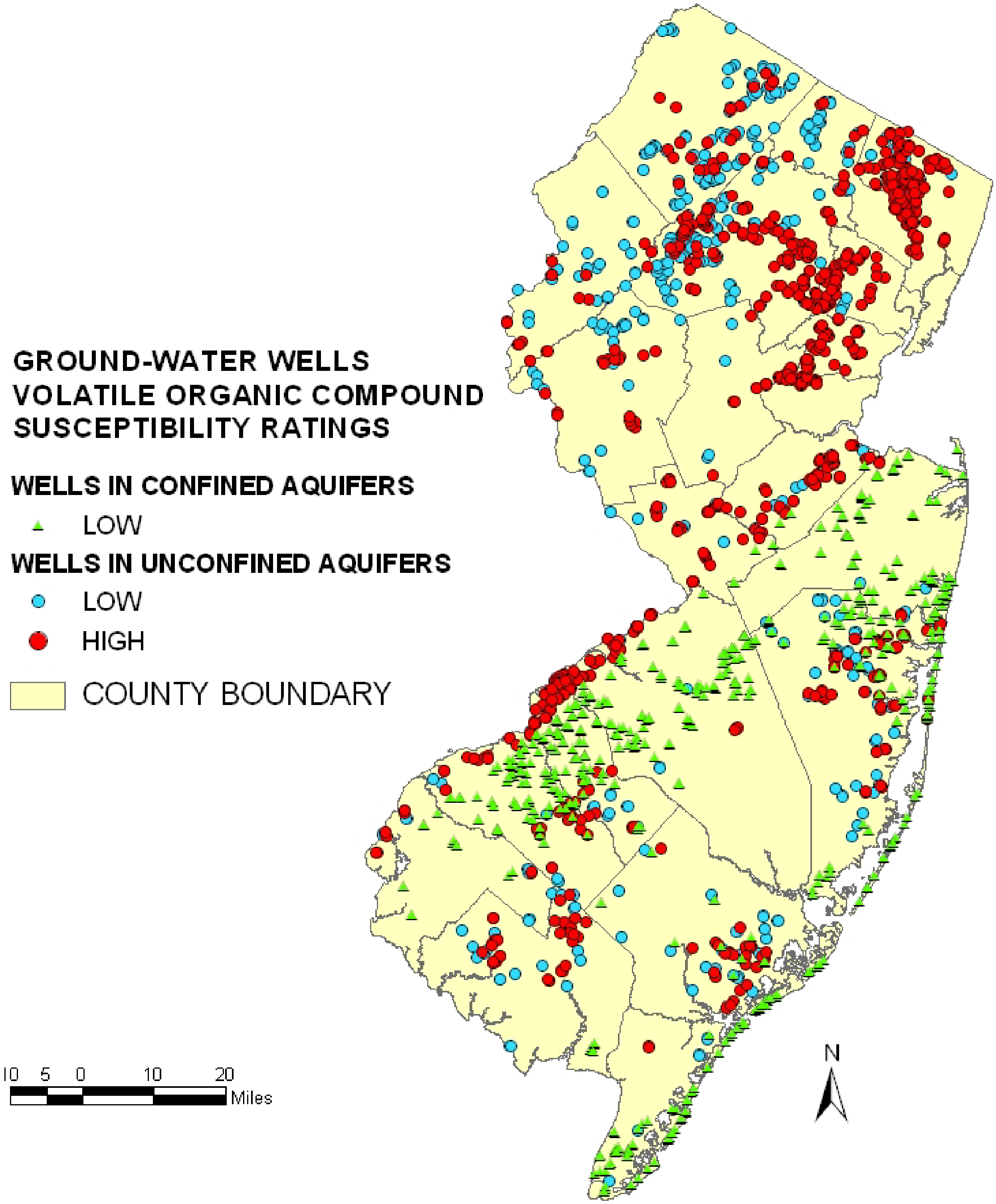

Figure 1. Susceptibility of 2,237 community water-supply wells in New Jersey to contamination by volatile organic compounds. [No medium VOC susceptibility rating was assigned; the model predicted that concentrations of VOCs would be either less than one-tenth the MCL of the respective VOC (low) or equal to or greater than one-half the MCL of the respective VOC (high).]

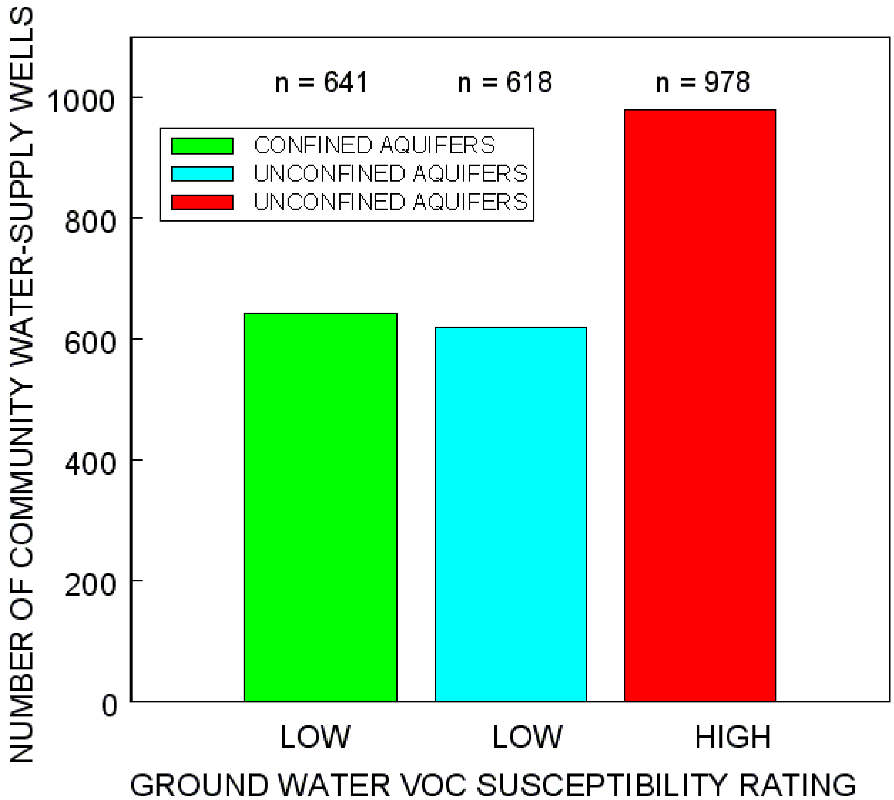

Figure 2. Number of community water-supply wells in New Jersey having low and high susceptibility to contamination by volatile organic compounds. [No medium VOC susceptibility rating was assigned; the model predicted that concentrations of VOC would be either less than one-tenth the MCL of the respective VOC (low) or equal or greater than one-half the MCL of the respective VOC (high).]

Background

Occurrence of VOCs in source water is widespread. VOCs have been identified as potential contaminants by 38 percent of community water systems in the United States (United States Environmental Protection Agency, 1997). Many VOCs have properties that make them likely to be persistent and mobile in the environment (Ayers and others, 2000). VOCs may be carcinogenic, mutagenic, and otherwise toxic to humans and aquatic organisms. Most VOCs are present in the environment due to human activity. VOCs can be found in degreasing solvents, fuels, paints, adhesives, refrigerants, deodorants, and petroleum-based fuels and in the production of pharmaceutical and agricultural products (Bloemen and Burn, 1993; Smith and others, 1988; Verschueren, 1983). Chloroform, used in industrial and manufacturing processes, is produced during the chlorination of drinking water. It also has been shown to form naturally in soils (Hoekstra and others, 1998). Fuel hydrocarbon sources include gas stations and other transportation and storage facilities (Fetter, 1998). Compounds in fuels include benzene, toluene, ethylbenzene, and xylenes, and, recently, methyl tert-butyl ether (MTBE). Tetrachloroethylene and trichloroethylene are widely used in dry cleaning, metal degreasing, and in some industrial and manufacturing processes. Fumigants applied to agricultural soils include 1,2-dichloropropane. The sources of VOCs in ground water include urban runoff, industrial and municipal wastewater discharges, and improper disposal and accidental leaks of petroleum products, solvents, paints, and dyes.

Definition of Susceptibility

The susceptibility of a public water supply to contamination by a variety of constituents is defined by variables that describe the hydrogeologic sensitivity and the potential contaminant-use intensity in the area that contributes water to that source. The susceptibility assessment models were developed by using an equation whereby the susceptibility of the source water is equal to the sum of the values assigned to the variables that describe hydrogeologic sensitivity plus the sum of the values assigned to the variables that describe potential contaminant-use intensity within the area contributing water to a well.

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 using, as guidance, the thresholds developed by NJDEP for use in the models. In general, the low-susceptibility category includes wells for which constituent concentrations in source water are not likely to equal or exceed one-tenth of New Jersey's drinking-water MCL, the medium-susceptibility category includes wells for which constituent concentrations in source water are not likely to equal or exceed one-half the MCL, and the high-susceptibility category includes wells for which constituent concentrations in source water may equal or exceed one-half the MCL. Two VOCs with Health Advisory Levels (HALs) were included in the VOC model and are grouped with the other VOCs; HALs are treated as MCLs in this report. The susceptibility rating for the VOC constituent group is based on the results of a susceptibility assessment model developed for 13 VOCs.

Susceptibility Model Development

The development of the susceptibility assessment model involved several steps (J.A. 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; (5) assessment of relations of the constituents to model variables; and (6) use of an independent data set to verify the model. 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 CWS 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.

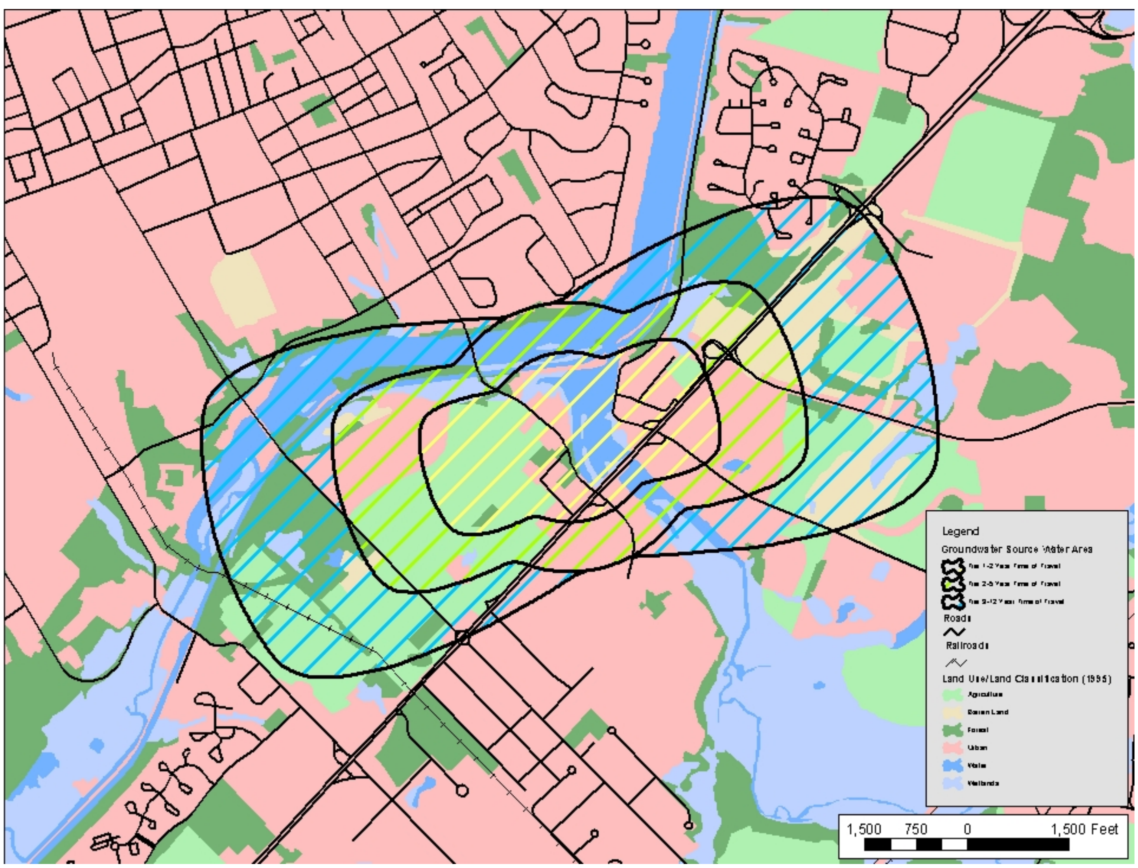

Figure 3. Example of delineated contributing area to a community water-supply well showing time of travel (TOT), land use, roads, and railroads.

Development of Data Sets

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

GIS

A GIS was used to quantify hydrogeologic-sensitivity and potential contaminant-use variables that may affect ground-water quality within areas contributing water to wells. The variables were calculated for each of the three ground-water tiers and for the entire source water assessment 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.

Water-Quality Data

Ground-water-quality data from June 1980 through October 2002 were obtained from the USGS 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, less precise methods were excluded. Analyses with known contamination problems also were not used.

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 of CWS wells finished in unconfined aquifers. 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 VOCs data, the constituents detected, and their MCLs are shown in table 1.

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 [μg/L = micrograms per liter, MCL = maximum contaminant level]

Constituent	MCL, μg/L	Number of wells for which data are available [1]	Number of wells at which constituent was detected	Number of wells at which concentration meets criterion 1 [2]	Number of wells at which concentration meets criterion 2 [3]	Number of wells at which concentration equals or exceeds MCL
Benzene	1	159	18	4	0	9
Bromodichloromethane	80 [4]	305	8	0	0	0
Bromoform	80 [4]	262	4	0	0	0
Carbon Tetrachloride	2	150	9	2	1	1
Chloroform	80 [4]	308	70	2	0	0
Dibromochloromethane	80 [4]	305	4	0	0	0
Meta-Dichlorobenzene	600	156	6	0	0	0
Ortho-Dichlorobenzene	600	156	10	0	0	0
Para-Dichlorobenzene	75	156	13	0	0	0
Dichlorodifluoromethane [5]	1,000	261	4	0	0	0
1,1-Dichloroethane	50	305	32	0	1	0
1,2-Dichloroethane	2	155	12	3	2	6
1,1-Dichloroethylene	2	152	31	9	3	0
cis-1,2-Dichloroethylene	70	102	26	3	0	0
trans-1,2-Dichloroethylene	100	308	21	1	0	0
1,2-Dichloropropane	5	150	9	2	2	1
Ethylbenzene	700	286	0	0	0	0
Methyl tertiary Butyl Ether	70	96	35	0	0	0
Methylene Chloride	3	127	4	0	0	4
Monochlorobenzene	50	262	8	1	0	0
Naphthalene	300	43	0	0	0	0
Styrene	100	152	0	0	0	0
1,1,2,2-Tetrachloroethane	1	86	0	0	0	0
Tetrachloroethylene	1	160	63	16	7	27
Toluene	1,000	331	1	0	0	0
1,2,4-Trichlorobenzene	9	37	0	0	0	0
1,1,1-Trichloroethane	30	308	54	1	1	0
1,1,2-Trichloroethane	3	86	0	0	0	0
Trichloroethylene	1	161	63	18	8	31
Trichlorofluoromethane [5]	2,000	261	13	0	0	0
Vinyl Chloride	2	151	3	1	0	1
Meta-Xylene, para-Xylene	1,000 [6]	41	1	0	0	0
Ortho-Xylene	1,000 [6]	41	2	0	0	0
Xylenes	1,000 [6]	125	1	0	0	0

[1] Number of wells represents all CWS wells in the NWIS database for VOC constituents with primary standards and may be different than the number of wells used to develop the model; two constituents with Health Advisory Levels are included.

[2] Criterion 1: Concentration is at least equal to one-tenth of the MCL, but is less than one-half of the MCL

[3] Criterion 2: Concentration is at least equal to one-half of the MCL, but is less than the MCL

[4] MCL for sum of trihalomethanes = 80 μg/L, the summed concentration of water from 2 wells exceeded one-tenth of the MCL

[5] Dichlorodifluoromethane and Trichlorofluoromethane have Health Advisory Levels rather than MCLs

[6] MCL for sum of Xylenes = 1,000 μg/L

If sufficient data were available to run all statistical tests, the subset of CWS wells in unconfined aquifers 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 in the NWIS database; consequently, values for sensitivity and intensity variables were not determined for wells lacking contributing area delineations.

Data Analysis

Federal and State Safe Drinking Water Regulations require routine monitoring for many VOCs at community water systems. For the purpose of modeling, NJDEP determined that concentrations greater than one-half of the MCL would be of greatest concern. Concentrations equal to or greater than one-tenth of the MCL also are considered in this report as an indication of an emerging problem, but health effects at this level are of less concern. The VOC 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.

Combining VOCs, rather than modeling individual VOCs where there were a limited number of wells yielding water with detections equal to or greater than one-tenth of the MCL, provided for a more robust data set from which to develop the statistical model. Two groups of VOCs were used to determine explanatory variables on the premise that a stronger model would be developed using two groups of VOCs rather than one to select explanatory variables; only tetrachloroethylene was common to the two groups (table 2). Percent frequency of detection (FOD) for the 11 regulated VOCs analyzed in water from 83 CWS wells in unconfined aquifers (data set for Model 1) and 13 regulated VOCs analyzed in water from 174 CWS wells in unconfined aquifers (data set for Model 2) was calculated for use in plotting and statistical tests.

The number of VOCs with concentrations equal to or greater than one-tenth of the respective MCL for each of the VOCs in the FOD group was divided by the total number of VOCs in the FOD group at each well site and multiplied by 100 to yield a percent frequency of detection.

$$\frac{\#\, VOCs\ with\ concentrations \geq 10\%\ MCL}{\#\, VOCs\ analyzed} \times 100 = \%\ FOD$$

As an example, for water from wells in which the concentration of one particular VOC out of the 13 VOCs in the 174-well CWS data set was equal to or greater than one-tenth the MCL, the percent FOD would be 8 percent, as shown below.

$$\frac{1\,VOC}{13\,VOCs} \times 100 = 8\ \%\ FOD$$

For statistical use, the wells for each model were separated into two groups; wells for which the FOD was zero and wells for which the FOD was greater than zero. Wells from Model 2 for which the FOD was zero (no VOCs were detected at equal to or greater than one-tenth of the MCL) and wells for which the FOD was greater than zero (at least one VOC was detected at equal to or greater than one-tenth of the MCL) are shown in figure 4.

Table 2. Groups of regulated constituents used to develop VOC Frequency of Detection Models [MCL = maximum contaminant level]

Model 1 [1]	Model 2 [2]
Benzene	Bromodichloromethane [3]
Carbon Tetrachloride	Bromoform [3]
1,2-Dichloroethane	Chloroform [3]
1,1-Dichloroethylene	Dibromochloromethane [3]
cis-1,2-Dichloroethylene	Dichlorodifluoromethane [4]
1,2-Dichloropropane	1,1-Dichloroethane
Ethylene dibromide	*trans*-1,2-Dichloroethylene
Methylene Chloride	Ethylbenzene
Tetrachloroethylene	Monochlorobenzene
Trichloroethylene	Tetrachloroethylene
Vinyl Chloride	Toluene
	1,1,1-Trichloroethane
	Trichlorofluoromethane [4]
[1]83 CWS wells in unconfined aquifers used in model 1	
[2]174 CWS wells in unconfined aquifers used in model 2	
[3] Trihalomethanes (THMs) in source water; chloroform is the only THM with a detection equal to or greater than one-tenth MCL	
[4] Dichlorodifluoromethane and Trichlorofluoromethane have Health Advisory Levels rather than MCLs	

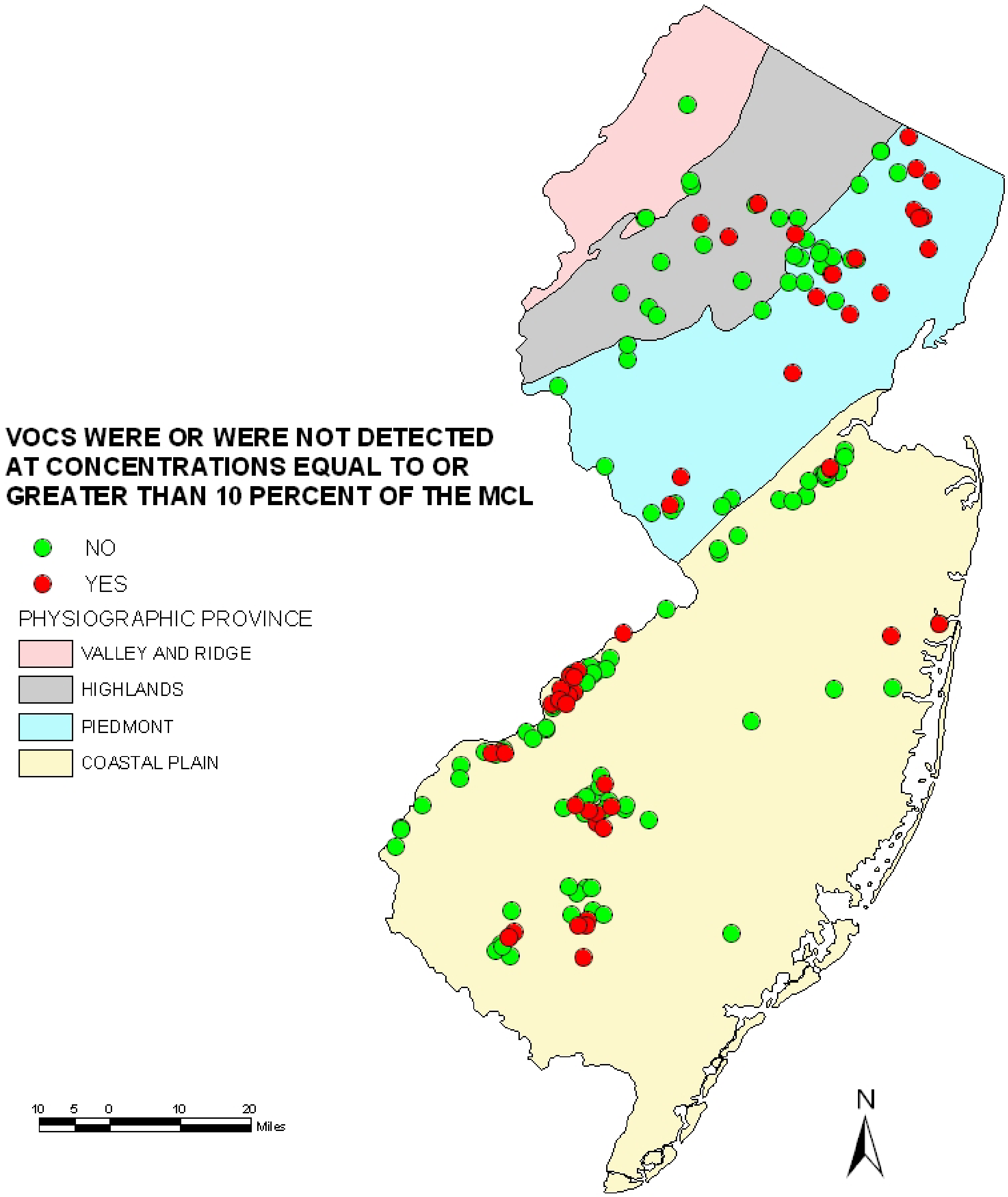

Figure 4. Occurrence of VOCs in samples in which one or more VOCs were or were not detected at concentrations equal to or greater than one-tenth of the MCL in water from 174 Model 2 community water-supply wells used for development of VOC model. [NO – No VOCs were detected at concentrations equal to or greater than one-tenth of the MCL (FOD = 0), YES – At least one VOC was detected at concentrations equal to or greater than one-tenth of the MCL (FOD ≥ 1)]. The Physiographic Provinces shown are regions with differing geologic and topographic characteristics.

Statistical tests and graphical procedures were used to evaluate the relation between VOC FOD and sensitivity and intensity variables to determine those variables that best describe the concentrations of VOCs in source waters. Univariate statistical tests were run on all variables. Univariate tests included the Kruskal-Wallis test and Spearman's rho rank correlation.

The Kruskal-Wallis test was used to determine whether distributions of variables differed between wells where VOCs in the group selected for model development were either not detected or were detected but concentrations were less than one-tenth of the respective MCL, and wells where one or more of the VOCs in the group selected for model development were detected at equal to or greater than one-tenth of the respective MCL (table 3). The size of the Kruskal-Wallis test statistic and corresponding p-value are used as a measure of the strength of differences between the groups; the larger the test statistic and the smaller the p-value relative to the other values within the data set, the more significant the test result. The magnitude of the test statistic depends on the size of the data set; the larger the data set, the larger the test statistic relative to the test statistic from a smaller data set.

Table 3. Results of univariate statistical tests for explanatory variables used in VOC Models [Model 1: FOD of 11 VOCs analyzed in water from CWS wells in unconfined aquifers; Model 2: FOD of 13 VOCs analyzed in water from CWS wells in unconfined aquifers]

	Model 1: FOD of 11 VOCs			**Model 2: FOD of 13 VOCs**		
	Kruskal-Wallis rank test			**Kruskal-Wallis rank test**		
Variable	**Kruskal-Wallis score**	**p-value**	**Conceptual variable**	**Kruskal-Wallis score**	**p-value**	**Conceptual variable**
Average percent organic matter	2.66	0.1028 [1]	Yes [2]	8.59	0.0034	No
Area of urban land use, 1995, in square miles	9.39	0.0022	No	19.62	0.0000	No
Percent impervious surface, 1995	14.37	0.0002	No	27.85	0.0000	No
Percent commercial and industrial land use, 1995	15.00	0.0001	No	20.23	0.0000	No
Density potential contaminant sites [3]	11.36	0.0008	No	29.67	0.0000	No

[1] Not significant at the alpha <0.05 level.
[2] This conceptual variable shows a graphical relation, improves the model, and is supported by scientific investigations.
[3] Density of solid-waste landfills, underground storage tanks, and sites on the Known Contaminated Site List

Spearman's rho, the nonparametric equivalent of a correlation coefficient, was used to evaluate linear trends between ranked variables because environmental variables rarely are normally distributed (Helsel and Hirsch, 2002). Correlation coefficients were calculated between the FOD of VOC concentrations and all sensitivity and intensity variables, and all relevant water-quality variables. Scatter plots and boxplots of all variables in relation to the FOD or concentration of individual VOCs were generated to confirm the results of statistical tests and 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. Only variables that were used in the model will be discussed.

Multivariate statistical tests were conducted on selected statistically significant and conceptual variables to narrow the list of variables to be used in the susceptibility assessment model and to determine those variables that collectively are best predictors of potential contamination of water from water-supply wells. Multivariate tests included logistic regression and principal components analysis. Variables used in the susceptibility assessment model were selected on the basis of results of summary statistics, univariate and multivariate statistical tests, and graphical procedures.

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.

The sensitivity variable for the VOC model is average percent soil organic matter. It was found to be statistically significant in Model 2 (Kruskal-Wallis p-value = 0.0034) but not significant in Model 1 (Kruskal- Wallis p-value = 0.1028). Because VOCs tend to sorb to soil organic matter (USEPA, 1993), average percent soil organic matter was considered as a conceptual variable for Model 1.

The consistency of explanatory variables selected in the two models relative to the other explanatory variables tested indicates they are good predictors of susceptibility to other regulated VOCs as well as unregulated VOCs. Thus, a final VOC model included variables from Models 1 and 2, which were virtually the same, but gave more weight to results for Model 2, developed with the larger data set of wells. Therefore, average percent soil organic matter was selected to represent hydrogeologic sensitivity of ground-water to contamination by VOCs. Percent impervious surface, percent commercial and industrial land use, area of urban land use (1995) land use, and density of solid waste landfills and underground storage tanks, and sites on Known Contaminated Site List were chosen to represent contaminant-use intensity.

Rating Scheme

A scoring method was developed for the final VOC model that gave a maximum of 5 points to each variable used in the model for ground-water sites (table 4). Relations observed in the graphs presented in this report were used as the starting point for devising the numerical code. For example, when percent impervious surface was statistically related (Kruskal Wallis score of 27.85 and p-value of 0.000) to Model 2 VOC FOD and the percent impervious surface for a well was low, a score of 0 was assigned. When the percent impervious surface for a well was mid-range, a score of 3 was assigned and when the percent impervious surface was higher, a score of 5 was assigned.

Table 4. Susceptibility rating scheme for VOCs in water from community water-supply wells

Ground Water VOC Model
VOC Rating: 0-17 LOW, 18-25 HIGH [1]

	Sensitivity Points – Wells in Unconfined Aquifers						**Conceptual variable**
Variable	0	1	2	3	4	5	
Average percent organic matter	> 8.0			> 2.5 – 8.0		0 - 2.5	No

	Intensity Points – Wells in Unconfined Aquifers						**Conceptual variable**
Variable	0	1	2	3	4	5	
Area of Urban Land Use, in Square Miles	0 – 0.2					> 0.2	No
Percent Impervious Surface, 1995	0 – 7.4			> 7.4 – 10.9		> 10.9	No
Percent Commercial/Industrial Land, 1995	< 7			7 – < 9		≥ 9	No
Density of solid-waste landfills, underground storage tanks, and sites on the Known Contaminated Site List	< 1			1 – < 3		≥ 3	No

Points – Wells in Confined Aquifers = 0

[1] No medium VOC susceptibility rating was assigned; the model predicted that concentrations of VOC would be either less than one-tenth the MCL of the respective VOC (low) or equal to or greater than one-half the MCL of the respective VOC (high).

Relation of VOCs in Ground Water to Susceptibility Variables

Relations between concentrations of VOCs 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 VOCs. Variables were selected using the FOD of VOCs in water from wells in unconfined aquifers.

The susceptibility ratings for VOCs are influenced mainly by the intensity variables of the model because most sources of VOCs are anthropogenic. Kruskal-Wallis values are larger for the intensity explanatory variables than for hydrogeologic sensitivity variables, such as average percent soil organic matter, indicating the occurrence of VOCs has a stronger relation to human activities than to a hydrogeologic variable. Of the five explanatory variables selected to develop the VOC model only one was a sensitivity variable. Soil organic matter was chosen because lipophilic VOCs tend to sorb to organic matter (USEPA, 1993) (fig. 5A).

The Long Island-New Jersey National Water-Quality Assessment Program (LINJ-NAWQA) reported detection frequencies and concentrations of the most frequently detected VOCs generally were highest in urban areas and lowest in agricultural and undeveloped areas (Ayers and others, 2000). The more frequent detection of VOCs is the result of increased human activity and greater VOC use in urban areas (fig. 5B) where VOCs can accumulate on impervious surfaces and can be flushed into a receiving stream during storms (Anderson and others, 2000) (fig. 5C) or spread to permeable soils and from there to ground water.

For samples of ground water underlying Nassau and Suffolk Counties on Long Island, New York, VOCs were detected most frequently (54 percent detection at concentrations greater than 1 μg/L) in water from areas where industry and commercial land use with use of VOCs interspersed with residential land use, and least frequently (3 percent) in water from agricultural and undeveloped areas (Eckhardt and Stackelberg, 1995). In New Jersey the median percent commercial/industrial land use was greater where VOCs were detected at concentrations equal to or greater than one-tenth of their MCLs (fig. 5D). The most frequently detected VOCs in stream and ground-water samples in New Jersey are compounds used in gasoline or commercial and industrial processes, or are byproducts of the chlorination of water (Ayers and others, 2000).

Solid-waste landfills, underground storage tanks and sites on the Known Contaminated Site List may be sources of contamination if the contaminant plume migrates towards ground water. Leaky storage tanks, spills, improper disposal of chemicals, and septic systems may be direct sources of VOC contamination to ground water (Terracciano and O'Brien, 1997). In New Jersey, the density of such potential contaminant sources generally is greater where VOCs are detected at concentrations equal to or greater than one-tenth of their MCLs (fig. 5E).

Of the 2,237 wells for which susceptibility ratings were developed, 641 are finished in confined aquifers. The susceptibility of wells in confined aquifer is considered to be low, although there are instances where breaches in confining units have permitted VOCs to be drawn into confined aquifers. Analytical results for samples from CWS wells open to confined aquifers indicate that instances of VOC detections are few; these results are stored in the USGS databases. VOCs were detected in two wells in water from confined aquifers; tetrachloroethylene was detected at a concentration greater than the MCL in one well and the summed concentration of chloroform and bromodichloromethane was greater than one-tenth of the MCL. In general, the farther downgradient from an aquifer's outcrop area a well is located, the less likely it is that well will be susceptible to contamination by VOCs.

Concentrations of 8 VOCs in raw source water from CWS wells in unconfined aquifers exceeded their respective MCLs; however, trichloroethylene, tetrachloroethylene, benzene, 1,2-dichloroethane, and methylene chloride were detected at 19, 17, and 6, 4 and 3 percent of the wells sampled, respectively. Vinyl chloride, carbon tetrachloride, and 1,2-dichloropropane were detected at less than 1 percent of the wells sampled.

The percentage of wells yielding water in which VOCs were detected at greater than or equal to one-tenth of the MCL varied by Physiographic Province. In particular, the median concentration of tricholorethylene (a commonly detected VOC) was greatest in the Piedmont Physiographic Province, and tricholorethylene concentrations were associated with urban land-use activities. Tricholorethylene also was detected frequently in water from wells in unconfined aquifers in the Coastal Plain Physiographic Province.

Aquifers in the three Physiographic Provinces in northern New Jersey (fig. 4) are unconfined aquifers in fractured bedrock and glacial deposits, whereas the aquifers in the Coastal Plain Province of southern New Jersey are both unconfined and confined. Coastal Plain aquifers are composed of sands and gravels. Factors that affect contaminant input and transport, such as land use and soil and aquifer characteristics differ among Provinces.

The variable selected to represent hydrogeologic sensitivity in water from CWS wells to contamination by VOCs is the average percent soil organic matter. The variables selected to represent potential contaminant-use intensity in water from CWS wells to contamination by VOCs are the area of urban land in 1995, the percent impervious surface in 1995, percent of commercial and industrial land use in 1995, and the density of solid-waste landfills, underground storage tanks and sites on the Known Contaminated Site List. No intensity variables were selected for wells in confined aquifers because the water in confined aquifers typically is not susceptible to contamination from the land surface.

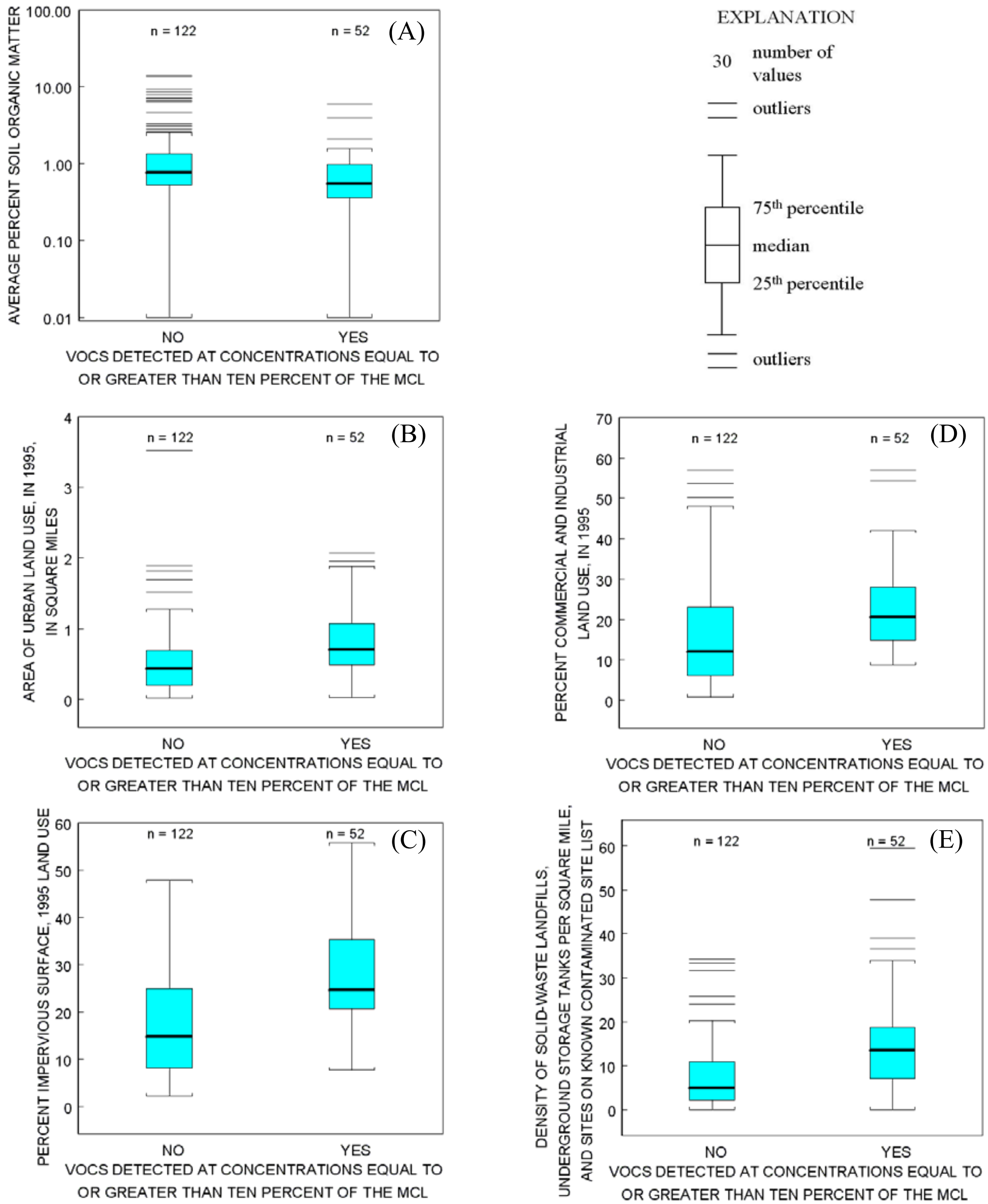

Figure 5. Distribution of (A) average percent soil organic matter, (B) area of urban land use, 1995, (C) percent impervious surface, 1995, (D) percent commercial and industrial land use, 1995, and (E) density of solid-waste landfills, underground storage tanks, and sites on the Known Contaminated Site List for samples in which one or more VOCs were or were not detected at concentrations equal to or greater than one-tenth of the MCL for 174 community water-supply wells in New Jersey.

Susceptibility of Ground-Water Sources

The results of the susceptibility assessment model indicate that, as intensity and sensitivity increase, frequency of detection of VOCs relative to one-tenth the MCL increases (fig. 6). Of the CWS wells used to develop the model, the susceptibility to contamination by VOCs was low for 39 wells (22%) and high for 135 wells (78%); only 1 out of 39 wells rated as low susceptibility has a frequency of detection greater than zero. The rating scheme created during model development was applied to the sensitivity and intensity variables of the 2,237 CWS wells for which the susceptibility was to be determined. The model predicted that concentrations would be either less than one-tenth of the MCL of the respective VOC or equal or greater than one-half the MCL of the respective VOC. No medium VOC susceptibility ratings were assigned to CWS wells. Of the 2,237 CWS wells to which the model was applied, the susceptibility to contamination by VOCs was low for 1,259 wells (56%) and high for 978 (44%) wells (figs. 1 and 2). Results of samples analyzed for VOCs in water from wells in confined aquifers indicate that wells in confined aquifers have low susceptibility to contamination by VOCs.

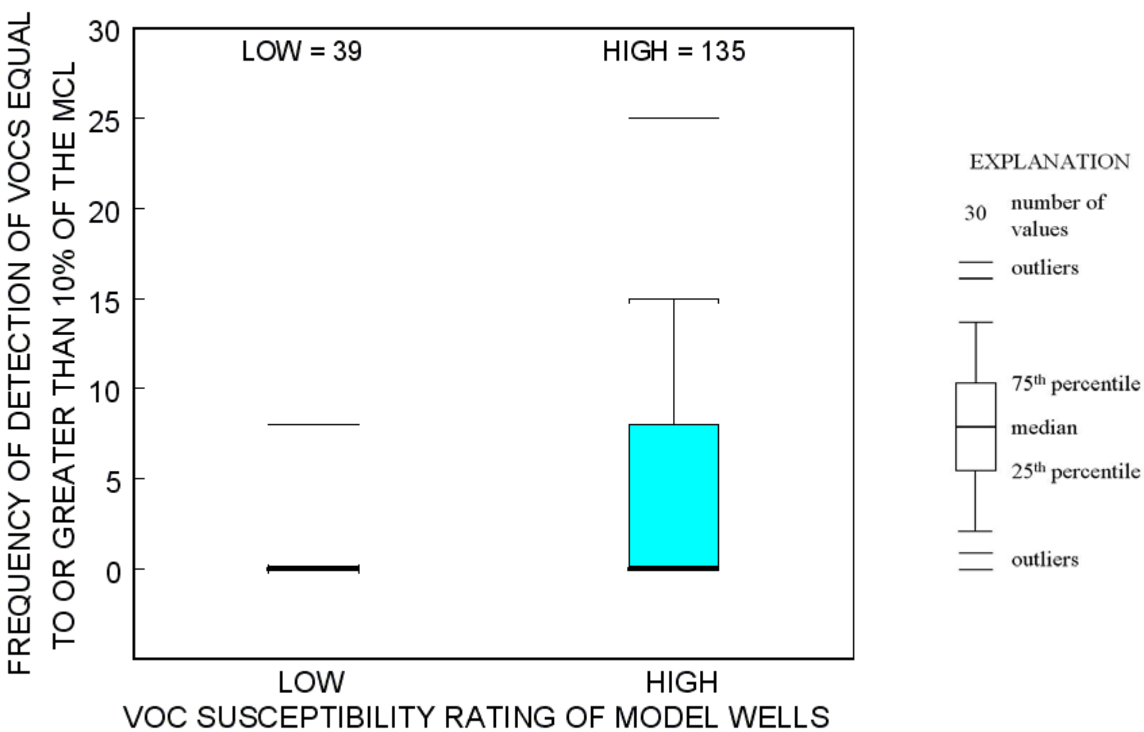

Figure 6. Results of volatile organic compound susceptibility assessment model for 174 community water-supply wells in New Jersey showing distribution of frequency of detection of VOCs relative to one-tenth of the MCL in water from Model 2 wells, by susceptibility rating. [MCL = maximum contaminant level]

Model Verification

The model was tested using only trichloroethylene concentrations in water from CWS wells used in model development. Trichloroethylene was not included in the group of 13 VOCs in the Model 2 data, although it was included in the group of 11 VOCs in the Model 1. As this compound played only a small role in the development, yet is a commonly detected VOC, it was a good candidate for testing the validity of the model. One out of 30 sites in the low-susceptibility category had a detected concentration of trichloroethylene greater than one-tenth of the MCL and the median concentration in the high susceptibility category was greater than one-tenth of the MCL (fig. 7), indicating the viability of the model.

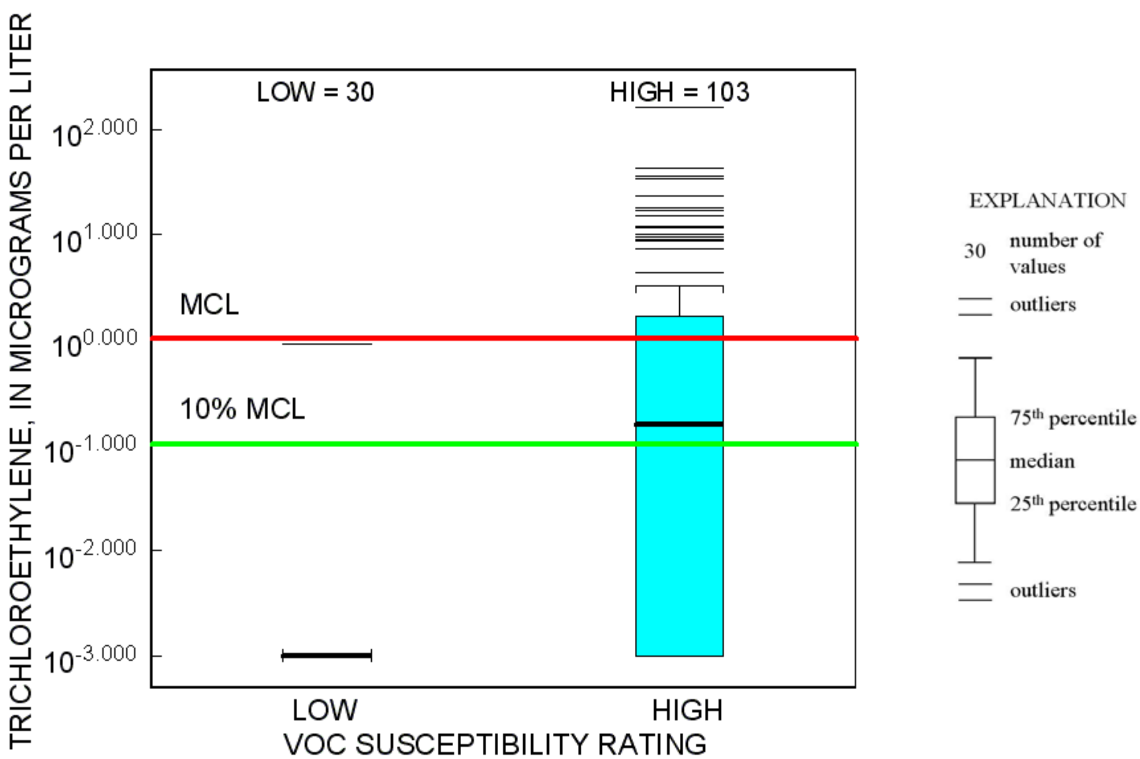

Figure 7. Distributions of concentrations of trichloroethylene in water from CWS wells in unconfined aquifers sampled by the U.S. Geological Survey, by VOC susceptibility rating.

Discussion

Several limitations to the susceptibility assessment models should be noted. These models should be used only as screening tools to identify potential contamination problems. The concentrations used for a well in the analysis were those measured in the most recently analyzed sample and do not take into account fluctuations in concentrations that may occur.

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 may bias statistical results, and land-use changes may cause spurious relations. 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.

Results of statistical tests performed on groups of VOCs, relative to the threshold of concern of the NJDEP, might differ if performed on individual VOCs. 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 well may be considered highly susceptible to contamination by VOCs and have no detections in samples from that well if VOCs are not used within the contributing area, or if contamination has not yet reached the well.

The database, GIS coverages, statistical analysis, and susceptibility assessment models can be used by scientists and water managers to help determine effects 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 can be used in determining and evaluating monitoring requirements for water purveyors to ensure public health.

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